U.S. Department of Energy

PHOTOVOLTAIC ENERGY PROGRAM CONTRACT SUMMARY

Fiscal Year 1999

INTRODUCTION

The goal of the Department of Energy's (DOE's) Office of Power Technologies is to create clean, competitive power technologies for the 21st century. In support of this goal, the mission of the DOE National Photovoltaics (PV) Program is to make PV a significant and vital part of the domestic economy in the years ahead, both as an industry and as an energy resource. Photovoltaics technology made major advances toward the promise of competitive electricity this year – with more record efficiencies and a rapidly growing industry. The Program's successes are described in the publication, *Photovoltaic Energy Program Overview, Fiscal Year 1999.*

The foundation of the Program's scientific success continues to rest in the partnership between the federal PV Program, universities, and industry. Direct research, as well as management of the bulk of subcontracted research performed by companies and universities in the Program, are provided by the two lead laboratories in the National Center for Photovoltaics (NCPV) – the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL). Brookhaven National Laboratory spearheads the efforts in environmental, safety, and health research. The Golden and Albuquerque DOE Field Offices also oversee subcontracted industry and university research.

This Contract Summary for fiscal year (FY) 1999 documents some 201 research projects supported by the PV Program, performed by 128 organizations in 33 states, including 66 projects performed by universities and 76 projects performed by our industry partners. Of the total 1999 PV Program budget of $70.56 million, the industry and university research efforts received $42.6 million, or more than 60%. And, of this amount, about 93% was for contractors selected on a competitive basis. Much of the funding was matched by industry cost-sharing. Each individual effort described in this summary represents another step toward improving PV manufacturing, performance, cost, and applications, and another step toward accomplishing the DOE PV Program's overall mission.

Two additional documents were produced during FY 1999 to guide Program's direction and strategy. The report, *U.S. Photovoltaics Industry: PV Technology Roadmap Workshop,* sets industry's ambitious goals for annual installed production capacity and PV system cost through the year 2020. The new *National Photovoltaics Program Plan, 2000-2004: Photovoltaics, Energy for the New Millennium,* details the R&D plan and accomplishments needed to make the journey charted out in the PV Industry Roadmap. The results presented in this summary show steady progress toward the Program's technical, performance, and economic milestones. The partnership that the Program has forged among industry, universities, and DOE represents a winning strategy—one that we will continue to rely on to maintain U.S. leadership in PV technology in the years ahead.

Program and Document Organization

The DOE National Photovoltaics Program supports efforts to make PV an important part of our economy through three main program elements: Research and Development, Technology Development, and Systems Engineering and Applications. The research activities are carried out in a coordinated manner by researchers from the national laboratories, industry, and universities.

Following is a brief description of the three main program elements:

- **Research and Development** activities generate new ideas, test the latest scientific theories, and push the limits of PV efficiencies in laboratory and prototype materials and devices. Other activities define environmental health and safety issues for facilities engaged in manufacturing PV products and for organizations engaged in PV research and development.

- **Technology Development** activities apply laboratory innovations to products to improve PV technology and the manufacturing techniques used to produce PV systems for the market.

- **Systems Engineering and Applications** activities help to improve PV systems and validate the improvements through tests, measurements, and deployment of prototypes. In addition, research on applications helps to validate sales, maintenance, and financing mechanisms worldwide.

The overall PV Program is a balanced effort of research, manufacturing development, and market development. All activities within the Program are planned and carried out in close collaboration and partnership with the U.S. PV industry. Critical to the success of this strategy is the PV Program's push to reduce the cost of electricity generated by photovoltaics. The program is tackling this goal in three primary ways: by making devices more efficient, by making PV systems less expensive, and by validating the technology through measurements, tests, and prototypes.

This document is organized into three main sections corresponding to the PV Program elements. The fourth section describes projects aimed at outreach and program planning, analysis, and management. Within each of the main sections, the first level of ordering of the projects is by the subareas listed in the Table of Contents. Individual projects are then ordered alphabetically according to the name of the performing organization. The appendices provide an indexing of the projects by name of the performing organization, state where the work is performed, and PV technology area. The following codes are used for the organization types:

CU College, Univ, or Trade School (Non-HBCU)
HB Historically Black College or University
FF Federally funded (R&D Lab Operated for Profit)
IN Private Industry
NP Foundation or Lab (Non-Profit)
ST Regional State, or Local Gov't Facility
TA Trade or Professional Organization
US Federal Agency
ZZ Foreign

Table of Contents

Research and Development

Fundamental and Exploratory Research

Standards for Future Generation PV Technologies

Contract #: AAD-9-18668-18	**Contract Period:** 5/19/99–7/18/02

<table>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $120,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The global objective of this project is to identify, explore, evaluate, and develop future generations of photovoltaic technologies that can meet the long-term goal of producing low-cost electricity from sunlight. The specific objectives of this project are two fold: (i) Develop qualification test standards for future generation PV technologies, and (ii) Explore absolute performance measurement issues for future generation PV technologies. The future generation PV technologies include CdTe, CIS and concentrators.

Approach/Background: Crystalline and amorphous silicon flatplate photovoltaic (PV) modules are currently listed or certified as meeting testing standards UL 1703 (Underwriters Laboratories), IEEE 1262 (Institute of Electrical and Electronic Engineers), and/or IEC 1215/1646 (International Electrotechnical Commission). The tests involved in these qualification standards provide assurance that the modules are durable, reliable, and safe. The existing test specifications in these test standards generally exclude, or are inappropriate for new technologies such as concentrator, CIS and CdTe. As a result, existing specifications must be expanded, or new test specifications developed, for each new technology.

New generation technologies are often developed by organizations that do not have the financial, equipment, or personnel resources to carry out the qualification testing. The developers of new technologies need access to a testing laboratory that will test at reasonable prices and test in a timely manner. Arizona State University - Photovoltaic Testing Laboratory (ASU-PTL) has long been involved in certifying the crystalline and amorphous silicon flatplate PV modules as per UL1703, IEEE 1262 and /or IEC 1215/1646 qualification test standards. With the current financial assistance of NREL, ASU-PTL is expanding its qualification test facility to accommodate the new generation technologies. During the course of this project, ASU-PTL will collaborate with NREL to develop the qualification test standards for new generation technologies.

Accurate measurement of absolute module performance is essential in order to: a) compare different technologies, b) measure module degradation and c) provide the buyer with assurance that they are getting what they pay for. ASU-PTL can measure large-area module performance with uncertainties of 3.6% or better for crystalline silicon modules, but accurate test methods have not been defined, developed or verified for the large area modules of other technologies. Furthermore, some of the new technologies do not lend themselves to performance testing by pulse type solar simulators. During the course of this project, ASU-PTL will develop OUTDOOR test methods for the accurate performance measurements of large area modules of new generation technologies.

Status/Accomplishments: The tasks related to achieve the first and second objectives constitute Phase II and Phase III of this project, respectively. Currently, this project is in the initial stage of Phase I and its objective is: Purchase and install necessary equipment to execute the tasks related Phase II and Phase III.

During the initiation period of this subcontract, most efforts were expended in determining the specifications, and writing the same, for the environmental chamber that will be used for testing concentrator type photovoltaic modules. The final version of shock chamber specifications/proposal was prepared by ASU-PTL after conducting an extensive telephone survey among the PV industry experts and consulting with the purchasing department of ASU. The primary specifications include: weight of test samples, temperature/humidity profile of the chamber, heating/cooling rates and interior workspace dimensions. The "request for proposal" was sent out to the potential suppliers at the end of September 1999. Currently, ASU-PTL is evaluating the responses received and will finalize the purchase by December 1999. In addition, one more conventional environmental chamber will be purchased (new or refurbished) and installed.

Two Eppley NIPS radiometers were obtained and sent to the National Renewable Energy Laboratory for calibration. These units will primarily be used for the evaluation of concentrator technologies. Design efforts for the mechanical load tester, water spray test station and wet insulation test station are under way.

Planned FY 2000 Milestones:
- Install equipment and conduct initial tests
- Support qualification test standards development for CIS, CdTe and concentrator technologies
- Develop additional test methods to test concentrator technologies
- Actively participate in the standards meetings such as IEEE Standards Association

Major Reports Published in FY 1999: The project is in the initial stage of Phase I and hence no major reports published yet.

Major Articles Published in FY 1999: The project is in the initial stage of Phase I and hence no articles published yet.

Fundamental and Exploratory Research

Low-Temperature, High Throughput Process for Thin, Large-Grained Poly Si

Contract #: AAD-9-18668-03	**Contract Period:** 5/24/99–7/25/02

<table>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $63,720</td><td>Cost Share Funding:</td></tr>
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Project Objective: The overall project goal is to understand the fundamental gas phase, surface and interface science issues relevant to low temperature (T < 600 ^oC synthesis of polycrystalline silicon films on low-cost (e.g., glass) substrates. This understanding will be used to delineate the path to break through existing barriers to high-rate synthesis of high-quality thin films for polycrystalline silicon photovoltaics applications. In this context, high quality refers to large grain size (> film thickness) and long (> film thickness) minority carrier diffusion length.

Approach/Background: The approach to high rate synthesis of large-grained films at low temperatures is twofold, consisting of

i) selective nucleation and solid phase epitaxy (SNSPE) growth to form a thin (< 1 μm thick) large-grained polycrystalline silicon template film from amorphous silicon starting material. The rate of solid phase crystallization is greatly enhanced relative to that for pure amorphous silicon via dopant-enhanced or silicide-enhanced crystallization, enabling large grain structures to be achieved at < 600 ^oC in reasonable times.

ii) high rate epitaxial growth of a thicker (1-30 μm thick) layer of silicon on the large-grained polycrystalline silicon template film by hot-wire chemical vapor deposition (HWCVD). The research on HWCVD is focused on both modeling and simulation of gas phase kinetic processes and film growth. Modeling efforts include quantitative models of gas phase species and reaction kinetics between the wire and substrate using continuum hydrodynamic transport couple to chemical kinetics simulations on a finite element grid as well as particle-based direct simulation Monte Carlo methods appropriate for low pressure reacting flows. Experiments include quadrupole mass spectrometry of gas phase species as well as film growth and characterization by reflection high energy electron diffraction, transmission electron microscopy, atomic force microscopy and Rutherford backscattering spectrometry.

Status/Accomplishments:

The accomplishments briefly noted below include but far exceed those outlined in the first year milestones of the original proposal.

- Determined relationship between SNSPE growth rate and P, B and Al dopant concentrations over concentration regime from $10^{19}/cm^2 – 10^{21}/cm^2$. Developed model for dopant enhanced solid phase epitaxy at high doping concentrations.
- Observed measurable vacancy concentration after solid phase epitaxy of P-doped silicon and identified P-vacancy correlation in silicon crystallized by solid phase epitaxy using multitechnique analysis including spreading resistance, secondary ion mass spectrometry, time-resolved optical reflectivity, transmission electron microscopy, positron annihilation spectroscopy (w/ Dr. K. Lynn of Washington State University)
- Demonstrated 30-50 μm silicon grain size during nickel silicide-mediated SNSPE at 550 ^oC.

- Identified the role of nickel-dislicide as a catalytic agent acting at the interface during selective nucleation and solid phase epitaxy, using microscale mapping of Ni concentration at doping levels using focused ion beam secondary ion mass spectrometry (FIB-SIMS) and microbeam X-ray fluorescence spectroscopy (w/ Dr. S. McHugo at Advanced Light Source, LBNL).
- Demonstrated the concept of completely solid state transformation approach to single crystal film formation on amorphous substrates by SNSPE with grain boundary filtration in mesa-patterned Ge/SiO_2.
- Demonstrated nanoparticle-induced selective nucleation using deposited Ni nanoparticles.
- Demonstrated Si epitaxial growth (by molecular beam epitaxy at 550 ^oC) on large-grained SNSPE polycrystalline silicon templates.
- Completed design and construction of hot-wire chemical vapor deposition system; began growth of polycrystalline silicon films by HWCVD using 1% silane in He.
- In HWCVD, demonstrated correlation between net polycrystalline film growth/etching rate and silane dilution (with hydrogen) as well as atomic hydrogen flux. Observed correlation between polycrystalline silicon grain size and silane dilution, using mass spectrometry and film growth rate measurements.
- Developed one-dimensional direct simulation Monte Carlo model for hot-wire chemical vapor deposition and applied model to reactor conditions of interest for amorphous silicon growth using pure silane and 1% silane diluted in He.

Planned FY 2000 Milestones:

- Continue investigation of template film growth processes.
- Continue investigation of nanoparticle-based selective nucleation, looking also at use of nanoparticle seeds to induce selective nucleation directly during HWCVD as well as SNSPE.
- Assess crystal quality in HWCVD films.
- Investigate HWCVD growth rate at $T < 500\ ^oC$.
- Investigate species concentrations in HWCVD gas phase ambient and compare with simulations.

Major Articles Published in FY 1999:

1. “Research Opportunities for Crystalline Silicon Photovoltaics for the 21st Century,” H.A. Atwater, B. Sopori, T. Ciszek, L.C. Feldman, J. Gee, and A. Rohatgi, in *Photovoltaics for the 21st Century*, V.K. Kapur, R.D. McConnell, D. Carlson, G.P. Ceasar and A. Roghatgi, Editors, PV 99-11, Electrochemical Society, Pennington, New Jersey (1999).
2. “The Role Of Vacancies And Dopants In Si Solid-Phase Epitaxial Crystallization,” C. M. Chen, S. Rassiga, T. Gessmann, M. P. Petkov, M. H. Weber, K. G. Lynn And H. A. Atwater, in *Amorphous and Heterogeneous Silicon Thin Films - Fundamentals to Devices*, H.M. Branz, R.W. Collins, H. Okamoto, S. Guha, and R. Schropp, editors. MRS Symposium Proceedings Volume 557, 1999.
3. “The Role Of Vacancies And Dopants In Si Solid-Phase Epitaxial Crystallization,” C. M. Chen, S. Rassiga, T. Gessmann, M. P. Petkov, M. H. Weber, K. G. Lynn And H. A. Atwater, *Proceedings of the 8th Workshop on Crystalline Silicon Solar Cell Materials and Processes*, Vail, CO, August 1999; NREL/BK-520-26941, pp 156-159.
4. “A Computational Model for Hot-Wire Chemical Vapor Deposition of Amorphous and Microcrystalline Silicon,” D. G. Goodwin in *Amorphous and Heterogeneous Silicon Thin Films - Fundamentals to Devices*, H.M. Branz, R.W. Collins, H. Okamoto, S. Guha, and R. Schropp, editors. MRS Symposium Proceedings Volume 557, 1999.
5. “A Relation Between Surface Oxide And Oxygen-Defect Complexes In Solid-Phase Epitaxial Si Regrown From Ion-Beam Amorphized Si Layers,” M. P. Petkov, C. M. Chen , S. Rassiga, H.A.Atwater, and K.G. Lynn, submitted to Applied Physics Letters November 1999.
6. “Grain Boundary Filtration By Selective Nucleation And Solid Phase Epitaxy Of Germanium Through Planar Constrictions,” H. Tanabe, C.M. Chen and H.A. Atwater, submitted to Applied Physics Letters, 1999.
7. “Hot-Wire Chemical Vapor Deposition of Poly-Si in Diluted Silane,” J.K. Holt, T. Bistritchan, M. Swiatek, D.G. Goodwin and H.A. Atwater, *Proceedings of the 8th Workshop on Crystalline Silicon Solar Cell Materials and Processes*, Vail, CO, August 1999; NREL/BK-520-26941, pp 160-165.

Fundamental and Exploratory Research

Elastic Properties of Thin-Film Silicon

Contract #: AAD–9–18668–12	**Contract Period:** 06/24/99 – 08/23/02

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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $ 62,250</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Thin–film silicon holds great promise as a semiconductor that can be produced economically on a large scale. Its exceptional properties for photovoltaic energy conversion have already been demonstrated and are the subject of intensive study worldwide. Yet, the entire field of heterogeneous thin–film silicon, also often referred to as polycrystalline silicon, is remarkably poorly understood, which is probably not too surprising given our limited understanding even of one of its constituents, amorphous silicon, in particular in its hydrogenated form. In the thin–film silicon, the interfaces between crystalline grains and between crystalline and amorphous regions appear to be of particular importance, since they are likely to lead to the exceptionally large optical absorption observed in these films, which exceeds that of both c–Si and a–Si:H. the understanding of the interfacial regions is however, entirely lacking. What is their fractional volume, and how can it be controlled? Where is the hydrogen located in these films, and what is its role for its electronic properties? A better understanding of these fundamental questions is crucial for the development of better photovoltaic devices, as well as for any other technological applications. This is the objective of the present study.

We will use the same elastic measuring technique used previously to study crystalline and amorphous films, utilizing the extensive experience and skills in film preparation and characterization available at NREL. Through such measurements, we hope to contribute to the understanding of heterogeneous solids in general, and in particular to help developing better and more durable photovoltaic devices.

Approach/Background: The thin films are deposited on a double–paddle oscillator etched out of high purity silicon. The bare paddle has an extremely small damping, and is therefore highly sensitive to any disorder in the film.

Status/Accomplishments: Since submitting the proposal leading to the present subcontract, we have discovered that excess hydrogen in amorphous silicon films produced by the Hot Wire Deposition Technique tends to collect at the interface between film and crystalline substrate, where it forms bubbles. The reason for this bubble formation is unknown. It is suspected that a similar formation may also occur in thin–film silicon, and possibly also at grain boundaries within those films. Thus, an understanding of the mechanism leading to the bubble formation seems to be a very important first step in understanding the role played by hydrogen in the thin–film silicon. We have subsequently discovered similar bubbles also in epitaxial silicon films, and are presently studying the conditions for their formation.

One of our main goals is to explore the disorder in thin–film silicon through its elastic properties. Our first measurements have yielded a very surprising result: As films are prepared with increasing hydrogen concentrations in the silane, their crystallinity is known to increase. As this crystallinity increased, the films internal friction was found to increase, indicative of an increased disorder, the opposite of what had been expected. The nature of this disorder is unknown.

Contract #: AAD–9–18668–12

Planned FY 2000 Milestones: 1) Amorphous to microcrystalline transition. Several paddles will be coated (PECVD and HWCVD) with a wide range of hydrogen dilution. Disorder will be studied through internal friction measurements. Film characterization will also be done at NREL, using IR absorption and x–ray diffraction. 2) Bubble formation at the epi–substrate interface will be studied through internal friction and optical microscopy. An important question we want to answer is the sensitivity of the elastic measurements for the detection of hydrogen bubble inclusions, and in particular whether this technique is useable for the detection of bulk hydrogen in thin–film silicon.

Major Reports Published in FY 1999:

Liu, X., Spiel, C.L., Pohl, R.O., Iwaniczko, E., Crandall, R.S. (1999) "Low Temperature Internal Friction Study of Light–Induced Structural Instability in Hydrogenated Amorphous Silicon," ICAMS–18, Snowbird, UT, to appear.

Metcalf, T.H., Liu, X., Pohl, R.O. "Internal Friction of Amorphous Silicon in a Magnetic Field," submitted to Phys. Rev. B.

Liu, X., Pohl, R.O., Crandall, R.S. "Lattice Vibrations of Amorphous and Disordered Crystalline Silicon," Physica B, in press.

Major Articles Published in FY 1999:

Fundamental and Exploratory Research

Photochemical Solar Cell Project

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $210,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: To develop and optimize the new dye-sensitized solar cell technology. Our overall goal is to develop cells that have a conversion efficiency of at least 15%, are cheaper to manufacture than existing PV solar cells and demonstrate long-term stability of 10–20 years.

Approach/Background: Dye-sensitized solar cells are a promising new kind of PV cell; they have demonstrated solar efficiencies of 10%–11% in a cell based on inexpensive materials and low-energy processing techniques. They have also been successfully employed in self-powered electrochromic windows. We are exploring methods of optimizing the performance and stability of the existing device while also exploring improved designs. To achieve these goals we are optimizing the parameters that affect cell efficiency such as the dye molecule, the redox relay system, electrolyte composition and modifications of the TiO_2 surface. Our improved designs are focused on an all-solid-state version of the dye cell and a tandem dye cell with an electron –injecting dye on the anode and a hole-injecting dye on the cathode.

Status/Accomplishments:

- Discovered that the PV characteristics of rutile-based TiO_2 solar cells are comparable to those of the convetional anatase-based TiO_2 solar cells for thin (<5 μm thick) TiO_2 films.
- Developed a method for preparing thick (12μm) crack-free nanocrystalline rutile TiO_2 films.
- Discovered that the J–V characteristics of an NREL fabricated cell, subject to continuous AM-1.5 illumination for 45 days, are essentially stable.
- Fabricated cells with a J_{sc} of 22.6 mA/cm^2 of a V_{oc} of 900 mV at AM 1.5 involving a non-state-of-the-art dye; these values are among the highest reported to date.
- Completed detailed studies on the influence of charge transport, and recombination on the photopotential and photocurrent conversion efficiency of dye-sensitized solar cells.
- Developed a model relating the time constants for charge collection and recombination to the charge-collection efficiency.
- Improved substantially methodology to obtain quantitative information on the recombination kinetics, charge-transport, and surface-state energy distribution in dye sensitized solar cells.
- Showed that treating the TiO_2 surface with methyl-trichlorosilane can slow the recombination rate by several orders of magnitude when using a ferrocene redox couple as a proxy for a solid state couple.

- Discovered that electropolymerizing a mixture of phenol and 2-allylphenol on the SnO_2 substrate electrode substantially reduces the rate of recombination at this surface.
- Developed improved methods for the synthesis of both TiO_2 and SnO_2 particles.
- Resolved a controversy by proving that the photovoltage is independent of the interfacial electrical potential but is controlled by the photoinduced gradient of the chemical potential.

Planned FY 2000 Milestones:

- Evaluate and quantify how electron transport and recombination limit PV characteristics.
- Explore a new material concept for improving electron transport.
- Evaluate and compare PV properties of rutile-based TiO_2 solar cells with those of the conventional anatase-based TiO_2 solar cells for thick (12 μm) TiO_2 films.
- Develop hole-injecting dye and high-surface-area p-type electrodes for tandem cell.
- Develop solid state electrolyte for solid state dye-sensitized solar cell.
- Test prototypes of tandem cell and solid state cell.

Major Articles Published in FY 1999:

Schlichthörl, G. et al., "Evaluation of the Charge-Collection Efficiency of Dye-Sensitized Nanocrystalline TiO_2 Solar Cells" *J. Phys. Chem. B* **1999**, 103, 782.

Park, N.-G. et al., "Dye-Sensitized TiO_2 Solar Cells: Structural and Photoelectrochemical Characterization of Nanocrystalline Electrodes Formed from the Hydrolysis of $TiCl_4$" *J. Phys. Chem. B* **1999**, 103, 3289.

Kopidakis, N. et al., "Ambipolar Diffusion of Photocarriers in Electrolyte-Filled, Nanoporous TiO_2" submitted.

Van de Lagemaat, J. et al., "Influence of Electrical Potential Distribution, Charge Transport and Recombination on Photopotential and Photocurrent Conversion Efficiency of Dye-Sensitized Nanocrystalline TiO_2 Solar Cells: A Study by Electrical Impedance and Optical Modulation Techniques," submitted.

Gregg, B. A. et al., "Dye-Sensitized Solar Cells: Energetic Considerations and Applications," *Z. Physik. Chem.* **212**, 11, (1999).

Deb, S. K., et al., "Photochemical Solar Cells Based on Dye-Sensitization of Nanocrystalline TiO_2," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*, AIP Conference Proceedings, Vol. 462, pp. 473-480 (1999).

Pichot, F., et al., "Flexible Solid-State Photoelectrochromic Windows," *J. Electrochem. Soc.* **146**, 4324 (1999).

Pichot, F., Gregg, B. A. "The Photovoltage-Determining Mechanism in Dye-Sensitized Solar Cells," in press, " *J. Phys. Chem. B* (1999).

Zaban, A., et al., "The Effect of the Preparation Conditions of TiO_2 Colloids on Their Surface Structure," submitted *J. Phys. Chem. B*

Aruna, S. T., et al., "The Effect of pH in Hydrothermal Synthesis of TiO_2 Colloids on Their Size and Crystal Structure," submitted, *Chem. Mater.*

Project Management

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $500,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:
- Develop information beyond the horizon of today's knowledge of photovoltaic technologies.
- Support fundamental research needed to help near-term and mid-term PV technologies meet long-term cost and performance goals.
- Support exploratory research directed towards non-conventional PV technologies having the potential to produce electricity at 5 cents/kWh.

Approach/Background:
- Fund the nation's best PV scientists at universities, national laboratories, and companies through competitive evaluation of proposals for basic research directed to PV program goals.
- Review the accomplishments and integrate promising results into the applied research and development activities of the DOE program.
- Assure the continuation of the program's support for fundamental and exploratory research. Decades of earlier support led to progress in amorphous silicon, CdTe, and CIS technologies, all technologies once known as non-conventional PV technologies and now important entrants in today's PV marketplace. Early support for GaAs compounds led to today's unprecedented success in high-efficiency tandem solar cells, now licensed by private companies for production and sales in markets for space satellite power systems. Further, this support, particularly at the nation's universities, has helped educate many of the staff of today's PV companies.

Status/Accomplishments: There was a significant rejuvenation in fundamental and exploratory research activities during fiscal year 1999.
- We awarded 18 subcontracts to universities in the Future Generation Photovoltaics competitive solicitation of research proposals. To make these awards we reviewed 71 proposals and found 41 to be in the competitive range worthy of funding. Limited funds permitted only 18 awards for the highest ranked proposals yet this is the largest percentage of proposals funded for fundamental and exploratory research in decades, more than 3 times higher than that awarded in the last solicitation. Supporting a large number of highly competent researchers, even with fairly low subcontract budgets, greatly increases the probability for successful, even breakthrough research results. And each subcontract supports at least two graduate students or post-doctorate researchers thereby providing an important supply of technically knowledgeable workers for PV companies. Finally, this solicitation, and an earlier FY 1998 competition for university PV research equipment, has significantly enhanced the participation and support of the academic community.
- In collaboration with the DOE Office of Science, we held a workshop on Basic Research Opportunities in Photovoltaics. The workshop brought together nearly 50 experts in PV and related fields to offer guidance for initiatives in high-payoff PV research

topics. The workshop was structured into eight areas: Amorphous and Microcrystalline Silicon, Crystalline Silicon, Cadmium Telluride, Copper Indium Diselenide, Gallium Arsenide-based Materials, Novel Materials for PV, Transparent Conducting Oxides and Characterization Techniques. After the workshop, the contributors in each area reviewed their key research issues and prepared final manuscripts for publication in a special volume of The Electrochemical Society entitled Photovoltaics for the 21st Century.

- In collaboration with The Electrochemical Society, Inc. we organized and convened a Symposium on Photovoltaics in the 21st Century as part of the 195th Meeting of the Electrochemical Society, held in Seattle,Washington, in May 1999. The Symposium focused on advanced concepts that are not currently being used in the PV industry, but that could be commonly used in the 21st century. The Symposium was the sequel to NREl's Future Generation Photovoltaics Technology Conference, first held in Denver, Colorado, in March 1997. More than two dozen presentations were made at the Seattle Symposium. Several excellent opening presentations covered the status of today's PV technologies and established criteria for tomorrow's PV concepts. Other presentations focused on nanocrystalline PV concepts, innovative material processing technologies, thin-film silicon, dye-sensitized PV cells, and techniques to characterize advanced materials. A half dozen presentations covered the exciting research developments in GaInNAs alloys, a material that could possibly enable a solar cell to convert an astounding 40% of sunlight to electricity. Such a cell would be suitable for concentrator modules that several private companies are developing. The symposium proceedings appeared in an Electrochemical Society Volume entitled Photovoltaics in the 21st Century along with the manuscripts from the Workshop on Basic Research Opportunities in Photovoltaics.
- Four key elements helped in preparing a plan for a Beyond the Horizon Photovoltaics initiative in FY 2000. The elements were the proposals submitted to the Future Generation Photovoltaics competitive solicitation, the first successful conference on Future Generation Photovoltaic Technologies in FY 1997, the sequel conference: the Symposium on Photovoltaics in the 21st Century and the recommendations from the workshop on Basic Research Opportunities in Photovoltaics. This plan for a new program on non-conventional, breakthrough PV technologies is under review by DOE. Implementation of the plan, including a competitive solicitation of proposals from the research community, is awaiting DOE approval pending Congressional budget appropriations for FY 2000.
- The first DOE/NREL Renewable Energy Academic Partnership (REAP) Program Review Meeting, to review progress on the subcontracts at eight Historically Black Colleges and Universities (HBCUs), was hosted by Southern University and A&M College in Baton Rouge, Louisiana in August 1999. The meeting provided an opportunity to bring HBCU undergraduates and professors together to learn from each other and other experts in their field. Presentations by advisors and students from each of the eight schools described projects including PV materials research, utility operation simulation of PV systems, PV in architecture, solar resource measurements, outreach activities at neighboring high schools, and international field projects in South Africa, Senegal, and Ghana. Outside of the school year, summer interns funded through this program reported on other PV projects at NREL and other institutions.

Planned FY 2000 Milestones:
- Provide timely funding for ongoing contract
- Convene HBCU Renewable Energy Academic Partnership Conference

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Major Articles Published in FY 1999:
V. K. Kapur, R. D. McConnell, D. Carlson, G. P. Ceasar, and A. Rohatgi, Editors, *Photovoltaics for the 21st Century, Proceedings of the International Symposium, Seattle, WA, May, 1999;* Proceedings Volume 99-11, The Electrochemical Society, Pennington, NJ

Fundamental and Exploratory Research

Solid State Spectroscopy of Photovoltaic Materials

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

<table>
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<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $330,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Recombination studies with submicron resolution in polycrystalline materials.

We propose to dramatically improve the spatial resolution (to ~100 nm) of our past Confocal Photoluminescence studies, and to combine these micro-spectroscopy techniques with our state-of-the-art ultra-fast spectroscopy capabilities in order to study thin-film photovoltaic materials with high spatial and temporal resolutions. Low-temperature scanning confocal microscopy (SCM) will be combined with time-resolved single-photon counting (TRSPC) detection to study polycrystalline CdTe thin films. Time-integrated PL spectral scans will be used to map the influence of domains and grain boundaries on photo-generated carriers. Time-resolved PL, will be used to study the effects of grain boundaries on photo-carrier recombination lifetime in the CdTe films. The resolution here will be better than 0.65µm.

Approach/Background: Although Atomic Force Microscopy and Scanning Tunneling Microscopy can achieve nano-scale surface topographic measurements, such structural data is only indirectly related to solar cell performance. Information on the electronic properties measured with microscopic resolution is certainly more desirable. Our approach can provide optical information on the submicron length scale, thus directly measuring the relationship between microstructure and photovoltaic properties. A systematic study of CdTe films that have been lifted off will be undertaken as a function of film growth parameters and grain boundary passivation techniques.

Status/Accomplishments:

- Completed study of CdTe grain boundary effect on lifetime studies.
- Published CdTe grain boundary recombination

Planned FY 2000 Milestones:

- Results of CdTe grain boundary effect on lifetime studies, Feb/00.
- Publications on CdTe grain boundary recombination, March/00
- Publications on GaAs:N, Jan/00 to Jun/00

Major Articles Published in FY 1999:

1. S. Smith, H.M. Cheong, B.D. Fluegel, J.F. Geisz, J.M. Olson, L.L. Kazmerski and A. Mascarenhas, "Spatially resolved photoluminescence in partially ordered $GaInP_2$," Appl. Phys. Lett. 74 (5) 706-8, 1 Feb 99.
2. J. D. Perkins, A. Mascarenhas, Y. Zhang, J. F. Geisz, D. J. Friedman, J. M. Olson, and S. R. Kurtz, "N-activated transitions, level repulsion and band gap reduction in $Ga_{1-x}As_xN$ (x<0.03)," Physical Review Letters **82**, 3312–3315 (1999).

Fundamental and Exploratory Research

Solid State Theory of PV Materials

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

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<tr><td>DOE Funding Allocation:
1999: $730,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

- Theoretical predictions of the fundamental physical properties of CdS/CdTe alloys, interfaces and impurities.
- Study defects in ZnO and explore new (including p-type) transparent conductors.
- Maintain, update and system-administrate the Solid State Theory Computer Network and develop new computer program for large scale computations on PV materials.

Approach/Background:

CdTe has an ideal band gap and high absorption coefficient which make it one of the strong contenders for low cost, high efficiency thin-film solar cell materials. CdS is also widely used as an n-type window material in solar cell device applications. However, many fundamental physical properties of the Cd-based semiconductor systems are not well understood. Our studies has contributed to the understanding of these important issues and can be used to guide future directions of R&D research in CdTe-based solar cells.

Transparent conducting oxides (TCO) are oxides that can sustain high concentrations of free charge carriers while, at the same time, maintaining a large band gap. There are only a handful of them despite the vast number of oxides existing in nature. Despite the technological importance of the TCOs in solar cell device applications, the origin of the native defect that controls the doping in TCO is not understood. For example, we do not know why there is an asymmetry in doping (almost all TCOs are n-type, rarely p-type). Our study is the first step towards the understanding of the unusual electronic properties of the TCOs.

Maintaining the SST computer network and developing new scientific computing programs are crucial for us to carry out the activities 1 and 2 above. Continued and stable PV support to this activity is needed.

Status/Accomplishments:

We have studied systematically the electronic properties of Cd-based compounds, alloys, interfaces and Cu_{Cd} and V_{Cd} impurities using the first-principles, self-consistent electronic structure theory based on the local density approximation (LDA). We calculated (a) the mixing enthalpy ΔH at x=1/2, (b) the valence band offset ΔE_v, (c) the band gap bowing parameters b, (d) the energy level of isovalent defects of Te substitution in CdS (CdS:Te), and (e) the formation energies and the transition energy levels of Cu impurity Cu_{Cd} and the Cd vacancy V_{Cd} in CdS and CdTe.

ZnO: We have found why ZnO can be doped heavily n-type while it cannot be doped p-type: there is a large difference between the formation energies of O vacancy and Zn vacancy that explains the above doping asymmetry. One can never dope ZnO p-type because the spontaneous formation of the O vacancy compensates all the intentional dopants, thus imposing a thermodynamic limit on p-doping. We also calculated the cation and anion dopants, Al and F. Both produce a shallow donor level near the CBM. We then calculated H impurity in ZnO. We found that the Zn-O bond center site is the stable site for neutral H, with a donor level 10 meV shallower than that of Al. Thus, H is the best dopant for ZnO among the impurities that we have studied; **(b) Cd_2SnO_4:** We found that bulk Cd_2SnO_4 is stabilized not in the normal spinel, but in the inverse spinel structure. We have studied the following important defects in this system: the Sn-on-Cd antisite, the Cd vacancy and O vacancy and the Cd interstitials. Similar to the case of ZnO, the O vacancy and the Cd interstitial have low formation energies while the cation (= Cd) vacancy has exceptionally high formation energy in such oxides. This explains why Cd_2SnO_4 is also an n-type TCO.

Develop new scientific computing program: Currently, most calculations for PV materials are performed using all electron linear augmented plane wave (LAPW) program based on local density approximation (LDA). Although the LAPW program is highly accurate, the computational effort required by LAPW is very intense. It is, thus, preferable to use the pseudopotential plane wave method (proportional to $N^2 \ln N$). The previous pseudopotential program developed at NREL is more than 10 years old. Compared to modern versions of similar programs, it is about 10 times slower and requires more memory. We developed a total energy pseudopotential program that has been fully tested. This new program is about 10 times faster than the previous pseudopotential program we have used extensively in our group.

We calculated the electronic structure of GaAsN alloys as a function of nitrogen concentration and pressure. We found that previous models that assume anti-crossing between the nitrogen level and the conduction band minimum (Gamma point) of GaAs are incorrect. The system exhibits instead a coupling between gamma, X_{IC} and L_{IC} states.

Planned FY 2000 Milestones:

- Theory of doping in CdTe (S.H. Wei)
- Theory of a-Si and micro-Si (S.B. Zhang)
- Theory of doping of CIGS (A. Zunger)

Major Reports Published in FY 1999:

Major Articles Published in FY 1999:

1) S.H. Wei, S.B. Zhang and A. Zunger, "Effects of Na on the electrical and structural properties of $CuInSe_2$," *J. Appl. Phys.* ***85***, 7214-7218 (1999).

2) S.B. Zhang, S.H. Wei and A. Zunger, "The microscopic origin of the phenomenological doping-limit-rule in semiconductors and insulators," *Physical Review Letters* (In Press).

3) S.B. Zhang, S-H Wei and A. Zunger, "Overcoming Doping Bottlenecks in Semiconductors and Wide-Gap Materials," submitted to ICDS-20.

4) S-H Wei, S.B. Zhang and A. Zunger, "First-principles Calculation of Band Offsets, Optical Bowings, and Defects in CdS, CdSe, CdTe and their Alloys," *J. Appl. Phys.* (In Press).

5) S.H. Wei, S.B. Zhang and A. Zunger, "Band structure and stability of zincblende-based semiconductor polytypes," *Phys. Rev. B. Rapid Communication 59,* R2478-2481 (1999).

6) S.H. Wei and A. Zunger, "Predicted band gap pressure coefficients of all diamond and zincblende semiconductors," *Phys. Rev. B.* 60, 5404-5411 (1999).

Fundamental and Exploratory Research

Novel Growth Methods for GaInNAs for High-Efficiency Solar Cells

Contract #: AAD-9-18668-08	**Contract Period:** 5/26/99–7/25/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: CU	**Congressional District**: 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Sala Bedair **Phone:** 919-515-5204 **E:mail:** bedair@eos.ncsu.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $59,590	**Cost Share Funding:**

Project Objective: We propose to investigate the $Ga_{1-y}In_yAs_{1-x}N_x$ material system for the bottom cell of the cascade structure. Lattice matching to GaAs can be achieved by adjusting the values of both x and y. A decrease in the bandgap from that of GaAs can be achieved by increasing the value of either x or y or both, while maintaining the lattice matching condition. Thus this quaternary alloy can offer, for the first time, the long awaited material system that can make possible optimum bottom cell performance in a cascade solar cell structure.

Approach/Background: GaInAsN suffers currently from incompatible growth conditions inherent to the chemistry of the material system. For example, (i) optimum growth temperatures of the respective GaN and GaAs compounds are ~1000 °C and ~700 °C respectively, (ii) the relatively low AsH_3/TMGa ratio required to allow for N incorporation in GaInAsN is not optimum for growth of good quality GaAs, and (iii) very poor incorporation efficiency of N due to the lack of efficient N sources at very low growth temperatures of ~600 °C or less. Conventional growth techniques such as MOCVD and MBE do not offer enough flexibility to address these incompatible growth conditions, resulting in the current status of relatively poor GaInAsN. We propose to use new techniques, developed in our lab, such as Atomic Layer Epitaxy (ALE) and Molecular Stream Epitaxy (MSE) where more flexibility can be offered by having separate exposures to column III and column V precursors. Precise control of exposure times to As and N containing precursors with optimum fluxes will benefit the controlled sequential growth of either the As or N sublattices. These techniques also allow growth at low temperatures since metal atoms (Ga or In) have higher mobility in the absence of column V species (As or N). Also, column V precursors decompose more readily on a growth surface occupied by metal species.

Status/Accomplishments: The necessary upgrades have been made to our MOCVD system to commence with GaInAsN growth: Bubblers of tertiarybutylarsine (TBA), tertiarybutylphosphine (TBP), and dimethylhydrazine (DMHz) have been installed and the necessary plumbing has been put in place to conduct growth experiments. The laboratory safety system has also been upgraded to add gas sensors for these toxic substances. Preliminary depositions of GaAs at low temperature (550 °C) have begun to calibrate the system and to assess initial film quality.

Planned FY 2000 Milestones: We plan to use atomic layer epitaxy (ALE) and molecular stream epitaxy (MSE) to enhance the incorporation of N in GaAs at low temperature by manipulating the precursor partial pressures, rotation speed, and sample exposure times to column III and V precursors. We also will investigate the effect of growth conditions on the quality of GaInAsN by reconciling optical and electrical properties with growth conditions.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999:

Parker, et al., "Critical layer thickness of GaN/$In_xGa_{(1-x)}N$ system," MRS fall meeting 1999, Boston, MA.

Fundamental and Exploratory Research

Improved Transparent Conducting Oxides for PV

Contract #: AAD-9-18668-05	**Contract Period:** 5/12/99–7/11/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: CU	**Congressional District**: 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Thomas O. Mason **Phone:** 847-491-3198 **E:mail:** t-mason@nwu.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1999: $75,520	**Cost Share Funding:**

Project Objective: This subcontract focuses on next generation transparent conducting oxides (TCOs) for improved photovoltaic performance. More specifically, there are two research foci—1) improved Sn-based, n-type TCOs aimed at enhanced CdTe PV cell performance, and 2) novel Cu-based, p-type TCOs applicable to a variety of existing and potential PV designs. The objective of the research under this subcontract is to identify, characterize, and optimize (e.g., by doping, annealing, etc.) novel compound transparent conducting oxides, both in bulk and in thin film form, for current and emerging photovoltaic technologies that can meet the long term goal of producing low-cost electricity from sunlight.

Approach/Background: Most current transparent conductors are primarily single-oxide host systems, e.g., based on In_2O_3, SnO_2 or ZnO. Our premise is that improvement in TCO behavior (higher conductivity, better optical transparency) will likely *not* be obtained in these already optimized materials. Our approach is to develop complex, compound oxide TCOs with improved TCO properties. Based upon well-known figures of merit for transparent conductivity, our approach is to develop high mobility, optically transparent materials. Several crystal-chemical strategies are being employed in this work—1) the development of layered TCO compounds, where doping takes place in carrier injection layers separate from the otherwise unperturbed conduction layers, 2) multi-site compounds, with separate sites involved in doping vs. conduction, and 3) electronic hybridization in multi-cation systems involving two or more TCO-active species (e.g., we are looking at ternary and higher combinations of d^{10} species like In, Sn, Zn, Cd, etc.). Cd_2SnO_4 is an excellent example of both multi-site and hybridization strategies and, as documented at NREL, possesses high carrier mobility. In addition, certain phases may form metastably in thin films which do not tend to form in the bulk. Again, Cd_2SnO_4 is an outstanding example. Our work (see below) shows that the orthorhombic form of Cd_2SnO_4 is stable in the bulk, whereas the high mobility spinel form can only be produced (and readily so) in films. Based on this and other similar observations, our approach calls for a combination of bulk and thin film methodologies to fully enable the development of novel TCO materials.

Status/Accomplishments: In the Cd-Sn-In-O system, two extensive solid solutions have thus far been found—a spinel phase extending from $CdIn_2O_4$ to between 75% and 80% Cd_2SnO_4, and a co-substituted bixbyite phase extending from pure In_2O_3 to at least x=0.18 in $In_{2-2x}Cd_xSn_xO_3$. One important ramification of the phase relations along the $CdIn_2O_4$-Cd_2SnO_4 vertical section is that beyond the solubility limit, the spinel phase is in equilibrium with essentially undoped orthorhombic Cd_2SnO_4 (having the Sr_2PbO_4 structure). This implies that the spinel form of Cd_2SnO_4 which forms in thin films is metastable, apparently stabilized by surface and/or strain effects.

Electrical property measurements (4-point conductivity, thermopower) and optical measurements (diffuse reflectance) were made on pellets of samples in both the $CdIn_2O_4$-Cd_2SnO_4 and $In_{2-2x}Cd_xSn_xO_3$ solutions. Conductivity (corrected for porosity) in both as-fired and reduced (annealed 6 h at 400°C in forming gas, in parentheses) specimens increases from 1600 S/cm (2300 S/cm) to 2600 S/cm (3600 S/cm) as x increases from 0 to 0.70 in the spinel system. These values extrapolate at x=1 (spinel Cd_2SnO_4) to values comparable to those reported in films, and are decidedly larger than we obtain for the orthorhombic phase of Cd_2SnO_4. This supports the notion that the cubic (spinel) form of Cd_2SnO_4 is metastabilized in thin films. Ongoing research on the spinel solid solution involves establishing the cation distribution between tetrahedal and octahedral sites via ALCHEMI (Atom Location by CHanneling Enhanced MIcroanalysis) and neutron diffraction Rietveld analysis. There is a precipitous rise in conductivity (and a similar drop in optical band gap, as determined by diffuse reflectivity) between 20% (optical) and 40% (electrical) $CdIn_2O_4$ in the $CdIn_2O_4$-Cd_2SnO_4 solid solution. We are investigating the possibility of a concurrent change in the site distribution of cations. The neutron diffraction results should also provide important clues about the intrinsic doping mechanism(s) of this phase (e.g., interstitial species). At the same time, we are carrying out room temperature thermopower measurements to ascertain whether the rise in conductivity is attributable primarily to increased carriers, mobilities, or both.

The bixbyite, $In_{2-2x}Cd_xSn_xO_3$, solid solution may also be of interest for potential PV applications. Conductivity in as-fired specimens remains relatively constant (~100 S/cm) over $0 \le x \le 0.16$, whereafter it increases rapidly to 700 S/cm at x=0.20. It should be cautioned that the ultimate solubility limit has yet to be firmly established for this phase. Nevertheless, given that these materials are neither intentionally Sn-doped or hydrogen-reduced, the values obtained are encouraging.

A program to investigate bulk p-type TCO behavior in the $CuAlO_2$-$CuGaO_2$-$CuInO_2$ system has just begun. Samples of $CuAlO_2$ and $CuGaO_2$ have been prepared and are being characterized.

Planned FY 2000 Milestones:

- Complete the Cd-In-Sn-O phase diagram.
- Fully characterize the phases (spinel, bixbytite, etc.) in the Cd-In-Sn-O system for TCO properties.
- Complete cation distribution analysis of $CdIn_2O_4$ and initiate similar studies (by TEM-ALCHEMI and neutron diffraction Rietveld analysis) in the $CdIn_2O_4$-Cd_2SnO_4 solid solution.
- Establish the origin of carriers (doping mechanism(s)) in Cd_2SnO_4.
- Fully characterize delafossite-based cuprates for potential p-type TCO behavior.
- Deposit films of $CdIn_2O_4$ and Cd_2SnO_4 by metalorganic chemical vapor deposition (MOCVD) and characterize for TCO properties.
- Deposit films of $CdIn_2O_4$ and Cd_2SnO_4 by pulsed laser deposition (PLD) and characterize for TCO properties.

Major Reports Published in FY 1999:

Kammler, D. R., Edwards, D. D., Ingram, B. J., Mason, T. O., Palmer, G. B., Ambrosini, A., and Poeppelmeier, K. R., "Novel Compound and Solid-Solution Transparent Conducting Oxides for Photovoltaics," in Photovoltaics for the 21st Century, Kapur, V. K., McConnell, R. D., Carlson, D., Ceasar, G. P., and Rohatgi, A., eds., Electrochem. Soc. Proc. 99-11 (1999) pp. 68-77.

Coutts, T. J., Mason, Perkins, J. D., and Ginley, D. S., "Transparent Conducting Oxides: Status and Opportunities in Basic Research," in Photovoltaics for the 21st Century, Kapur, V. K., McConnell, R. D., Carlson, D., Ceasar, G. P., and Rohatgi, A., eds., Electrochem. Soc. Proc. 99-11 (1999) pp. 274-288.

Major Articles Published in FY 1999:

D. R. Kammler, T. O. Mason, and K. R. Poeppelmeier, "Phase Relationships, Transparency, and Conductivity in the Cadmium Indate-Cadmium Stannate System, Chemistry of Materials, submitted.

Fundamental and Exploratory Research

Chemical Reaction Modeling for Encapsulants in Photovoltaic Modules

Contract #: AAD-9-18668-16	**Contract Period:** 5/24/99–7/23/02

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E:mail: robert_mcconnell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $54,170</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this work is to develop a database of the fundamental processes that can occur at the interfaces between the inorganic oxides, SiO_2, Al_2O_3 and TiO_2, and an organic polymer which contains the types of organic functional groups (OFGs) that are present in the EVA pottant layer in a field-exposed PV device. The database is expected to cover the effects of temperature and humidity, the effects of acetic acid and associated reaction rates and parameters for those processes likely to be critical in PV field degradation.

Approach/Background: The fundamental chemical processes that occur at model inorganic oxide(IOX)/OFG interfaces are to be explored experimentally through the use of model structures that incorporate essential features of actual PV structures. A comprehensive body of possible reactions will be tested for using two different types of basic structures: those made from self-assembled monolayers with specific OFGs and those made using polymer films. In the first structure, OFGs are to be reacted with vapor-deposited SiO_2, Al_2O_3 and TiO_2, with the emphasis on SiO_2. The effects of acetic acid (HOAc), T, and RH will be investigated with variations of T up to 85 °C. In the second structure polymer films will be formed on oxide substrates and the effects of HOAc, T, and RH studied. Once important processes are identified, ways will be developed to measure the reaction rates. The aim is develop reliable data that eventually can be used as input for predicting the long-term consequences of exposure of these interfaces to the environment.

Status/Accomplishments: The project funding started in June of this year (1999). During the summer an entering graduate student was trained in how to carry out the basic laboratory procedures necessary as a platform for doing the project work. In Sept. the student enrolled in the Chemistry graduate program and started the actual project work. For the 3 months from Sept. through Nov., the student has: 1.) Got the vacuum system running, 2.) completed the interface to an infrared spectrometer. 3.) obtained good spectra, and 4.) begun testing a new electron beam deposition apparatus. Further, the student has begun the deposition of thin (~20-30 Å polymer films (PMMA) onto sol-gel SiO_2 surfaces on Au substrates and native SiO_2 surfaces. Once these films are prepared work will start on studying the effects of T and RH on the interfaces.

Planned FY 2000 Milestones:
The preparations of IOX/OFG Structures will be optimized and initial runs with SiO_2 pursued. The new IR chamber wiill be working and the new XPS forechamber will be upgraded for e-beam deposition capability. All molecules for self-assembled monolayers (SAMs) will have been synthesized, at least 2 different SAMs prepared and characterized, initial runs with PVD SiO_2 deposition made using *in-situ* IR characterization and T-effects studied *in-vacuo.*

Polymer films on SiO_2 sol-gel films on Au supports will be prepared, characterized with emphasis on EVA, PVOAc, PVOH and PMMA. Characterization will include IR, ellipsometry, QCM and AFM. The effects of T, RH and HOAc will be studied. Initial thermally induced reaction rate runs will be summarized. From these initial sol-gel trials run and decision made whether to continue this route will be made.

Contract #: AAD-9-18668-16

Work will start with vapor deposition of SiO_2 on spin cast EVA, PVOAc, PVOH and PMMA films. Work will have begun on using small molecule models to see if the results will help understand polymer data.

Major Reports Published in FY 1999: In view of the short period of time since the project start, no reports have been made.

Major Articles Published in FY 1999: In view of the short period of time since the project start, no articles have been written..

Real Time Optics for the Growth of Textured Silicon Film Solar Cells

Contract #: AAD-9-18668-09	**Contract Period:** 8/13/99–8/12/02

<table>
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<tr><td>Organization Type: CU</td><td>Congressional District: 5</td></tr>
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1617 Cole Blvd.
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<tr><td>DOE Funding Allocation:
1999: $66,700</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The encompassing objective of this research project is to apply novel spectroscopic probes including ellipsometry and polarimetry both *in situ* and in real time to study the fabrication of textured thin films used in photovoltaics technology. The specific objectives of such studies are as follows: (i) to characterize thin film materials in their textured states as used in photovoltaic module production, (ii) develop improved optical models for surface roughness and non-uniformity from microscopic to macroscopic scales, and (iii) develop methods for measuring and controlling the evolution of roughness and texture in thin film solar cell fabrication.

Approach/Background: Thin film solar cell designs based on silicon employ textured film surfaces and interfaces to scatter the incident solar radiation into oblique angles so that it can be captured and absorbed within the film more efficiently. In effect, the texturing serves to increase the optical path length of the weakly-absorbed near-infrared rays within the silicon film, leading to an increase in overall absorptance, and hence an increase in solar cell efficiency. In spite of the importance of textured Si thin films, much of the basic research on materials and solar cells employs untextured (or specular) sample structures owing to the complexities introduced by light scattering. As a result of this emphasis, a basic understanding of the role of surface texturing has lagged behind other materials optimization issues. In this project, we develop and apply optical techniques that are suitable for real time analysis of textured surfaces during solar cell fabrication. Ellipsometric and polarimetric techniques are developed in which incident polarized light is directed at the textured surface at an oblique angle, and full spectra (275-825 nm) in the reflected beam (i) irradiance, (ii) polarization tilt and ellipticity angles, and (iii) degree of polarization are all determined with a time resolution of 50 ms. With such a capability, it is expected that one can design textured silicon surfaces based on a deeper understanding, rather than on trial-and-error.

Status/Accomplishments: Several important accomplishments toward the above objectives have resulted from efforts in FY 1999:

- Multichannel unnormalized Stokes vector spectroscopy has been developed for the first time; in this spectroscopy, one directs a polarized white light beam obliquely at a textured surface and measures the reflected beam irradiance, polarization ellipse, and depolarization versus photon energy. Because a photodiode array detector is used, this spectroscopy can be performed at high speed, opening up the way for real time measurements of textured surfaces during fabrication.
- Textured transparent conductors including doped SnO_2 from BP Solarex and Asahi Glass Co. have been measured in an ex situ mode using the unnormalized Stokes vector spectroscopy. Analysis of the reflected light beam characteristics provides spectra in the index of refraction n and extinction coefficient k for the bulk SnO_2 films, as well as the microscopic and macroscopic structure of the SnO_2. The microscopic structure includes surface roughness with in-plane scales less than the wavelength of the solar radiation (and so does not scatter the radiation), whereas the macroscopic structure includes roughness with scales on the order of the wavelength which leads to scattering.

- The fabrication of amorphous silicon solar cells on textured SnO_2-coated glass has been monitored in real time using unnormalized Stokes vector spectroscopy. The following information has been extracted: optical properties (n, k) of the individual p-type, intrinsic, and n-type layers; thickness evolution and deposition rates of the individual layers; and the evolution of the microscopic and macroscopic roughness layers on the surface of the film.
- Procedures have been developed to determine the evolution of the thickness uniformity in microcrystalline silicon p-layers deposited on specular ZnO-coated glass surfaces. This is an important capability since highly uniform growth over large areas is required for doped contact layers. The approach used here is now being extended to textured ZnO surfaces.

Planned FY 2000 Milestones:

Optical Modeling:

- Assess the need for effective medium theories, scalar and vector scattering theories, and geometric modeling to characterize light trapping and absorptance enhancement in solar cell component layers.
- Develop a database for the angular dependence of scattering from the surfaces of textured single-interface structures used in photovoltaics including opaque Si, Ag, and etched glass.

Materials Fabrication and Real Time Analysis:

- Complete operational rf plasma-enhanced chemical vapor deposition system for high rate microcrystalline silicon films.
- Develop capability of determining grain size evolution of μc-Si:H and poly-Si films from the thickness evolution of the micro/macro structure and the dielectric function.

Major Reports Published in FY 1999:

C.R. Wronski, R.W. Collins et al., "Wide-band-gap solar cells with high stabilized performance; Stable a-Si:H based multijunction solar cells with guidance from real time optics," in NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999) p. 241.

Major Articles Published in FY 1999:

P. I. Rovira and R. W. Collins, "Analysis of specular and textured SnO_2:F films by high speed four-parameter Stokes vector spectroscopy," *J. Appl. Phys.* **85**, 2015 (1999).

Joohyun Koh, et al., "Real time spectroscopic ellipsometry studies of the nucleation and growth of p-type microcrystalline silicon films on amorphous silicon using B_2H_6, $B(CH_3)_3$, and BF_3 dopant source gases," *J. Appl. Phys.* **85**, 4141 (1999).

Joohyun Koh, et al., "Amorphous/microcrystalline phase control in silicon film deposition for improved solar cell performance," *Mater. Res. Soc. Symp. Proc.* **536**, 451 (1999).

R. W. Collins et al., "Real time characterization of non-ideal surfaces and thin film growth by advanced ellipsometric spectroscopies," *Mater. Res. Soc. Symp. Proc.* **569**, 43 (1999).

Fundamental and Exploratory Research

Synchrotron Radiation Studies of Photovoltaic Materials and Devices

Contract #: AAD-9-18668-14	**Contract Period:** 4/21/99–6/20/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: CU	**Congressional District**: 27
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Y. H. Kao **Phone:** 716-645-2576 **E:mail:** yhk@acsu.buffalo.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $58,330	**Cost Share Funding:**

Project Objective: To determine the relationship between PV characteristics and interface morphology, stability of microstructures around heterointerfaces, and variation of PV material properties with local structural changes and defects.

Approach/Background: Study interfaces in various thin film PV materials using synchrotron radiation. As appropriate, carry out grazing incidence x-ray scattering (GIXS), x-ray absorption fine structure (XAFS), angular dependence of x-ray fluorescence (ADXRF), x-ray diffraction (XRD), and anomalous x-ray scattering (AXS) measurements to provide new information on the microstructures, interfaces, and layer-structured devices.

Status/Accomplishments: X-ray techniques using synchrotron radiation have been demonstrated to be very useful for probing short-range structures and interfaces in layer-structured PV materials. These nondestructive characterization methods are particularly useful for studying buried interfaces in layered materials from which useful information about conformality and texture of interfaces can be obtained.

The GIXS techniques can be conveniently used in PV materials characterization for:

-- Accurate determination of buried layer thickness
-- Measurement of interfacial roughness
-- Measurement of correlation lengths of interface height fluctuations
-- Determination of texture coefficient

The ADXRF and XAFS techniques can provide element-specific information about depth profile and local structures, especially useful for PV materials studies concerning:

-- Interdiffusion of constituent elements across heterointerfaces
-- Location of impurity atoms

These x-ray methods, in conjunction with XRD, have recently been applied to PV materials studies of the following systems and obtained some useful results:

Interface morphology in CdTe/CdS heterojunctions and its variation with annealing conditions.
Atomic depth distribution in CdTe/CdS and $CuInSe_2$(single crystal)/CdS heterojunctions.
Interface morphology between CdS and Cd_2SnO_4.
Microstructures in $In_xGa_{1-x}As_{1-y}N_y$ (x=0.07-0.08, y=0.02-0.03) and to determine the location of N impurities.
Morphology of interfaces between μc-Si, *a*-Si, SiGe, and c-Si

Much of these research projects as well as continued on-going experiments are carried out in collaboration with NREL research staff. Some results have already been reported at conferences and also published in refereed conference proceedings and journals.

Contract #: AAD-9-18668-14

Planned FY 2000 Milestones: To continue the present successful on-going experiments for the investigation of interface morphology and microstructures in various types of thin film PV materials. Further development of the ADXRF technique will be necessary in order to obtain more quantitative information on the intermixing of constituent atomic species in the heterojunctions such as CdTe/CdS, and the new junction systems formed between CdS and Cd_2SnO_4 or Zn_2SnO_4. A new model for statistical description of the interfacial height fluctuations and correlation lengths will be developed. Further, some optical measurements will be carried out to correlate some physical parameters relevant to PV performance with the microstructures determined from the x-ray experiments. Investigations of Cu-doped CdTe will also be conducted in order to acquire a better understanding of the location of Cu impurities in the host as well as the chemical state and bonding of Cu atoms with Cd and Te; this research will be of value for making improved back-contacts to the CdTe/CdS solar cells.

Major Reports Published in FY 1999:

Major Articles Published in FY 1999:

S. Huang, Y.L. Soo, M. Bechmann, Y.H. Kao, X. Wu, T.J. Coutts, R. Dhere, H.R. Moutinho, "Interface Morphology of CdS Thin Films Grown on Cadmium Stannate and Glass Substrates Studied by Grazing Incidence X-ray Scattering," *J. Vac. Sci. Technol.* **A17**, 2685 (1999).

Y.H. Kao, "Characterization of Microstructures and Interfaces in Thin-Film Photovoltaic Materials Using Synchrotron Radiation: A Review," *Photovoltaics for the 21st Century*, Proceedings of the International Symposium, The Electrochemical Society Procedings **99-11**, 153 (1999).

Y.H. Kao, Lawrence Kazmerski, Kelvin G. Lynn, and Angelo Mascarenhas, "Photovoltaics Characterization: An Overview," *Photovoltaics for the 21st Century*, Proceedings of the International Symposium, The Electrochemical Society Procedings **99-11**, 289 (1999).

Y.L. Soo, S. Huang, Y.H. Kao, J.G. Chen, S.L. Hulbert, J.F. Geisz, Sarah Kurtz, J.M. Olson, Steven R. Kurtz, E.D. Jones, and A.A. Allerman, "Local Structures and Interface Morphology of $In_xGa_{1-x}As_{1-y}N_y$ thin Films Grown on GaAs," *Phys. Rev.* **60**, 13605 (1999).

Fundamental and Exploratory Research

Photovoltaic Devices Based on New Nanocrystal Composites

Contract #: XAD-9-18668-02	**Contract Period:** 7/19/99–9/19/02

<table>
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None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $68,680</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this proposal is to prepare novel photovoltaics based on nanocrystal/polymer composites.

Approach/Background: There is a great need for inexpensive routes to prepare advanced photovoltaics. Colloidal nanocrystals may be a building block for such materials, since they afford the possibility of inexpensively preparing samples that display quantum size effects. By tuning the size of the nanocrystal it is possible to adjust the band gap and oscillator strength of the absorbing medium. The nanocrystals can be mixed with polymers, yielding a photovoltaic composite. Variations in the polymer can allow us to control the pathways for electrical conductivity.

Status/Accomplishments:
Prepared CdSe nanocrystals of various sizes
Prepared nanorods of CdSe
Prepared InP nanocrystals of several sizes
Prepared polymer composites with MEH-PPV and P3HT polymers
TEM characterization of all samples above
Preliminary electrical characterization

Planned FY 2000 Milestones:
- Evaluate electrical and photovoltaic properties of CdSe nanorod/P3HTphotovoltaics
- Further control morphology of nanorod/polymer composites
- Study morphology of nanorod/nanocrystal composites

Major Reports Published in FY 1999:
None

Major Articles Published in FY 1999:
None

Fundamental and Exploratory Research

GaInNAs Structures Grown by MBE for High-Efficiency Solar Cells

Contract #: AAD-9-18668-07	**Contract Period:** 6/25/99–8/24/02

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<tr><td>Directing Organization:
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $66,030</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: To investigate novel materials for high-efficiency multi-junction solar cells (SC's).

Approach/Background: To increase the conversion efficiency, tandem SC's, consisting of semiconductor SC's with different band gaps, are realized in monolithic or mechanically stacked design. Monolithic GaInP/GaAs tandem SC's, where GaInP has a larger bandgap than GaAs, has achieved record-setting efficiencies of 26% under the AM0 spectrum, and 30% at 500 suns terrestrial. If a SC with a bandgap smaller than that of GaAs can also be fabricated, the efficiency can be increased further.

Recently we and others have demonstrated that a new material, GaInNAs, can be grown lattice-matched to GaAs substrates and has a range of lower bandgaps than GaAs, in particular, 1.0 eV. We grow GaInNAs by gas-source molecular beam epitaxy using elemental Ga and In, thermally cracked arsine, and a RF plasma nitrogen radical beam source. This approach is expected to result in less carbon contamination as compared to metal-organic chemical vapor deposition.

Status/Accomplishments: A problem with GaInNAs is its low carrier mobility and short minority carrier lifetime due to alloy scattering and degradation of material quality with nitrogen incorporation. To minimize alloy scattering, we have investigated a short-period superlattice of GaAsN/InGaAs as a digital alloy of GaInNAs. The preliminary results are quite encouraging. The photoluminescence intensity is improved by a factor of 2.5 to 3, and the electron mobility is improved by a factor of almost two (227 vs. 133 $cm^2V \cdot s$).

Because we have found that suitable rapid thermal annealing improves the quality of many materials, we annealed the GaInNAs bulk layer and superlattice alloy samples. We found type conversion, from n-type to p-type, and we are continuing to investigate this issue. We are waiting for the results of secondary ion mass spectroscopy (SIMS) measurements for possible background contamination problems.

We have sent four samples to Dr. John Geisz of NREL for his electrochemical quantum efficiency measurements. He found the samples to have high n-type carrier concentration, but our Hall measurements indicated a low carrier concentration. We are waiting for SIMS results.

We have also grown a solar cell structure, according to the suggestion of Dr. Dan Friedman of NREL, and that sample needs further characterization and processing.

Since GaInNAs is a quaternary compound, it is better to study fundamental and unusual properties associated with nitrogen incorporation with the simpler ternary GaNAs compound. So far we have a very fruitful collaboration with Drs. Angelo Mascarenhas and Yong Zhang of NREL in elucidating physical properties of GaNAs and related material GaNP. Through them we are also collaborating with Prof. Venky Narayanamurti of Harvard University. Specifically we are investigating the underlying physical mechanisms of bandgap reduction, anomalous increase of electron effective mass, and observation of new interband optical transitions. Manuscripts were already submitted to journals, and abstracts were also submitted to conferences..

Planned FY 2000 Milestones: Continue the investigation of the short-period GaAsN/GaInAs superlattice approach to optimize mobility and carrier lifetime.

Investigate the type conversion and high p-type doping after annealing.

Grow solar cell structures with such a digital alloy and make comparison with random alloys of GaInNAs.

Major Reports Published in FY 1999:

Major Articles Published in FY 1999:
M. Kozhevnikov, V. Narayanamurti, C.V. Reddy, H.P. Xin, C.W. Tu, A. Mascarenhas, and Y. Zhang, "Evolution of GaAsN conduction states and giant Au/GaAsN Schottky barrier reduction studied by ballistic electron emission spectroscopy," was submitted to Physical Review Letters.

Other manuscripts are in draft form.

Fundamental and Exploratory Research

Growth and Characterization of GaInNAs for High-Efficiency Solar Cells

Contract #: AAD-9-18668-17	**Contract Period:** 7/29/99–9/28/02

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<tr><td>Organization Type: CU</td><td>Congressional District: 22</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $54,170</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:
UCSB:
Development of high quality (In,Ga)(As,N) by MOCVD and by MBE.

Harvard (subcontractor from UCSB):
Characterization of (In,Ga)(As,N) by STM and BEEM.

Approach/Background:
UCSB has carried out an extensive literature review of all previous work on GaNAs and InGaNAs. The reported properties, growth by MBE, CBE, and MOCVD, characterization and devices are being evaluated. Of particular interest in the early stages of our project are the MOCVD growth and device work – since our early focus will be on MOCVD growth. Many groups are using alternative precursors, particularly tertiarybutylarsine (TBA) and dimethylhydrazine (DMHy) for the group V sources due to their lower dissociated temperature, usually 500 – 600 C, which is advantageous as numerous studies have shown that higher growth temperatures result in lower N content of the films. Using N_2 as a carrier gas further enhances N incorporation into the films. It has also been shown that the N incorporation decreases with higher In concentrations in InGaNAs films. Again, however, using N_2 as the carrier gas helps with raising the N content. The optical quality of the films is greatly improved by post-growth rapid thermal annealing, as shown by many studies that shown an increase in PL intensity following this treatment.

At Harvard, Narayanamurti has collaborated quite closely with Prof. Charles Tu (UCSD) to make the first STM and BEEM measurements of MBE-grown GaNAs alloys for N concentrations ranging from 0.3% to 2.1%. The BEEM results clearly identify bands which vary markedly with N concentration. They show that N introduces significant band mixing between γ and L and that the impurity induced N resonant level is a smaller, pertubative effect. These measurements have shed a new light on the effects of N on the band structure which previously had relied solely on optical measurements, whose interpretation is controversial.

Status/Accomplishments:
UCSB: Two graduate students are being trained on MOCVD for this project. A new protocal is being developed for machine usage given the incorporation of arsenic into the reactor. A vertical showerhead reactor will be used for the epitaxy. The machine has been evaluated for the growth of GaNAs and InGaNAs and it has been found that no modifications will be necessary for the system. All necessary supplies have been ordered, including dimethyl hydrazine and a new reactor liner and susceptor. Initial growths will proceed in Dec. 99 or Jan. 00.

Harvard: The BEEM results clearly identify bands which vary markedly with N concentration. They show that N introduces significant band mixing betweem γ and L and that the impurity induced N resonant level is a smaller, pertubative effect. These measurements have shed a new light on the effects of N on the band structure which previously had relied solely on optical measurements, whose interpretation is controversial.

Planned FY 2000 Milestones:
UCSB:
1. Development of initial flow conditions for GaAs in the reactor (which is currently only used for GaN growth)
2. Development of complete flow, substrate temperature parameter space for the growth of GaNAs
3. Optimization of GaNAs growth based on doping level, PL intensity, morphology, and structure.
4. Provide samples to collaborators at Harvard.

Harvard:
During the course of the work, the Harvard group will maintain close ties with Drs. A. Mascarenhaus and Y. Zhang at NREL. In the coming year we plan to simultaneously measure the electro-reflectance (NREL) and BEEM (Harvard) on a wider range of NREL-grown MOCVD samples, particularly at very low concentrations of Nitrogen. We also plan to measure UCSB grown InGaAsN grown by MOCVD.

Major Reports Published in FY 1999:
This is the first year of the UCSB/Harvard program.

Medium Range Order and Stability in Amorphous Silicon

Contract #: AAD-9-18668-04	**Contract Period:** 6/23/99–8/23/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	University of Illinois Department of Materials Science and Engineering Urbana, IL 61801	
	Organization Type: CU	**Congressional District**: 15
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** John Abelson **Phone:** 217-333-7258 **E:mail:** abelson@uiuc.edu J. Murray Gibson **Phone:** 217-244-2278 **E:mail:** gibson@anl.gov	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $75,520	**Cost Share Funding:**

Project Objective:
This new contract is intended to resolve whether medium range structural order (MRO) is involved in the formation of metastable electronic defects in a-Si:H films used in solar cells. In order to understand the possible influence of MRO, we must (i) measure and model the existence of MRO in films deposited by various methods; (ii) determine how the order changes upon light soaking, and if reversibly; (iii) understand how the growth process, particularly the large flux of atomic H at the film surface, produces MRO in the microstructure; (iv) predict, through collaborations with solid-state theorists, the electronic structure associated with particular type and volume fraction of MRO in Si:H films; and (v) develop approaches to modify the MRO of a-Si:H films grown in industrial production, in order to reduce the Staebler-Wronski effect and increase solar cell efficiency.

Approach/Background:

The MRO of amorphous materials can be represented by higher order correlation functions of atomic positions. We recently developed a new technique called variable coherence transmission electron microscopy (VC-TEM) and shown that it is highly sensitive to three- and four-body correlation functions. Essentially, one is probing the statistical fluctuations in a mesoscopic volume containing about 1000 atoms, which is exquisitely sensitive to medium-range ordering. At present, the most effective way of analyzing our data is based on model simulations. The models we have used are a continuous random network and a “paracrystalline” structure that may be thought of as the fine-grained limit of the nanocrystalline state.

a-Si:H films which are resistant to metastable defect formation can be deposited under carefully chosen conditions: H_2 diluted silane plasma CVD and hot wire CVD are the most feasible in terms of practical solar cell production. The properties of a-Si:H films grown by hot wire CVD at high substrate temperature are substantially different from those of conventional films, including excellent electronic quality at a bonded H concentration of only a few atomic percent, a lower susceptibility to metastable defect formation, and the lack of an internal friction signature characteristic of all other amorphous materials. We will set up a hot-wire CVD system for the growth of a-Si:H films, and analyze the surface and sub-surface H reactions using RIR.

The detailed mechanisms by which reactive growth species interact with a growing surface to produce a-Si:H or μc-Si:H are complex and not well understood, but it is known that the insertion and removal of H from Si–Si bonds plays a key role in the development of the Si microstructure. We have developed an optically enhanced mode of real-time IR reflectance (RIR) spectroscopy to quantify the evolution of Si–H bonding during thin film growth or modification through changes in vibrational mode absorptions. Variations in the intensity, position, line width, and polarization dependence of the IR absorptions correspond to the quantity, configuration, local environment, and orientation of the bonds, respectively.

We will also use real-time spectroscopic ellipsometry (SE) to provide information complementary to RIR. Our SE instrument provides information on the film nucleation, microstructure, crystallinity, bandgap and composition via the optical dielectric response.

Contract #: AAD-9-18668-04

Status/Accomplishments:

In the first quarter of this new contract, we made the following progress:

• The analysis of TEM fluctuation microscopy data has been refined in order to precisely determine the degree of medium range order in Si:H samples of interest. (1) A method has been devised to accurately subtract the incoherent scattering background from the samples: a dark field image is collected at high scattering vector k, where the MRO produces no scattering modulation. (2) The thickness-dependent amplitude of the scattering modulation has been measured using a series of a-Si films, and the data modeled by a $t^{-1/3}$ dependence. These refinements will allow us to precisely compare data between different samples, or on a single sample after light soaking or annealing treatments. Any reversible structural change associated with the Staebler-Wronski effect may prove to be small.

• The minimum structural unit necessary to quantify MRO in a sample has been derived based on the Schlafli "circuit symbol" method in crystallography, which examines the number of neighbors and symmetry associated with all bonded loops (circuits) starting from a given atom. This method provides a rigorous mathematical definition of MRO, and has been used to clearly delineate the topologically amorphous vs. ordered regions in the "paracrystalline" structural model.

• We designed and constructed a HW-CVD apparatus in our laboratory, based on extensive consultation with the NREL in-house laboratory concerning the design of the filament / gas flow / substrate geometry and the parameters used to deposit interesting films, e.g., those with 1-2 at. % H content. Our filament assembly is compatible with both our 3-chamber system for device fabrication, and with our system containing the in-situ diagnostics of reflection IR spectroscopy and spectroscopic ellipsometry.

Planned FY 2000 Milestones:

We will obtain evidence for the degree of medium range order in the a-Si:H films, supplied by NREL team participants, which exhibit enhanced stability, as well as for changes in order upon light soaking. We will also obtain initial results on the mechanisms by which atomic hydrogen influences the film structure during deposition by hot wire CVD.

- Obtain a-Si:H films which exhibit enhanced stability from several research and industrial laboratories.
- Examine samples by VC-TEM to monitor the depth dependence of the structure.
- Perform VC-TEM on the a-Si:H films to assess the existence of MRO.
- Light-soak the films and perform VC-TEM to determine if the MRO changes.
- Deposit a-Si:H films in our laboratory using hot-wire and plasma-CVD.
- Analyze the growth reactions during hot-wire CVD using RIR, and formulate initial models.
- Formulate a molecular dynamics (MD) model of the paracrystalline structure, and test the stability as a function of the degree of hydrogenation.

Major Reports Published in FY 1999:

(None – new contact)

Major Articles Published in FY 1999:

(None – new contact)

Fundamental and Exploratory Research

Experimental Studies of Light-Induced Changes in Long-Ranged Disorder in Amorphous Silicon

Contract #: AAD-9-18668-13	**Contract Period:** 5/14/99 – 7/13/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	The University of Minnesota School of Physics and Astronomy Minneapolis, MN 55455 **Organization Type**: CU	**Congressional District**: 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** James Kakalios **Phone:** 612-624-9856 **Fax:** 612-624-4578 **E:mail:** kakalios@physics.spa.umn.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $42,920	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The principal objective of the proposed research is the experimental study and elucidation of the role that long ranged disorder plays in the light-induced metastable conductance changes in hydrogenated amorphous silicon (a-Si:H).

Approach/Background: Long range disorder (LRD) , due to compositional modulations or potential fluctuations on length scales of 100 – 1000 Angstroms, is believed to influence the current carrying states at and near the mobility edge in a-Si:H. Amorphous silicon films grown under varying deposition conditions, which have enhanced microstructure, have been synthesized. Experimental studies of the thermopower/conductivity activation energy difference, along with the non-Gaussian statistical properties of the conductance fluctuations, will be employed to quantify the long range disorder in these films, providing a connection between the structural and electronic disorder. Changes in the LRD with light soaking and annealing treatments will then be investigated.

Status/Accomplishments: A series of n-type doped a-Si:H films for which the deposition temperature during film growth was varied from 25 < T < 300 C for an rf power of 3W/50 cm^2 has been synthesized. Infra-red spectroscopy measurements confirm that the hydrogen content and microstructure (in particular the relative concentration of silicon-dihydride bonds) increases monotonically as the deposition temperature is decreased from 300 C to 25 C. The thermopower/conductivity activation energy difference also displays a nearly uniform increase as the deposition temperature is lowered, indicating that the electronic disorder is indeed sensitive to the hydrogen microstructure. However, we have found no change in this activation energy difference after 17 hours of white light exposure, even though both the conductivity and thermopower display clear reversible light induced changes. This preliminary result suggests that the LRD is unaffected by light soaking; a conclusion at odds with results reported by other groups. However, we have recently observed a small but real change in the activation energy difference, and hence in the LRD, in a film grown at 60C, that is, with much higher levels of initial disorder. Moreover, preliminary studies of the 1/f noise spectral density for these films find that the noise power <u>increases</u> following light exposure. This result agrees with independent studies by Verlag and Dijkhuis, who also find a reversible increase in the noise power magnitude following illumination, but is in conflict with the conventional interpretation of the 1/f noise as arising from charge trapping and release from localized defects (the well known increase in the density of defects with light soaking should <u>decrease</u> the noise power, due to ensemble averaging effects).

Planned FY 2000 Milestones:

The preliminary results sketched above indicate that for a-Si:H films with a large initial level of LRD, that there <u>is</u> a light induced increase in the activation energy difference. In the upcoming year we will:

1) Fully characterize the influence of light soaking on the thermopower/conductivity activation energy difference for this series of films for which the deposition conditions have been varied.

2) Continue studies of the 1/f noise, and ascertain the conditions for which the noise magnitude shows the largest increase following illumination.

3) Begin studies of the influence of high temperature anneals (that is, at temperatures above the deposition temperature of the material but below the temperature for which hydrogen evolves from the film) on the LRD and light-induced conductance changes. Nuclear magnetic resonance studies have found that such high temperature anneals can irreversibly alter the hydrogen microstructure without changing the total hydrogen content in the film.

Major Reports Published in FY 1999:
None.

Major Articles Published in FY 1999:
Quicker, D., West, P. W. and Kakalios, J., "Long Range Disorder and Metastability in Amorphous Silicon," Proceedings of the *18th International Conference on Amorphous and Microcrystalline Semiconductors; August 23- 27, 1999, Snowbird, Utah,* (in press).

Fundamental and Exploratory Research

Novel Capacitance Measurements in Copper Indium Gallium Diselenide Alloys

Contract #: XAD-9-18668-15	**Contract Period:** 7/1/99-8/31/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $41,670</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this research is to measure the electronic properties of copper indium semiconductors and copper indium/gallium diselenide alloys using several well-developed capacitance techniques appropriate for probing materials with a continuous distribution of electronic energy states in the gap. We will follow trends in the measured quantities as a function of different synthesis techniques and annealing conditions. Samples obtained through collaborations with related research teams at NREL will be compared with CIS and CIGS films grown at Oregon using elementally modulated reactants . The growth/suppression of particular defect levels and the importance of electronically active defects at grain boundaries will be probed. We will measure the valence band offset between copper indium diselenide and copper indium/gallium diselenide alloys using a heterostructure sample and an optical pulsing experiment.

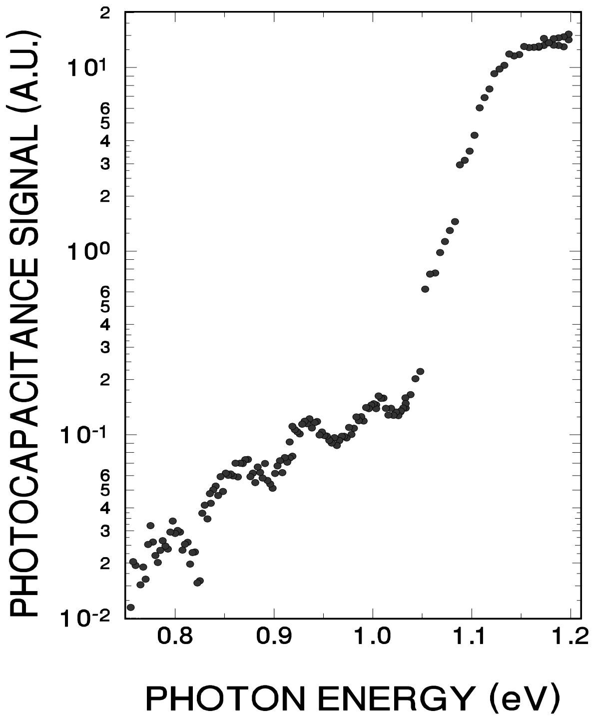
Approach/Background: The use of elementally modulated reactants has permitted the synthesis of many new compounds which are thermodynamically unstable with respect to disproportionation. In this synthesis approach, the ability to design reactants consisting of thin (10-100 Angstrom) elemental layers repeatedly deposited on a substrate gives control over the subsequent evolution of this reactant. Low temperature annealing results in an amorphous reaction intermediate. Nucleation controls what compound forms from this reaction intermediate, permitting thermodynamically stable reaction intermediates to be avoided. This approach is being used to prepare high quality samples of $CuIn_{1-x}Ga_xSe_2$ alloys. An advantage of this approach is the ability to grade composition and control the local concentration of defects and dopants. We are combining this new synthesis approach with sophisticated optical and capacitance techniques which will permit us to develop an understanding of the interaction between structure of the initial elementally modulated reactant, annealing conditions and defect levels in $CuIn_{1-x}Ga_xSe_2$ alloys. We intend to characterize optimized samples, both from our synthesis approach and from other related research teams at NREL, with the anticipation of following trends in the number of total defects, the growth and or suppression of particular defect levels, and the relative importance of defects at grain boundaries as a function of both synthesis approach and annealing conditions.

Status/Accomplishments: Growth and measurement studies have both been initiated. The sub-band-gap spectrum of a CIGS device measured at Oregon is presented on the next page.

- Cu, In, Ga and Se sources have been calibrated in the growth system.
- Initial ternary $CuInSe_2$ samples have been verified to be single phase using XRD.
- Sub-band-gap spectrum of a CIGS device was measured using transient photocapacitance spectroscopy.
- Band edge and Urbach tail with characteristic energy, E_o, of less than 20 meV was clearly identified.
- Urbach tail energy is related to level of disorder – a valuable characterization tool in the development of CIS technology
  - Can be measured in a working device
  - E_o in single crystal CIS is 7 meV
  - E_o in a sample grown using stacked elemental layers ~ 100 meV.
- Deep defect transition extending from 0.75 to 1.0 eV also observed – additional experiments underway to further characterize deep defects.

Contract #: XAD-9-18668-15

Photocapacitance sub-band-gap spectrum of one CIGS thin film solar cell device obtained from A. Delahoy at EPV. This type of spectroscopy is similar to other types of sub-band-gap spectroscopic methods except that, in this case, the detected signal originates from trapped charge which is optically excited into mobile conduction and valence band states so that it can escape from the depletion region near the barrier junction.



Planned FY 2000 Milestones:

- Synthesize $CuIn_{1-x}Ga_xSe_2$ films where x = 0, 0.2, 0.5
- Synthesize $CuIn_{1-x}Ga_xSe_2$ films with suitable contacts for capacitance measurements
- Conduct preliminary capacitance measurements of $CuIn_{1-x}Ga_xSe_2$ films where x = 0, 0.2, 0.5
- Follow the evolution of defects in $CuIn_{1-x}Ga_xSe_2$ films where x = 0, 0.2, 0.5 as a function of annealing temperature and time.
- Use optimized annealing conditions to prepare Schottky barriers on single-phase films.
- Measure continuous distribution of gap states of films grown at Oregon using capacitance and drive level profiling measurements
- Continue measuring continuous distribution of gap states of samples provided by NREL research teams using capacitance and drive level profiling measurements

Major Reports Published in FY 1999:
None

Major Articles Published in FY 1999:
None

Fundamental and Exploratory Research

Porous Polycrystalline Silicon Thin Film Solar Cells

Contract #: AAD-9-18668-06	**Contract Period:** 5/25/99–7/24/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $70,800</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:
The goal of this work is to develop an efficient thin film photovoltaic device using porous polysilicon technology.

Approach/Background:
The primary innovation incorporated into this project is the electrochemical etching of LPCVD polysilicon to form a porous polysilicon layer. This processing step provides three critical advantages that we believe will boost the efficiency of these solar cells. First, the porous surface is highly textured, leading to efficient collection of solar radiation with minimal reflection. Secondly, it is well known that the bandgap of porous silicon can be increased beyond that of crystalline silicon due to quantum confinement effects in the nanostructure of the porous material. This effect could be used to tune the bandgap of porous polysilicon toward the theoretical optimum bandgap of 1.5eV for maximal efficiency. Third, efficient photoluminescence of porous silicon could allow for the down conversion of higher energy (blue/UV) solar radiation into longer wavelength light (red/IR) which is absorbed more efficiently by bulk silicon.

The experimental approach is to first optimize our porous polysilicon photovoltaic device on a standard silicon wafer. Using a silicon wafer allows for simplified processing and an efficient back contact to the devices, while parameters such as doping concentrations, etching conditions, and top contact formation can be optimized. After optimal conditions are known, the Si wafer will be replaced with a glass substrate coated with a highly conducting ITO or silicide layer. The final device will then be optimized

Status/Accomplishments:

- The project just started very recently and it is now moving from the planning stage to the first results.

- The University of Rochester group met with subcontractor Prof. Sidhartha Duttagupta from Boise State University to plan initial steps for fabrication of devices. We looked into available fabrication facilities at the Rochester Institute of Technology (RIT), Cornell University, and several other sites across the country. We also gathered equipment and discussed a setup for in-house evaluation of our devices, which will later be benchmarked to the NREL testing facilities.

- Two graduate students went through orientation and initial training at the Cornell Nanofabrication Facility (CNF). Training has been completed on photolithography, the use of steppers and mask aligners, and reactive ion etching machines. Training on LPCVD will be completed by the end of the year.

Contract #: AAD-9-18668-06

- Initial substrate preparation has done at RIT and two students have become familiar with the facilities and the operation of LPCVD, reactive ion etchers, furnaces, and general lithography. The students have also be trained in the use of Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) at the University of Rochester for characterization of the porous films. Several preliminary electrochemical etching, porosity determination, and I-V measurements have also been conducted.

Planned FY 2000 Milestones:

- Produce a complete porous polysilicon device on a Si wafer with efficiency near 5% that can be tested at NREL and used to calibrate our testing facilities.

- Complete the setup and necessary programming for our light and dark I-V and spectral response characterization equipment.

- Completely characterize and optimize our device on a Si wafer.

- Begin working on the transfer of the device to a glass substrate.

Major Reports Published in FY 1999:
NA. The project just started a few months ago.

Major Articles Published in FY 1999:
NA. The project just started a few months ago.

Fundamental and Exploratory Research

Biomimetic Photovoltaics Employing Semiconducting Nanocrystal Multicomposites

Contract #: AAD-9-18668-11	**Contract Period:** 5/24/99–7/23/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Vanderbilt University Department of Chemistry Nashville, TN 37235 **Organization Type**: CU	**Congressional District**: 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** S. Rosenthal **Phone:** 615-322-2633 **Fax:** 615-343-1234 **E:mail**: sjr@femto.cas.vanderbilt.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $62,250	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The project seeks to develop a molecular photovoltaic (PV) device whose performance exceeds that of existing PV technologies (crystalline and thin-film semiconductor systems) in terms of device efficiency, flexibility of applications, and cost of production. To achieve this there are three primary design goals: 1) Efficient absorption of light and conversion into charge carriers. 2) Efficient (low-loss) transport of both electrons and holes to the external electrodes. 3) A cheap, scalable manufacturing process with the potential for making large area devices at costs (in $/kWh energy produced) competitive with conventional energy technologies.

Approach/Background: The design philosophy employs a biomimetic approach borrowing concepts from both conventional PV technology and photosynthesis. The main points are the use of an efficient molecular light-harvesting compound for converting light into charge carriers, coupled with balanced charge transport to the external electrodes. The former is achieved with the use of cadmium selenide (CdSe) nanocrystals (nc's). These nanocrystals are a robust, direct bandgap material whose absorption peak can be tuned over most of the visible solar spectrum. Hole transport is accomplished using a semiconducting polymer. Proof of principles for both of these concepts have been demonstrated in the literature. In addition, we intend to incorporate an efficient electron transporter in the form of soluble fullerene derivatives. The completed device will be a sandwich layer device using in order, a metal electrode layer, the photoactive composite layer consisting of conducting polymer, nc's, and fullerenes, a transparent conducting oxide (TCO) layer as the top electrode. An important design goal is assembly of the device using mild conditions, i.e minimization of energy-intensive (expensive) processes involving high temperature or high-vacuum. Hence, solution-based, wet-chemical techniques are preferred wherever possible. For instance, the assembly of the composite layer is accomplished simply by spin-coating a solution containing the various components onto a TCO-coated glass substrate.

In practical terms, there are three main components to the project: 1) Syntheses of the materials used in the device. This includes the nc's as well as the polymer and fullerene derivatives. In the case of the polymers, there also exist commercially obtainable alternatives. Similarly TCO's are commercially available on glass substrates (e.g. ITO, SnO_2). 2) Assembly of the device: This involves functionalizing the various components such that they are compatible with each other and the processes employed in building up the various device layers. 3) Testing and characterization of both the materials and completed devices. Due to the novelty of the materials and device architecture this necessarily involves a significant amount of basic research into the behavior of individual components as well as their interfaces.

Status/Accomplishments:

Materials procurement:
At this point all materials for the assembly of prototype devices have been obtained. We have:

- CdSe nc's in various sizes, synthesized in our lab, solubilized in chloroform

- poly-(2-methoxy, 5-(2'-ethyl-hexyloxy) p-phenylene vinylene) abbreviated as MEH-PPV, synthesized in our lab
- poly-3-hexyl-thiophene, abbreviated P3HT, purchased from Aldrich Chemical Corp and purified
- various C_{60} derivatives, soluble in chloroform, synthesized in our lab
- SnO_2 coated glass substrates, purchased

Materials characterization:
- Ultrafast fluorescence upconversion measurements on CdSe nc's in solution show two decay times on the picosecond and subpicosecond timescale, indicating the necessary timescales for efficient charge transfer to avoid recombination.
- STEM-EELS measurements on CdSe nc's embedded in MEH-PPV polymer demonstrate the existence of oxide at the nc-polymer interface.

Device assembly and characterization:
- Working prototype sandwich junction structure devices have been prepared using Al cathodes, SnO_2 anodes and photoactive composite layers of CdSe nc's in MEH-PPV and CdSe nc's in P3HT.
- Based on its superior solubility and better resistance to degradation under operation, P3HT seems to be the preferred polymer material at this stage. Device efficiencies appear to be similar for the two polymers, but at present we do not have sufficient data for meaningful statistical analysis.
- We have spin-coated polymer films up to 2000Å thick, with an optical density of ~1.
- We have performed plan-view TEM on a single MEH-PPV/CdSe/C_{60} composite. At the concentrations used, phase segregation resulted in the absence of a visible path for carrier percolation.

Miscellaneous:
- We have modified an existing pulsed-laser deposition system to allow the fabrication of 0^{18} doped indium tin oxide (ITO) electrodes for oxygen migration studies using Rutherford backscattering spectroscopy (RBS).

Planned FY 2000 Milestones: The next milestone will be the assembly of a functional prototype device containing all three components in the active layer, i.e. a polymer/CdSe/C_{60} composite. Given our current results, we will focus on the use of P3HT for the polymer. The preparation procedure for the composite layer will be further optimized to ensure reproducible results can be obtained. We expect this step to be completed in the first quarter of 2000. Once reproducibility has been achieved we will start to extract quantitative performance data from devices as a function of composition. Key among these quantities will be device efficiency and we will expend considerable effort to ensure that we have the facilities to ensure accurate and meaningful results. This includes procurement of a calibrated light source, which we hope to obtain soon through a collaboration with Oak Ridge National Laboratory. Additional, we are currently preparing our ultrafast fluorescence upconversion spectrometer to measure charge transfer rates in the composite films and expect to have results in the second half of the year. With a reproducible fabrication process established, it will also become meaningful to pursue structural analysis of the device. This will include RBS measurements on devices employing O^{18} doped ITO electrodes and further STEM-EELS analysis of the nanocrystal polymer interface, as well as cross-sectional TEM of device structures for defect analysis.

Major Reports Published in FY 1999:
None.

Major Articles Published in FY 1999: Kadavanich, A.V., Taylor, J., Underwood, D.F., Kippeny, T., Erwin, M.M., Pennycook, S.J., Rosenthal, S.J. "Analysis of the Nanocrystal Interface in Composite Photovoltaic Device Structures with an Active Layer Based on Semiconducting Nanocrystals." Proceedings of the Electrochemical Society, in press.

Kadavanich, A.V., Kippeny, T., Erwin, M., Rosenthal, S.J., Pennycook, S.J. "Z-contrast STEM Imaging and EELS of CdSe Nanocrystals: Towards the Analysis of Individual Nanocrystal Surfaces" in Semiconductor Quantum Dots – 1999. MRS Symposium Proceedings, in press.

Fundamental and Exploratory Research

Novel Characterization Methods for Microcrystalline Silicon

Contract #: AAD-9-18668-01	**Contract Period:** 5/24/99–7/23/02

<table>
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<tr><td>Organization Type: CU</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
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<tr><td rowspan="2">Technical Monitor:
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E:mail: robert_mcconnell@nrel.gov</td><td>B&R Code EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $ 75,520</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this project is to develop a detailed understanding of the nature of the defect states and the relationship between these defect states and their effect on photo-excited carrier processes in microcrystalline silicon and related materials using a combination of novel positron beam and femtosecond optical techniques. In particular, we expect to develop an understanding of the defect states and carrier dynamics as they occur in the different phases of heterogeneous thin film silicon and in amorphous silicon, with an emphasis on how they are influenced by deposition and processing techniques, so as to optimize the photovoltaic properties of the materials. This project has been limited owing to the lack of full funding in support of the two projects.

Approach/Background: This work incorporates both positron beam measurements and femtosecond laser spectroscopic measurements to directly determine the relationship between the nature of the defect complexes and their effect on photo-excited carriers. Positron annihilation measurements provide detailed information about the defect complexes in the microcrystalline and amorphous materials, and can identify both the type and concentration of defect states. Femtosecond optical measurements reflect the evolution of photo-excited carriers which, in the materials of interest, can involve carrier interactions with the defect states, including the carrier trapping and recombination processes that are crucial to understand and, thereby, control in order to develop and optimize the materials for photovoltaic applications. The optical studies include measurements sensitive to interactions involving the band-tail states near the mobility edge, which are expected to strongly influence the electronic properties of these materials. Positron annihilation and femtosecond laser spectroscopic measurements are carried out on various series of samples of microcrystalline and amorphous semiconductor materials. These studies are designed both to understand important fundamental properties of the materials, and to evaluate the effects of deposition and processing conditions.

Status/Accomplishments: Since the start of the project at the end of May, 1999, we have achieved a number of significant results.

In the positron annihilation studies, an initial experiment to understand the process of amorphization by $^{29}Si^{+}$-implantation and recrystallization to microcrystalline Si produced confusing results. Further investigation led to the first direct evidence that oxygen from a thin (≤5 nm) surface oxide layer is introduced into the bulk. The O atoms transported by multiple recoil off primary beam ions. O-defect complexes are formed during thermal treatment. The impurity-defect complexes could be identified by correlating the results from positron annihilation spectroscopy (PAS), secondary-ion mass spectroscopy (SIMS), and Monte Carlo simulations (TRIM). The signatures of large V_mO_n formations are observed after anneals at 800 °C, which implies the existence of smaller species at lower temperatures. The technological importance of these O-defect complexes calls for further detailed studies of their properties.

Our femtosecond studies have focussed on a-SiGe:H alloys prepared at NREL via hot-wire chemical vapor deposition (HWCVD). We have carried out measurements of the relaxation dynamics of photoexcited carriers in these materials using femtosecond pump-probe techniques, and have studied the response as a function of alloy composition (Ge content ranging from 0 to ~ 50 %), carrier excitation density, and excitation energy relative to the band gap (i.e. excitation of extended states vs. band tail states). As expected, the observed carrier relaxation dynamics are strongly dependent on carrier density, and the results at times ≥ 1 ps are well-approximated by bimolecular recombination kinetics. At shorter times, typically ≤ 500 fs, we have observed a dramatic departure from simple bimolecular recombination that is more pronounced for excitation near the band gap. This unusual early-time response, which to our knowledge has not been reported previously, results from an initial carrier distribution originating in band tail states rather than in more extended states above the mobility edge. We have designed and are carrying out a series of experiments to investigate in more detail the underlying physical mechanisms responsible for the dynamics. These studies should contribute to elucidating the nature of the carrier relaxation processes near the mobility edge.

During the last quarter, the PI (SLD) also met with NREL scientists Dick Crandall, Brent Nelson, and Harv Mahan to discuss additional materials for further studies. Brent Nelson has prepared a second set of HWCVD a-SiGe:H films with Ge content ranging from 0 to 10%, on which we are currently carrying out measurements, and additional studies of microcrystalline silicon and HWCVD a-Si:H as a function of the degree of crystalline order are currently planned.

Planned FY 2000 Milestones: With full funding, we expect to accomplish our next series of planned objectives:

We plan to extend our positron annihilation spectroscopy studies by carrying out measurements to examine the amorphous-crystalline interface at several stages of SPE. The remaining amorphous layer will be etched away to enhance the sensitivity of the spectroscopy to the thin interface region. The influence of co-implanted dopant ions will be examined. It is expected that results will be easier to interpret once the native oxide layer is removed prior to ion implantation. In addition, we will study the samples investigated in the femtosecond laser spectroscopic measurements using the positron beam apparatus. These measurements will be performed with and without light and the two measurements will be correlated.

We plan to extend our femtosecond studies on photoexcited carrier dynamics in hydrogenated amorphous Si and SiGe alloys by systematically investigating the influence of excitation energy, temperature, and degree of order. We also plan to begin our proposed studies of microcrystalline silicon to investigate relaxation processes of photoexcited carriers as they relate to relevant material parameters.

Major Articles Published in FY 1999:

Petkov, M.P., Weber, M.H., Lynn,K.G., Crandall,R.S., and Ghosh,V.J., "Direct evidence of phosphorous-defect complexes in n-type amorphous silicon and hydrogenated amorphous silicon," *Phys. Rev. Lett.* 82, 3819 (1999).

Kao, Y.H., Kazmerski, L., Lynn, K.G., and Mascarenhas, A., "Photovoltaics Characterization: An Overview." *Basic Research Opportunities in Photovoltaics, Proceedings, May 1999, Seattle, WA.*

Petkov, M.P., Chen, C.M., Rassiga, S., Atwater, H., Lynn, K., "A relation between surface oxide and oxygen-defect complexes in solid-phase epitaxial Si regrown from ion-beam amorphized Si layers," to be submitted to Appl. Phys. Lett.

Young, J.E., Nelson, B.P., and Dexheimer, S.L., "Photoexcited carrier dynamics in the band tail states of hydrogenated amorphous silicon," to be submitted to Phys. Rev. Lett.

Conference Presentations

Glasko, J.M., Weber, M.H., Lynn, K.G., Beaman, K., and Rozgonyi, G., "An investigation of the defects involved in the gettering of Fe in Mev ion implanted in Si," Material Research Society Spring Meeting: March 26, 1999, San Francisco, CA.

Weber, M.H., Petkov, M., Lynn, K.G., Crandall, R.S., and Ghosh, V.J., "Defect spectroscopy in hydrogenated amorphous silicon using positrons," International Conference on Amorphous and Microcrystalline Silicon, August 22-27, 1999, Snowbird, UT.

Young, J.E., Dexheimer, S.L., Nelson, B.P., and Crandall, R.S., "Ultrafast Carrier Dynamics in HWCVD Hydrogenated Amorphous Silicon Alloys," presented at OPTO-NorthWest, SPIE Regional Meeting on Optoelectronics, Photonics, and Imaging, 1-2 November 1999, Bellevue, WA.

Young, J.E., Nelson, B.P., and Dexheimer, S.L., "Ultrafast Dynamics of photoexcitations in HWCVD Hydrogenated Amorphous Silicon Alloys," submitted to Materials Research Society Symposium: Amorphous and Heterogeneous Silicon Thin Films—2000, Materials Research Society Spring Meeting, April 24-28, 2000, San Francisco, CA.

Dexheimer, S.L, Young, J.E., and Nelson, B.P., "Ultrafast dynamics of band tail carriers in hydrogenated amorphous silicon," to be submitted to the APS March Meeting, March 20-24, 2000, Minneapolis, MN.

Fundamental and Exploratory Research

Nanostructure Arrays for Multijunction Solar Cells

Contract#: AAD-9-18668-10	**Contract Period:** 5/12/99–7/11/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King / Jeffrey Mazer
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E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">West Virginia University
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Morgantown, WV 26506-6109</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Biswajit Das
Phone: 304-293-6371 x525 E:mail: das@csee.wvu.edu</td></tr>
<tr><td rowspan="2">Technical Monitor:
Robert McConnell
Phone: 303-384-6419
Fax: 303-384-6481
E:mail: robert_mcconnell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $66,700</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this project is to develop multijunction photovoltaic cells using stacked layers of semiconductor nanostructures. This will be accomplished by the fabrication and characterization of single junction PV cells using quantum wires, stacked single junction cells using quantum dots, and finally stacked multijunction cells using quantum dots.

Approach/Background: Nanostructure based PV cells have been previously proposed for their potential to provide a very high energy conversion efficiency due to quantum confinement effects. However, a major impediment to the development of this technology has been the inability to fabricate large arrays of semiconductor nanostructures with the required periodicity and size control at a low cost. To meet this challenge, we are currently using a template based nanostructure fabrication technique for developing high efficiency PV cells. The fabrication technique is based on electrochemical synthesis of semiconductor nanostructures on a template formed by the anodization of an aluminum thin film. This approach provides the ability to fabricate a variety of semiconductor materials on an arbitrary substrate with good control over the size, shape and periodicity of the nanostructures.

The above objective will be accomplished in three phases. First, n-type and p-type semiconductor quantum wire arrays will be fabricated and characterized. Then, these materials will be combined to form arrays of p-n junction quantum wires. Finally, stacked layers of uniform sized quantum dots will be fabricated and characterized. This will require innovation in the electrochemical fabrication of doped compound semiconductor nanostructures, the ability to fabricate abrupt interfaces between different materials using electrochemical synthesis, and an analysis of both the optical and electrical properties of doped semiconductor quantum wires.

Status/Accomplishments: This project is currently in Phase I with a primary objective of fabricating n-type semiconductor quantum wires. The principal accomplishments during FY 1999 have been to hire the initial research team, upgrade our fabrication facilities, and to identify the size, composition and the substrate material needed for quantum wire fabrication. This has been accomplished through the following specific tasks:

1) The thermal evaporation capabilities at WVU have been upgraded to enhance the efficiency and purity of our metal deposition process. This is essential to avoid defects and chemical contamination in the aluminum oxide templates. In addition, our anodization apparatus has been redesigned to increase the efficiency of the template formation process both in terms of time and material utilization. An article describing the final design has been submitted to the Journal of Scientific Instruments.

2) We have developed and refined the process recipes for the substrate cleaning and aluminum deposition processes. In addition, we have developed a process for the deposition of transparent, conducting gold layers for use as electrical contacts to the nanostructure layers. Finally, we have discovered a potential method for the anodization of aluminum thin films without the need for a second back contact. This approach is currently being investigated to determine the resulting pore uniformity.

3) A computer program has been developed using Mathematica to relate nanostructure size and composition to the absorption edge to determine the optimum material for nanostructure synthesis. The results of this model are being compared with other theoretical and experimental results to calibrate this model.

4) The most suitable substrate material for use in this research and for future commercial applications has been identified to be commercial plate glass. This will provide a substrate material and an associated manufacturing/transportation infrastructure at a very small additional cost. To evaluate this option, we have identified a large commercial manufacturer of architectural glass to provide information on integrating the nanostructure fabrication process for volume production. For the initial process development, we have determined that reclaimed silicon wafers are the most economical substrates for fabrication. However, test runs will be conducted on glass and plastic substrates to verify the compatibility of the fabrication process on other materials without substantial degradation in the nanostructure properties.

Planned FY 2000 Milestones: The goals for FY 1999 include the objectives for the last half of Phase I, and the first half of Phase II. In particular, we will fabricate and characterize an array of n-type semiconductor quantum wires. Then, we will identify the best p-type doping material and fabricate p-type quantum wire arrays. This will be accomplished using the following procedure:

1) Semiconductor quantum wires formed in the II-VI material system (Cd,Zn),(S,Se) will be electrochemically fabricated using the aluminum oxide templates with pore diamters in the 4-20 nm range. The resulting quantum wires arrays will be characterized by standard photoluminescence measurements to determine the optical properties of these materials. They will also be investigated using a Scanning Auger technique to determine material uniformity of the quantum wires and the presence of any contaminant materials. Finally, the electrical properties of the quantum wires will be determined experimentally.

2) Collaboration with other researchers is currently being developed to investigate the electrical properties of the p-n junction quantum wires. This is important for the determination of the optimum material configuration for the final photovoltaic cell structures. Since this work would also be of general scientific interest, funding from other agencies will be solicited for this research.

3) We will continue to work to improve the size uniformtiy and periodicity of the aluminum template. In particular, we will evaulate whether recent results indicating a self-ordering behavior in these films for certain process conditions can be used to create a near-perfect template material.

Major Articles Published in FY 1999:

1. B. Das, S.P. McGinnis, and P. Sines, "A Low Cost High Efficiency Multijunction Photovoltaic Cell Using Electrochemically Fabricated Semiconductor Nanostructures," Invited Presentation, *Photovoltaics for the 21st Century,* 196th ECS Meeting, Seattle, WA, May 1999.

2. C. Garman, P. Sines, S. McGinnis and B. Das, "An improved automated anodization apparatus for fabricating nanostructure devices and porous silicon," Rev. Scientific Instruments (in review).

HBCU PV Research Associates Program

Renewable Energy Technology & Technology Applications for Developing Countries

Contract#: XAK-8-18675-01	**Contract Period:** 3/29/99–3/28/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Central State University Office of Sponsored Research Wilberforce, Ohio 45384	
	Organization Type: CU	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Clark W. Fuller **Phone: 937**-376-6312 **Fax:** 937-376-6598 **E:mail**: cfuller@prodigy.net	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1999: $ 21, 856	**Cost Share Funding:**

Project Objective: As sponsored by the National Renewable Energy Laboratory, Golden, Colorado, the Central State University HBCU Photovoltaic Research Associates Program provides undergraduate scholarship and program support funds for the pursuit of study and research in the field of renewable energy and photovoltaics at Historically Black Colleges and Universities (HBCUs). The aim is to attract qualified sciences, engineering and business students toward pursuing a career in these areas with emphasis in photovoltaic technology.

Approach/Background: Since the early 1990's, Central State University has utilized its experience and expertise with the "Northern Senegal Water Management Project" (NSWMP) to form the core in developing the foundation for student training and research under the NREL program. The NSWMP is a natural resources project in Senegal, West Africa, and is designed to develop self-sufficiency among Senegalese villagers by providing them with the expertise and materiel to install and maintain their own renewable energy water pumping systems (wind and solar energy technology). While under the sponsorship of the NREL scholarship program, students who participate in the program not only learn the basics of wind and solar technology, but they also focus on research in ways in which photovoltaics can provide new and supplemental energy sources to address the critical shortage of water in many developing countries. Students have the opportunity to participate in hands-on research at many domestic locations and laboratories as well as participate in one or two overseas projects located in South Africa or Senegal.

Status/Accomplishments: From April 1, 1999 through October 1, 1999, three Central State students have benefited with partial scholarships under the program (Charlie Hurt, prime student, Junior, Water Resources Management major; Michael Ayeni, alternate student, graduating Senior, Manufacturing Engineering major; and Kishinna Foxie, alternate student, Junior, Water Resources Management major.

- All three students enrolled in and successfully completed the course ENG 450, "Applied Renewable Energy Technology".
- All three students participated in the construction and testing of renewable energy water pumping devices installed as part of an energy demonstration site located on the Central State University campus.
- All three students planned, coordinated or participated in a one week, Central State University Renewable Energy Summer Camp conducted on-campus for 25 regional high school students.
- One student (K. Foxie) completed a summer internship at Texas Southern University as part of the Renewable Energy Academic Partnership (REEP) program in South Africa.

- One student (C. Hurt) completed a summer internship with World Vision International as part of a renewable energy water project in Senegal, West Africa.
- All three students participated in the HBCU Science and Technology Conference hosted by the Ohio Aerospace Institute, Cleveland, Ohio.
- All three students provided technical input for the CSU/NREL program briefing presented at the Renewable Energy Academic Partnership (REEP) Conference, Southern University.
- One student participated in the Annual Farm Science Review held in London, Ohio.

Planned FY 2000 Milestones:

Fall Academic Quarter, 1999: Prime student (Charlie Hurt) and alternate student (Kishinna Foxie) present oral and written presentations at on-campus and off-campus functions regarding their summer renewable energy internship experiences. The prime student also performs regional visits to renewable energy manufacturer locations, interconnects the on-campus weather station and the local test and demonstration site, and conducts various electronic research tasks on the Internet to solve various renewable energy technology problems.

Winter Academic Quarter, 2000: Prime student (Charlie Hurt) and alternate student (Eben Smith) both enroll in an advanced course related to renewable energy technology. Students also provide input for a Central State University presentation at the American Indian Science and Engineering Society Conference, Minneapolis.

Spring Academic Quarter, 2000: Prime and alternate program students assist in planning the CSU Renewable Energy Summer Camp 2000 for high school students. Both students perform installation and construction tasks at the on-campus Renewable Energy Test and Demonstration site. Both students attend regional technology conferences and fairs (Renewable Energy Exposition, Madison Wisconsin and HBCU Technology Conference, Cleveland, Ohio).

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Major Articles Published in FY 1999:
None.

HBCU PV Research Associates Program

Undergraduate PV Research Projects

Contract #: XAX-5-15021-2	Contract Period: 9/21/95–5/31/01

Sponsoring Office Code: EE-11	Performing Organization(s)	
DOE HQ Program Manager: Richard King — Phone: 202-586-1693 — Fax: 202-586-8148 Jeffrey Mazer — Phone: 202-586-2455 — Fax: 202-586-8148 E:mail: Richard.King@ee.doe.gov E:mail: Jeffrey.Mazer@ee.doe.gov	Clark Atlanta University James P. Brawley at Fair Street, SW Atlanta, GA 30314	
	Organization Type: HB	**Congressional District**: 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Gerald W. Grams **Phone:** 404-880-6907 **E:mail** ggrams@cau.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1997: $20,122 1998: $60,365 1999: $0	**Cost Share Funding:**

Project Objective: The Clark Atlanta University (CAU) Historically Black Colleges and Universities (HBCU) Photovoltaic Research Associates Program provides financial support and research opportunities for undergraduate students to enhance the student's knowledge in the field of photovoltaic research and to encourage them to pursue careers in photovoltaics.

Approach/Background Research activities initiated by past collaborations between Clark Atlanta University and Vista University in Port Elizabeth, South Africa, will be continued. The primary goal of that work was to determine the effects of atmospheric variability on the production of solar energy by photovoltaic devices. A combination of solar radiation measurements, meteorological observations, and computer modeling work will be used to carry out an assessment of the efficiency of operation of photovoltaic modules under different atmospheric conditions. Another goal of this project is to promote the use of photovoltaic technology to provide electric power to remote areas in developing countries. Specific plans for activities to promote the use of photovoltaic energy in Ghana will be developed under this project. We also plan to develop a collaborative project with Dr. Godfrey Augustine of the Northrup Grumman Science and Technology Center who has a background in modeling and design optimization of Indium Phosphide solar cells and who has volunteered to mentor a student on such a project. A student will work with Dr. Augustine to optimize the design of current InP solar cells.

Status/Accomplishments: CAU's Earth Systems Science (ESS) program operates an Atmospheric Optics Observatory (AAO) on the roof of the Research Center for Science and Technology. The AAO provides a platform for operating instruments to monitor the amount of solar energy reaching Earth's surface throughout the day. A Brewer ultraviolet spectrometer measures the ground-level intensity of the attenuated incident solar radiation at five specific ultraviolet wavelengths. An Ascension Technology RSP (Rotating Shadowband Pyranometer) measures the global, direct, and diffuse radiation at the surface for visible wavelengths. In addition, a NOAA automated weather station operated at the AAO site provides simultaneous data on atmospheric pressure, temperature, humidity, wind speed and direction. Data from these instruments can be used as input to validate models of the effects of atmospheric aerosol and water vapor variations on the amount of solar energy reaching the earth's surface.

- To improve our ability to interpret data obtained by the RSP instrument, we began the development of a simple, inexpensive atmospheric haze sensor that uses an LED (light-emitting diode) as a narrow-band detector. Six (6) different LED wavelengths are available and data from such a device operated throughout the day at multiple wavelengths can be used to determine the fraction of incident solar energy that has been lost due to the presence of haze (aerosol particles) in the atmosphere. Successful operation of this device will improve our ability to model atmospheric effects on the solar resource. The relatively low cost and ease of operation of these devices also makes them an ideal candidate for some of our ESS outreach programs involving high school students and teachers.
- Two students (Bryant Pierson and Akil Sutton, Physics students from Morehouse College) began work on the development of the LED haze sensor during the 1999 Summer Session. A working model was completed and preliminary measurements were obtained

prior to the REAP (Renewable Energy Academic Partnership) Conference sponsored by NREL and held at Southern University in Baton Rouge, LA, August 9-13, 1999. Both students attended the REAP conference and presented their results.

- The InP modeling work began during Fall Semester 1999. Dr. Augustine visited our group at CAU and a plan was formulated to involve another PV Associate in carrying out literature searches and updating an existing model for optimizing the design of InP solar cells for higher efficiency and more radiation tolerance. A student has been selected for this project. Mr. Robert Easley, a Physics and Mathematics major from Morehouse College will begin working on the project during the Spring 2000 semester.

Planned FY 2000 Milestones: *Fall Semester 1999:* Two students will continue to work on optimizing the performance of the LED haze sensors and the computer software required for analysis of data. Initial work on the model for optimizing the performance of InP solar cells will begin and a qualified student for the project will be selected. A search will begin for a student on the project for promoting the use of photovoltaic energy in Ghana.
Spring Semester 2000: The study of the effects of the atmospheric on the performance of solar energy systems will continue. The literature search needed to update the model for optimizing the performance of the InP cells will be completed and work on the model will continue. A student will be selected and work will begin on the Ghana PV energy project.
Summer Semester 2000: The work on atmospheric effects will be incorporated into a summer project for an NSF sponsored summer research program conducted by the Principal Investigator at CAU. The project will involve 10 undergraduate students from different universities working on various aspects of the problem of developing a model for the effects of aerosol particles and meteorological parameters on solar radiation reaching Earth's surface. Models and data bases obtained by our PV Associate students during the Spring 2000 semester will be used in this summer research program.
Fall Semester 2000: Work will continue on all projects – atmospheric effects, PV applications in Ghana, and the InP modeling. Each of the 3 projects should have at least one student carrying out studies that should lead to publishable research topics during this semester.

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Major Articles Published in FY 1999:
None.

HBCU PV Research Associates Program

The Floating Theater: A Demonstration of Photovoltaic Technology in a Marine Architectural Context

Contract #: AAK-9-18675-07	**Contract Period:** 8/6/99–8/5/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
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<tr><td>Organization Type: HB</td><td>Congressional District: 3</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
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Robert McConnell
Phone: 303-384-6419
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E:mail: robert_mcconnell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $33,333</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: To demonstrate the applicability of photovoltaic and renewable energy technology to marine based architecture by studying, researching, designing, and simulating a Floating Theater which is a marine architectural structure. As a Department of Architecture located in the Hampton Roads region, a region of seven municipalities whose access to the ocean, rivers, waterways and coasts is vast, this project addresses the following:

- That the Theater uses a form of renewable energy, i.e. Photovoltaic technology.
- That the facility can be designed for educational, demonstration of energy technologies,
- That its mobility, its waterway access to many points along the Hampton Roads makes it an effective facility;
- That it can be designed to be a visitors' attraction;
- That it can serve as a conference/gathering facility; and
- That it could be a self-sufficient operation.

Approach/Background: Approaching the project objective by taking advantage of our design and simulation skills which is an integral part of our educational goals in our 5-year professional architecture program seems appropriate. We approached this design and simulation project as a design problem that will fit into the third year design studio sequence where students, under the supervision of the principal investigators will spend 4 weeks each in fall and spring semester designing the Floating Theater. These designs will be collected, analyzed, and compiled as responses and possibilities from that particular class towards the project objectives.

Status/Accomplishments: Since the commencement of the subcontract in September 1999,we have accomplished the first of the six design classes this semester. In the fall 1999 architectural design studio we had twenty one (21) students who spent four weeks developing a design for the Floating Theater. Out of the twenty one design proposals the two student associates together with the principal investigators are compiling, selecting, analyzing, redrawing, and rewriting the proposals generated for a Floating Theater. The result of the selection, analysis, and reconfiguration of the design proposals shall be completed and submitted to NREL by Jan 15, 2000. As the first part of a six-semester design and simulation process, this stage has been a learning stage.

Planned FY 2000 Milestones: The academic year 2000 holds a rigorous two semester investigation of the design for the Floating Theater. In the Spring semester (Jan. 2000 - May 2000), the students who have participated in the Fall 1999 design studio will continue to come up with fresh proposals for the Theater. As the second stage of the design process, the students' familiarity with the program of the design since they have done it in the Fall 1999 class should afford all of us a better knowledge base from where we can formulate better proposals. The fall 2000 class will build up on the knowledge of the previous class and produce more exciting possibilities. In addition since we will have enhanced access to tools of design and making in the coming year, the FY 2000 will produce many well-developed designs for the Theater.

Contract #: AAK-9-18675-07

Major Reports Published in FY 1999:
The principal investigator has presented The Floating Theater Project's brief at the REAP Conference held at Southern University in August 1999

Major Articles Published in FY 1999:
None.

HBCU PV Research Associates Program

Electronically Controlled Photovoltaic (PV) Power Using Artificial Neural Network

Contract #: AAK-9-18675-06	**Contract Period**: 4/19/99–4/18/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Jeffrey Mazer — **Phone:** 202-586-2455 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Howard University Department of Electrical Engineering 2300 6th Street, NW Washington, DC 20059	
	Organization Type: HB	**Congressional District**: NA
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** James A. Momoh **Phone**: 202-806-5350 **Fax**: 202-806-6588 **E:mail**: jm@scs.howard.edu	
Technical Monitor: Robert McConnell **Phone:** 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code** EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $ 33,333	**Cost Share Funding**:

Project Objectives: The project is aimed at developing:

a. Developing a fault analysis scheme using Genetic Algorithm
b. Load forecasting (management) as a function of time using Artificial Neural Networks
c. Power electronic applications for power quality and voltage stability
d. Furthermore, we need to incorporate knowledge of PV with pre-college students and senior students:

- Virtual design Laboratory for Photovoltaic power system
- PV system design for pre-college students' projects.

Approach/Background: Several research works have been in place to conduct fault analysis and power tracking of PV systems. The existing methods include such approached as experimental and optimization techniques using SPICE and GAMS. Those techniques are limited because of their inability to incorporate:

- Fault systems and determining the multiple optimal points which, may lead to sub-optimal or local optimal points.
- The control techniques are not adequate and have limited ability for self-tuning and stabilization.

Our method plan is to overcome these weak points as we have developed an ANN with GAs approach for optimal power tracking. In this scheme, the ANN computes the load changes over time and the global optimization is done using GA technique. The scheme is tested on a 3-parallel array PV system. The research results are used to attract undergraduate and pre-college students. During the year, undergraduates have built a virtual PV laboratory for testing, analyzing, design, and control of PV system. Two senior students are engaged in development of senior projects in PV systems. The work exploits the electronic control aspect of the project to gain experience on stabilization and power quality. Also, pre-college students during summer'99 implemented two hands-on projects:

a. Security Light/Street Light powered by solar with automatic turn ON/OFF
b. Basket ball display powered by Photovoltaic power system

We continue to test the prototype version of the three tasks described herein for robustness and reliability.

Status/Accomplishments: During the first year of the project, the following outcomes have been completed by our research team:

1. Literature review on PV power tracking and controls
2. Evaluate different control and optimization techniques
3. We have also, assembled an outstanding research team and attracted student's interest to participate in support of system-based PV using emerging technology. Especially, we have:
    - Developed and tested GAs-based optimization program for detecting the optimal tracking points during a faulted PV system.
    - Developed and tested a robust ANN using back-propagation for load tracking
    - The integrated scheme is being tested under different loading and contingency scenarios.

4. We have also, completed studies using virtual laboratory concept on PV system. The Lab is being tested and used to be available to the faculty students to be used in their degree classes.
5. Initial results for controlling PV stabilization process and power quality is being tested

The design-based score board and street light projects were completed by the undergraduate during the year. The research result to enhance our work will be published soon.

Planned FY 2000 Milestone: The research work planned involves

- Testing of integrated GAs and ANN PV system under different faulted conditions
- Extend the controls options such as Fuzzy Logic for achieving a robust maximum power tracking
- Develop and test the electronic control schemes for stabilization and power quality problems caused by PV system.
- Demonstrate the PV Virtual Lab system for design and teaching classes in power & energy conversion Laboratory
- Implementation design of PV tracker system for a faulted system
- Continue to design a pre-college assignment for summer 2000.
- Publish papers, attend conferences, support complete of Master thesis and B.Sc. senior projects

Major Reports Published in FY 1999

1. First Quarter ending July 15th, 1999 for NREL
2. HBCU Photovoltaic Research and Associates and REAP Workshops
    a. James A. Momoh, Muzar Jah, Lashawn Montgomery, "Virtual Laboratory for PV Systems," Annual Conference in Baton Rouge, LA, August 1999.
    b. James A. Momoh, Joel Njoroge, Hasan Greene, "PV Systems Design Projects," Annual Conference in Baton Rouge, LA, August 1999.
    c. James A. Momoh, Joel Njoroge, "Optimal PV System Matching using Genetic Algorithm," Annual Conference in Baton Rouge, LA, August 1999.

Major Articles Published in FY 1999

James A. Momoh, Joel Njoroge, "Power Mismatch Compensation for PV System using Genetic Algorithm," North American Symposium (NAPS), CA, 1999.

HBCU PV Research Associates Program

Solar Radiation Measurements

Contract #: XAX-5-15021-06	**Contract Period:** 10/6/95–10/5/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	Mississippi Valley State University Natural Sciences Dept. Itta Bena, MS 38941	
	Organization Type: HB	**Congressional District:** 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** William Mahone **Phone:** 662-254-3740 or 6737 **E:mail:** trifour@netdoor.com	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax**: 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1994: $40,000 1997: $11,236 1995: $0 1998: $33,708 1996: $42,400 1999: $0	**Cost Share Funding:**

Project Objective: This report will constitute a summary of the current activities associated with the photovoltaic undergraduate research program at Mississippi Valley State University. Our program's primary objective is to familiarize our students with various aspects of energy related research, particularly those associated with the developing photovoltaic industry.

We began FYy99 by asking ourselves, what needs to be done to stimulate a need for solar generated energy. This led us to realize that areas optimal for solar power generation are not necessarily areas local to powerlines, or areas of maximum power consumption. A second question is what factors affect the solar power intensity profile at regional surfaces.

Approach/Background: Our approach, to dealing with the above questions, was multifold. First we began doing a detailed study of the solar radiation profile. We want to quantitate the effect of cloud cover, and planetary motion on the various aspects of the solar radiation profile, which should lead to an estimate of the average available power for a region. Second we want to be able to store solar energy as chemical energy. In our case we are researching how solar energy can be stored as active metals. These active metals can then be used as precursors for hydrogen generation. A third aspect of our research is centered on alternative energy generation using active metals in various electrochemical systems. While not directly related to photovoltaic systems, electrochemical systems maybe instrumental in developing a demand for solar generated energy.

Status/Accomplishments: During the 1999 fiscal year we carried out a series of measurements using an astrolabe, which allowed us to develop a projection of the sun's daily path through the sky as a function of the time of the year. In concert with these measurements we have been studying the solar radiation intensity, as a function of time of day, time of year, and cloud cover. Also these functional dependencies have been duplicated with measurements using commercial solar panels.

Under our efforts at solar power storage, we have carried out an initial series of zinc Electro-deposition experiments using a solar panel as an energy source. We were able to deposit significant amounts of zinc from solution with ease. We are continuing these experiments to understand controlling factors and to prepare an estimate of cost of operation. Experiments to date indicate that zinc can be electrodeposited from solution in a cost-effective manner.

We have completed the design for a preliminary rotating platform, which will allow us to optimize the plane rotation angle component of the solar vector. We believe that we can use this technique to increase collected daily power by 25 to 50%. A prototype platform will be constructed within the next few months.

Under our alternative power generation efforts, we have developed several electrochemical cells of various types made from metals that can be Electro-deposited using solar panels as an energy source. We have made several copper zinc cells of varying configurations. We have also made a, prototype aluminum carbon dry cell based on the lelanche design, a zinc-air cell and a hydrogen-oxygen fuel cell which runs on hydrogen generated from active metals which can be Electro-deposited using a solar energy source.

Planned FY 2000 Milestones: Our milestones for FY2000 are [1]the construction and testing of a rotating platform , [2]complete a study of the solar radiation profile and it's functional dependencies [3] Complete a detailed study of the Electro-deposition processes for active metals and [4] continue our studies of electrochemical cells.

Major Reports Published in FY 1999:
We presented a summary of our work at the REAP99 conference.

Major Reports Published in FY 1999:

HBCU PV Research Associates Program

Investigation of Photovoltaic and Thermophotovoltaic Semiconductors

Contract #: AAK-9-18675-03	**Contract Period:** 1/12/99–1/11/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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Durham, NC 27707</td></tr>
<tr><td>Organization Type: HB</td><td>Congressional District: 4</td></tr>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $49,959</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Our research objective is to establish several methods to study low temperature structural modification and characterization of photovoltaic and thermophotovoltaic semiconductors. Part of the objective is to identify electro-optical properties critical to the performance of these samples semiconductors and establish an adequate explanation of the observed variable behaviors of some of the selected solar cells. One of the principal aims of the task is to employ Free Electron Laser (FEL) capabilities in electron and vibrational excitations for Raman and high-resolution photoluminescence (PL) spectroscopy for characterization of thin films, as well as bulk samples.

Other objectives are to select three PV Research Associates with outstanding academic background (GPAs greater than 3.0 on a 4.0 scale), train them in PV related research, and provide full support to each participating Associates during the academic year. PV Associates will be trained to perform a variety of measurements and characterizations of silicon based solar cells.

Approach/Background: We are exploring specific FEL capabilities, such as, its tunability over a wide range of excitation energies (from infrared to ultra violet), brightness of the source (several orders of magnitude larger than that of conventional sources), and the superior control of the beam intensity, for modification and, as well as, characterizations of solar cells materials and devices.

Impurities in solar cell materials are usually consequences of the preparation method and in most cases cannot be removed in cost effective way. In some cases, impurities, like carbon and oxygen in silicon, build different kind of agglomerates and become electrically inactive. Conventional annealing procedure involves subjecting the sample at high temperature for an extended period of time. Here by direct transfer of energy to the certain defect by choosing specific wavelength of FEL source, kinds of problems, which may arise due to the presence of impurities and thus effect the performance of the solar cells, can be treated much more efficiently, at relatively low temperature. Low temperature crystallization and annealing is especially important for thin film devices, due to prevention of unintentional interdiffusion, chemical reactions, or deformation caused by excessive heating. Successful applications of these procedures can provide a scope to realize the manufacture of low cost solar cells with high efficiency.

Wavelength tunability of the FEL source provides an excellent scope to perform resonance Raman spectroscopy, which can enhance the resolution of the measurements, in some cases by orders of magnitudes.

Status/Accomplishments: During this reporting period, our studies have been primarily on silicon-based materials and devices. Materials Modifications: To study the low temperature crystallization and defect annihilation, thin films are exposed to radiation from the FEL source, at a certain wavelength, as a function of time and energy. Some preliminary work has been performed on amorphous hydrogenated silicon carbide thin films by using Mark III at Duke's FEL laboratory. The 3.4 µm beam, corresponding to maximum of stretching vibration of C-H bonds, was focused on the samples, containing various amounts of silicon. Effects of annealing were monitored by Raman spectroscopy. Raman spectra show two peaks, one of which is due to graphite and the other

- one is on 1355 cm^{-1} and may well be partly due to microcrystalline graphite and partly due to diamond. Further analysis is in progress at this time.
- EFG grown poly-silicon has been examined by scanning FEL beam of excitation energies in the range between 0.35 and 0.41 eV. Photoluminescence spectra at 100 K in the EFG poly-Si sample show two broad peaks, one at 0.27 eV and another one at 0.30 eV, whereas the excitation energy is of value 0.41 eV. In this examination, detector employed was gold-doped Ge, operated at liquid nitrogen temperature. Additional studies are in progress to understand the origins of these two broad bands observed in the PL spectra.

- IR spectra of several poly-Si samples grown by EFG techniques, with various oxygen concentrations, were collected from 5000 to 400 cm^{-1} , 4 cm^{-1} resolution, to study the effect of oxygen contents. Float zone single crystal silicon wafer was used as a reference to remove multiphonon absorption.

Planned FY 2000 Milestones:
- Annealing and Crystallization Study: Two main FEL characteristics, wavelength tunability and ultrashort-pulse operation (~10 ps) with intense peak power (~MW), will be utilized to perform and study their effects on amorphous silicon with different degrees of ordering, and ultimately extend to other polycrystalline thin films, like (Cd, Zn)S, $CuInSe_2$ films.
- Materials Characterization: Internal photoemission technique using FEL will be applied to study heterojunctions and metal-semiconductor devices. The conduction and valance band discontinuities at the interfaces buried deep into bulk can be directly measured by the FEL-IPE technique. This technique will be particularly useful to study the relation between the material and the junction quality of the (Cd, Zn)S/$CuInSe_2$ devices, performance characteristics of which are yet to be fully realized.
- Experimental methods applying conventional, as well as, FEL techniques, which are complementary to each other, will continue to be utilized in various experimental procedures. Such an overlap between conventional and FEL techniques will provide a desirable control on the merit of using FEL.

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999:

Davor, D., et al., "Annealing, Crystallization, Lithography, and Characterization of Amorphous and Polycrystalline Semiconductors by FEL," Conference Proceedings of the Laser Processing Workshop, Thomas Jefferson National Accelerator Facility, June 17-18, 1999.

Dutta, J. M., et al., "Investigation of Photovoltaic and Thermophotovoltaic Semiconductors," South Eastern Section American Physical Society, Chapel Hill, NC, November, 1999, to be appeared in Bulletin American Physical Society.

Davor, D., Bogdanovic, I., Borjanovic, V., Jaksic, M., Dutta, J. M., and Vlahovic, B., "Quantitative Analysis of a-$Si_{1-x}C_x$:H thin films by Vibrational Spectroscopy and Nuclear Methods," to be published.

Davor, D., Bogdanovic, I., Borjanovic, V., Jaksic, M., Dutta, J. M., and Vlahovic, B., "IR-FEL Crystallization of a-$Si_{1-x}C_x$:H thin films," to be published.

Borjanovic, B., "Interaction of light undoped ingredients and structural defects in Si," Ph.D. thesis under preparation.

Davor, D., Dubcek, P., Borjanovic, V., Vlahovic, B., Rodriguez, B., and Nemanjic, R."Structural Properties of Amorphous SiliconCarbide Thin Films," to be published.

<u>Unpublished Contributed Presentations at Meetings and Invited Seminars:</u>
- Invited seminars at NREL by Davor Gracin and Vesna Borjanovic, May, 1999.
- 3 presentations, out of which two were from PV Associates at the Renewable Energy Academic Partnership (REAP) meeting in Baton Rouge, LA, Aug. "99.
- 3 abstracts submitted by three PV Associates to the National Conference on Undergraduate Research, April 24-26, 2000.

HBCU PV Research Associates Program

Thin Film Electrodes and Electrolytes for Photoelectrochemical Cells

Contract #: AAK-9-18675-02	**Contract Period:** 1/27/99–1/26/02

<table>
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Surface Science, Spectroscopy, and Solid State Ionics Laboratory
Department of Physics
Baton Rouge, LA 70813</td></tr>
<tr><td>Organization Type: HB</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $36,060</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this project is to train and create interest in photovoltaics among the selected African American students at Southern University and A&M College, Baton Rouge. We aim at teaching the principles, concepts, research methods and advantages of renewable energies over the conventional fossil fuels and motivate them for careers in alternative energy technologies. In this project, we are focusing on preparation and characterization of doped oxide and sol gels immersed in strong electrolytes for photoelectrochemical cells [PECs] applications. We aim at understanding electrode-electrolyte interfaces by studying their charge transfer reactions, interfacial integrity, structural and conversion efficiency relations using electrochemical, surface and X-ray spectroscopy techniques.

Approach/Background: The PECs will provide viable alternative to solid state PVs since they may be easier to manufacture and may have greater efficiencies due to sensitizing techniques. PECs have the advantage over the conventional PVs in six main areas: 1) By tailoring the electrolyte solution, the band bending of the semiconductor can be varied. 2) There are no solid to solid junctions which need to be created, so it is easy to fabricate a cell. 3) There is no need for antireflective coatings 4) the differential expansion is not a problem for PEC system and 5) the conventional fuels (hydrogen) can be produced directly with heterogeneous systems. PECs depend upon the irradiation of an electrode or an electrolyte to produce change in the open circuit potential or the current in the closed circuit system The construction of PECs are similar to the construction of electrochemical cells (batteries) in which one of the metal electrodes of a conventional electrochemical cell is replaced by a semiconductor electrode, PECs utilize the input optical energy to drive electrochemical reactions. In this reporting period, we have investigated TiO_2, CeO_2, Ag_2O SiO_2 gels and explored their utility as electrode materials for PECs, Batteries, Fuel Cells, and also their role in the development of light activated photoelectrochemical sensors.

Status/Accomplishments: Mr. Charles Wayne was heavily involved in the synthesis and characterization of nanosized TiO_2 and SiO_2 by sol gel process. Titanium dioxide , TiO_2, is a material with a large number of applications due to optical, chemical and mechanical properties. In particular TiO_2 is utilized as catalyst support gas, gas and humidity sensor, optical coating and is a basic material for integrated wave guides and photovoltaic electrochemical cells. The behavior of TiO_2 ceramics, powders and films depend on their structural morphology and phases. For Photovoltaic (PV) applications, it is very important to control the phase, nanosize/nanocrystalline and the presence of defects during synthesis. Our goal in this project is to prepare nanocrystalline or nanosized TiO_2 powders by sol gel route and characterize them using spectroelectrochemical techniques. Using precursor chemicals such as titanium tetraethoxide, $Ti(OEt)_4$ and ethanol as solvent, we have prepared TiO_2 powders using sol gel process. We are present characterizing these powders using various analytical techniques.

Ms. Candice Dixon is investigating structural and electrical properties of mixed conducting oxides during this semester. We are trying low temperature synthesis methods such as sol gel, spray pyrolosis and thermal hydrolysis techniques to synthesize mixed conducting oxides. Ms. Candice Dixon has surveyed the literature to explore their applications in solar batteries and gain the hands on experience to operate the instruments in the laboratory during the first semester in the NREL-PV program. The employment of nanosized particle materials in electrodes is one of the important ways to scale up and to enhance the performance of these ionic devices. Our main goal in this project is to elucidate microstructural relations via characterizing the materials using in situ STM, TEM, SEM, UV-VIS-NIR absorption spectroscopy, FT-IR, solid state 7Li NMR, EDS.and EXAFS techniques.

A. Astanam has been studying ethanol oxidation of polymer electrolyte fuel cells using cyclic voltammetry technique. Simultaneously, she was involved in preparation of biocatalysts for the production of bioethanol from biomass.

Planned FY 2000 Milestones:

1. Complete the characterization of naonostructured TiO_2 and use the same material for constructing PECs. Study their performance in the laboratory environment. We will involve the NREL PV scholars in every stage of the work.

2. Complete the solid oxide fuel cell work using CeO_2. Measure the surface structures using Scanning Tumneling Electron Microscope.

3. Learn the technology of producing bioethanol from biomass. We will explore the opportunities for our students to work in a local Bioethanol industry (BCI Internatiuonal) in Louisiana.

4. We ensure our NREL PV scholars will present their work in national and regional conferances and workshops.

Major Reports Published in FY 1999:

1. Effect of low temperature synthesis on the ionic transport and structural properties of Li_2O -SiO_2 Dried gels. N. Satyanarayana, Charles Wayne and B. Rambabu. Presented in 12th International conferance on Solid State Ionics, June 6-12, 1999, University of Patras, Greece. Accepted for publication in the *Journal of Solid State Ionics*.

2. Silver Silicate Gels for Primary Batteries: B. Rambabu and Charles Wayne, 1st REAP workshop, August 8-13, 1999, Southern University, Baton Rouge.

3. XANES study of rare earth dopants in CeO_2 for SOFCs. B. Rambabu and Candice Dixon. 1st REAP workshop, August 8-13, 1999, Southern University, Baton Rouge.

4. Sol gel synthesis and Characterization of Ag_2O -SiO_2 System, N.Satyanarayana, X. Xie, and B. Rambabu, Materials Science and Engineering; Solid State Materials and Advanced Technolgy, [SM9921] [In Press].

Major Articles Published in FY 1999:

1. XANES and Ionic Conductivity Measurements of trivalent dopants in Ceria based Electrolytes. J. Hormes, Bryan Balazas and B. Rambabu, presented in 12th International Conferance on Solid State Ionics, Accepted for publication in the *Journal of Solid State Ionics*.

HBCU PV Research Associates Program

Design, Analysis and Testing of PV Stand-Alone and Grid-Connected Systems and the Development of an Education Study guide

Contract #: AAK-9-18675-05	**Contract Period**: 12/28/98–12/27/01

Sponsoring Office Code: EE-11	**Performing Organization**	
DOE HQ Program Manager: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Texas Southern University School of Technology Houston, TX 77004	
	Organization Type: HB	**Congressional District:** 18
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator:** Joshua Hill **Phone:** 713-313-7007 **Fax:** 713-313-1853 **E:mail:** tchajxhill@tsu.edu	
Technical Monitor: Robert McConnell **Phone**: 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1999 - $50,000	Cost Share Funding:

Project Objective: Provide undergraduate students support for photovoltaic energy research and education at HBCUS, with the aim of attracting qualified science, engineering, and business students toward pursuing a career in these areas with emphasis in photovoltaic technology. The objective is to also strengthen the PV research capabilities of HBCUs' and to continue achieving the goals of the DOE/NREL PV Program within these schools.

Approach/Background: With the use of renewable energy technology, Texas Southern University School of Technology is committed to channeling more HBCU students and faculty into photovoltaic research and applications. TSU has three (3) Research Associates. The approaches for this program during 1999 were as follows: One PV Research Associate is conducting a literature search to review and report on photovoltaic and renewable energy study guide for teachers, including any developed by TSU faculty for the TSU's Renewable Energy and Environmental Protection (REEP) Academy. Two PV Research Associates are receiving in-depth training in the design and installation, testing, and analysis of PV systems in order to perform system load-data analysis of stand-alone systems and one Associate will establish a method for evaluating a grid-connected PV system.

Status/Accomplishments: A number of papers and articles have been written and presented.

- American Solar Energy Society: Proceedings of the 1999 Conference, The REEP Academy.
- Presentation at the NREL REAP Conference, Southern University, Baton Rouge, 1999
- Hill, Joshua "Reflections on Activism in Energy and Education," a paper presented at the African Development Conference on Energy & Environment in Port Elizabeth, South Africa, 1999
- Students participated in the design and construction of a PV refrigerator.
- Students participated with the Houston Renewable Energy Group during the Enron's Earth Day Festival and won first prize for best booth using PV display and hands on activities.
- Students participated in the initiation of a solar club in the School of Technology at Texas Southern University.
- Students held a PV demonstration for hundreds of students in the pavilion at Texas Southern University.
- Research Associates have learned to use a 4KW PV system to test low voltage household appliances using LabView Data Acquisition software.

Planned FY 2000 Milestones:

- Outline design parameters of garage apartment to be connected to PV and solar thermal powered facility
- Apartment to be grid connected
- Design PV system to be installed; Conduct load calculation and wire and BOS sizing
- Develop equipment procurement data and documents
- Manage PV installation and testing
- Maintain log and monitor system performance

- Write report on phase one-system operations
- Follow up on discussions to collaborate with Peninsula Technikon and housing minister for the Western Cape, South Africa
- Work on plans for an affordable housing development which will be powered by PV, wind, and solar thermal for hot water production
- Formulate an action plan on the above inclusive of timelines and responsible persons
- Continue work on-site with PV refrigerator manufacturer
- Continue work on heat pump/solar refrigerator to prepare for commercialization
- Maintain log on system performance relative to design parameters and criteria
- Complete prototype for field-testing in South Africa
- Develop training / operating manual for users in South Africa
- Complete logistical plans for transporting refrigerator to village in South Africa
- Write progress report
- Assist with maintenance and expansion of TSU 4kw PV array
- Conduct degradation tests on existing 4kw PV array
- Perform indicated maintenance on BOS
- Continue literature search, identification, and collection of related educational study guides to support the production of renewable energy guides
- Draft outline of proposed revise manual/study guide for discussion with NREL educational staff
- Complete REEP Web site to include helpful instructional references and hints for teachers
- Conduct analysis and monitor implementation of recently passed Senate Bill (renewable energy legislation) and post-relevant findings on REEP Web site
- Assist with the formation of plans for the development of a PV powered African Village on campus

Major Reports Published in FY 1999: For the FY 1999, one major report was published for the Renewable Energy and Environmental Protection Summer Academy.

- REEP Academy Annual Report FY 1999

Major Articles Published in FY 1999:

- "TSU Reaches for the Sun in Energy Focus," School Center Teaches about Solar-Power use, Houston Chronicle, 1999
- "From Darkness to Light," REEP Brightens South Africa, an article in the Houston Defender, 1999
- "TSU Give Light to Rural South Africa" an article in The International Guardian, 1999
- "Texas Southern University's School of Technology is Exploring Energy for the Future," Students Will Play Leading Role in Alternative Energy, an article in The International Guardian, 1999
- TSU Renewable Energy Center, "An Asset for Addressing the State's New Energy Needs and Education," The International Guardian, 1999

Analytical Microscopy

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/98–9/30/99

<table>
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<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
DOE Office of Solar Energy Technology
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E:mail: pete_sheldon@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $1,172,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:
The Analytical Microscopy task provides measurement support, carries out collaborative research, and develops new measurement techniques for the advancement of Laboratory, subcontractor, and industry driven PV R&D. The main objective is to advance the development of PV devices via:

- Providing short-term support (routine analysis) of PV samples with quick turn-around time
- Providing long-term characterization research support on key problems/issues facing PV materials and devices
- Developing new characterization techniques to tackle material problems that cannot be addressed by our current capabilities

Approach/Background:
The Analytical Microscopy Task has provided extensive support for both our in-house and subcontract groups. A wide variety of techniques was utilized to characterize PV materials and devices. Compositional measurements are performed by electron probe microanalysis (EPMA) using either energy dispersive or wavelength dispersive X-ray analysis. Structural and defect analyses are carried out by transmission electron microscopy (TEM). A project for the development of microdiffraction and Fourier analysis of electron diffraction patterns in the TEM was completed during FY99 enabling us to analyze the diffraction patterns from areas as small as 200Å. Additionally, scanning electron microscopy (SEM) in its various modes, such as secondary electron, cathodoluminescence (CL) and EBIC imaging, is providing a very wide support for measuring the topographical, luminescent and microelectrical properties of PV materials and devices.

In addition to the above-mentioned capabilities, this task has provided extensive support to the PV program in the nano-scale characterization area. AFM examination has been used to study the morphology and surface structure of a wide variety of materials and devices. Examples of these are: SnO_2, CdS, CdTe, Si, CIGS and III-V films.

All of the research activities carried out by this task are planned through other in-house tasks, National Teams, and our subcontractors.

Status/Accomplishments:
Over 4000 analyses were performed in support of our in-house teams and NREL's subcontractors. This includes measuring the composition, topography, structure, and the microlectrical properties. The following is a few highlights of some of the collaborative research project s we carried out in FY99:

In collaboration with NREL's CdTe Team, we deposited CdTe thin films by close-spaced sublimation using an alternative procedure that involves temperatures about 170 °C lower than the ones used in the standard procedure. These films were used in the fabrication of all thin-film CdTe/CdS solar cells. We treated the cells using the well-established $CdCl_2$ dipping process, as well as the new vapor treatment. The morphology and microstructure of these structures were studied and closely correlated with cell parameters.

Contract #: DE-AC36-99GO10337

The microstructure of SnO_2 and Cd_2SnO_4 transparent conducting oxides was studied using high resolution TEM. Significant differences were observed that explain the superiority of Cd_2SnO_4 as a front contact to CdTe cells.

The defect structure of CSS-deposited CdTe was studied. The structure is dominated by a high density of planar faults. Additionally, the chemical properties of the CdS/CdTe interface were studied by x-ray analysis in the TEM. Considerable amount of S diffusion into CdTe was observed in samples deposited at high temperatures.

In support of NREL's High Efficiency Concepts Team, $Ga_{1-x}In_xAs_{1-y}N_y$ and $(GaAs)_{1-x}(Ge_2)_x$ alloy layers were characterized by TEM and AFM for the possible use as 1.00eV cells in three-junction devices. While the and $(GaAs)_{1-x}(Ge_2)_x$ layers exhibited a great del of phase separation and sometime high density of structural defects, no structural defects were observed in $Ga_{1-x}In_xAs_{1-y}N_y$ layers. It is still not clear what cuses the poor electrical properties of the latter.

In collaboration with the a-Si Team, TEM, electron channeling patterns, and EBIC were used to fully characterize hot wire deposited, epitaxial Si. A large number of parameters with widely varying values needed to be addressed. The study resulted in epitaxial Si with greatly reduced defect density.

Planned FY 2000 Milestones:

- Complete analytical SEM development and apply to the Thin-Film Project
- Identify the role of S and Cl in growth and annealing process for CdTe
- Identify the concentration and distribution of Na in CIGS
- Investigate the morphology, microstructure of Mo films on glass
- Provide characterization support for PV program

Major Articles Published in FY 1999:

"Structural and Chemical Characterization of CdS/CdTe," M.M. Al-Jassim, K.M. Jones, and R.D. Dhere, *Proc. Eleventh International Conference on Microscopy of Semiconducting Materials*, Oxford, UK, March 21-25, 1999.

"Microanalytical Characterization of Structure and Defects for the Development of Low Temperature Silicon Epitaxial Growth," K.M. Jones and J. Theiesen, *Proc. of the Microscopy and Microanalysis 99 Meeting*, Portland, Oregon, August 1-5, 1999.

"An Alternative Procedure for the Fabrication of Close-spaced Sublimated CdTe Solar Cells," H. Moutinho, R. D. Dhere, C. Ballif and M.M. Al-Jassim, presented at the National Symposium of the American Vacuum Society, Seattle, October 1999, and has been submitted to the *Journal of Vacuum Science and Technology.*

"Ge-related Faceting and Segregation During the Growth of Metastable $(GaAs)_{1-x}(Ge_2)_x$ Alloy Layers," A.G. Norman, J.M. Olson, J. F. Geisz, J. F.; H.R. Moutinho, and M.M. Al-Jassim, *Appl. Phys. Lett*., **47**, 1999, 1393.

Measurements and Characterization

Electrooptical Characterization

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Richard Ahrenkiel **Phone:** 303-384-6670 **Fax:** 303-384-6604 **E:mail:** richard_ahrenkiel@nrel.gov	
Technical Monitor: Pete Sheldon **Phone**: 303-384-6533 **Fax**: 303-384-6604 **E:mail**: pete_sheldon@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $1,164,900	**Cost Share Funding:**

Project Objective;
The overall objective of the electrooptical characterization task is to develop and provide electrical and optical measurement support for both in-house and subcontract photovoltaic (PV) device research, so as to accelerate commercialization of the respective technologies.

Approach/Background;
- We are using measuring techniques that have been developed in our laboratory to analyze the samples submitted from the above sources. These are used for both routine characterization and collaborative research with the various materials groups.
- We are developing new measuring techniques that will enhance to the characterization and parameterization of the various materials and devices that have been developed by the PV program.
- We are doing collaborative research with the various materials groups to better understand and improve their technologies. This includes active participation in the various Teams to aid our expertise to the activity of improving materials and devices.

Status/Accomplishments:
- We have used Fourier Transform (FT) techniques to analyze the persistent impurities in the CdS thin films used in both CdTe and CIS technologies. These measurements have identified acrylamides or methyl acetamides, and silicates as residual and possibly detrimental impurities in CdS grown by chemical bath deposition. The analyses showed that a (cadmium) cyanamide impurity species is prevalent in the CdS films.
- We have used both energy resolved and FT photoluminescence techniques to analyze the composition of graded-bandgap CIGS films as a function of depth. These measurements are used to develop the optimum compositional structure of this material.
- We have continued a project with AstroPower Corporation for diagnosing the material used in their polycrystalline technology. These devices were cut from solar cells and were classed by AstroPower as "good" cells and "bad" cells. A number of measurement techniques have been used including the UHFPCD lifetime, deep level impurity (DLTS) analysis, and FTIR analysis to relate the material quality to specific impurity specifies. These studies have identified some silicate and iron complexes as the possible efficiency “killers’ in their wafer material. DLTS studies showed that devices from good cells had not significant minority-carrier traps that produced resolvable signals from 80 K to 300 K. However, the devices from bad cells has a very strong electron trap that was evident near room temperature. The trap concentration was about $1x10^{12}$ cm^{-3} but the electron capture cross section appears to be very large. Based on the preliminary data, this trap could reduce the electron lifetime below 0.1 µs, which is about one order of magnitude lower than the lifetime that we measure in good devices.

A number of measurements have been made on III-V materials developed by the in-house Team for very high efficiency solar cells. We have identified a persistent oxygen impurity as possible source of poor performance in some of the GaInAsN materials. Basic minority-carrier lifetime studies of GaAsN and GaInAsN have shown that the conduction band of the nitride materials is composed of regions localized ‘band tails’ produced by the nitrogen component of the alloy. The indication of this work indicates that the electrons in this conduction band are localized to these potential wells and consequently have negligible minority-carrier diffusion length. Studies however, indicate that photo holes are quite mobile indicating that n-type layers may be useful components of solar cells. Using transmission-mode spectroscopy, the FTIR lab examined two hydrogen-passivated GaInAsN/GaAs samples provided by the III-V High Efficiency Team for the presence of N-H covalent bonding. No evidence for N-H covalent bonding was found. By photoluminescence techniques, we have found that there are several processing steps in NREL's present device fabrication sequence which result in increased resistance at the back contact. Such devices have higher series resistance, which results in lower fill factor and lower efficiency. Our characterization of the back surface composition provides a clear understanding of how and why device performance degrades in those situations.

- Energy and time-resolved photoluminescence measurements were performed on a series of CIGS films grown at IEC. The resulting TRPL spectra are non-exponential, indicative of trapping mechanisms, and all exhibit a very fast (<1 ns) initial decay time. Correlation with the energy resolved data indicate either an increasing material/interface quality or increasing majority carrier concentration with increasing Ga content.

Technique Development: We developed a technique to measure cross-plane mobility of a thin film using magnetoresistance. Magnetoresistance can be used to obtain mobility when the sample geometry does not allow van der Pauw contacts or when sample geometry is not favorable for Hall voltage measurement.

Technology Transfer: Their patent application (NREL 96-35) was issued on July 27, 1999. The Patent No. will be 5,929,652. The patent was entitled "Apparatus for Measuring Minority Carrier Lifetimes in Semiconductor Materials" and the inventor is Richard K. Ahrenkiel.

Planned FY 2000 Milestones:

- Monitor internal and subcontractor satisfaction relevant to support.
- Development of IQE System
- Install nanosecond step-scan time-resolved interferometer in the FT-PL/FT-Raman spectrophotometer, contingent upon approval of GPE funding.
- Transfer measurement technologies to at least one industry partner.

Major Reports Published in FY 1999:

- *NCPV FY 1998 Annual Report*.
- Webb, J. D.; Keyes, B. M.; Ahrenkiel, R. K.; Wanlass, M. W.; Ramanathan, K.; Gedvilas, L. M.; Olson, M. R.; Dippo, P.; Jones, K. M. 16 pp.; NICH Report No. CP-520-25037. (1998)

Major Articles Published in FY 1999.

- D. N. Bose, R. K. Ahrenkiel and S. Bhunia, J. Appl. Phys. **86**, 6599 (1999).
- R. K. Ahrenkiel and S. W. Johnston, Surface Science (in press, 1999).
- S. P. Ahrenkiel, S. W. Johnston, R. K. Ahrenkiel, D. J Arent, M. C. Hanna, and M. W. Wanlass, Appl. Phys. Lett. **74**, 3534, (1999).
- R. K. Ahrenkiel, R. Ellingson, S. Johnston, J. Webb, J. Carapella, and M. Wanlass, AIP Conference Proceedings **460**, p. 282, (1999).
- Woods, L.M.; Woods, L.M.; Levi, D.H.; Kaydanov, V.; Robinson, G.Y.;
- Ahrenkiel, R.K, AIP conference proceedings **462**, 1, pp. 499-504 (1999).
- Ahrenkiel, R.K. and Johnston, S.W., AIP conference proceedings **462**, 1, pp. 483-491 (1999).
- Song, W.; Mao, D.; Kaydanov, V.; Ohno, R.R.; Trefny, J.U.; Ahrenkiel, R.K.; Levi, D.H.; Honston, S.; McCandless, B.E., AIP conf. Proc. **462**, pp. 194-199, AIP press (1999).
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- Ahrenkiel, R.K.; Ellingson, R.; Johnston, S.; Webb, J.; Carapella, J. and Wanlass, M.W., AIP conference proceedings **460**, pp. 282-288, AIP press (1999).
- Ahrenkiel, S.P.; Johnston, S.W.; Ahrenkiel, R.K.; Arent, D.J.; Hanna, M.C.; Wanlass, M.W., Appl. Phys. Lett. 74, pp. 3534-3536 (1999).
- Ahrenkiel, R.K.; Ellingson, R.; Johnston, S.; Wanlass, M.W., Appl. Phys. Lett. 72, pp. 3470-3472 (1999).
- D.H. Levi**,** L.M. Woods, D.S. Albin and T.A. Gessert, AIP Conf. Proc. **462**, pp.461-466.
- H.R. Moutinho, R.G. Dhere, M.M. Al-Jassim, B. Mayo, D.H. Levi, L.L. Kazmerski, AIP Conference Proceedings **462**, pp. 517-523, AIP press (1999).
- W. Song, D. Mao, J.U. Trefny, R.K. Ahrenkiel, D.H. Levi, and S. Johnson, AIP Conf. Proc. **462**, pp. 188-193 (1999).
- F. Alsina, J. D. Webb, A. Mascarenhas, J. F. Geisz, J. M. Olson, and A Duda, Phys. Rev. **B 60**, p. 1484 (1999)
- J. D. Webb, L. M. Gedvilas, M. R. Olson, X. Wu, A. Duda, M. W. Wanlass, and K. M. Jones, AIP Conf. Proc. **460** p. 269, AIP Press (1999).
- M. W. Wanlass, J. J. Carapella, A. Duda, K. Emery, L. Gedvilas, T. Moriarty, S. Ward, J. D. Webb, and X. Wu, AIP Conf. Proc. **460** p. 132 (1999).
- R. K. Ahrenkiel, R. Ellingson, S. Johnston, J. Webb, J. Carapella, and M. Wanlass, AIP Conf. Proc. **460** p. 282, AIP Press (1999).
- X. Wu, A. Duda, J. J. Carapella, J. S. Ward, J. D. Webb, and M. W. Wanlass, AIP Conf. Proc. **460** p. 517, AIP Press (1999).
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- Keyes, B. M.; Geisz, J. F.; Dippo, P. C.; Reedy, R.; Kramer, C.; Friedman, D. J.; Kurtz, S. R.; Olson, J. M., Optical Investigation of GaNAs. AIP Conference Proceedings **462**. Woodbury, NY: American Instituteof Physics; pp. 511-516; (1999).

Solar Cell and Module Characterization

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Keith Emery **Phone:** 303-384-6632 **Fax:** 303-384-6604 **E:mail**: keith_emery@nrel.gov	
Technical Monitor: P. Sheldon **Phone**: 303-384-6533 **Fax**: 303-384-6604 **E:mail**: pete_sheldon@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $920,800	**Cost Share Funding:**

Project Objective: The performance of photovoltaic devices of all sizes and technologies are evaluated within this activity. This team supports the entire photovoltaic community by providing: secondary calibrations of photovoltaic modules and cells, efficiency measurements with respect to a given set of standard reporting conditions, efficiency verification of contract deliverables, current versus voltage (I-V) measurements under varying temperature, spectral irradiance and total irradiance. Support is provided for in-house programs in device fabrication, module stability, module reliability, PV systems, and alternative rating methods by performing baseline testing, specialized measurements and other assistance when required. This activity also supports the entire PV community by providing information on PV measurement equipment and systems that are appropriate for the end user, I-V measurement procedures, and uncertainty analysis. Included in the uncertainty analysis are the determination of potential artifacts in the I-V results because of equipment or procedures, and realistic estimates of the elemental error sources. This activity is committed to obtaining the lowest possible uncertainty in the measurement of the standardized PV performance of single- and multi-junction cells and modules.

Approach/Background: The photovoltaic current versus voltage characteristics are measured with respect to standard terrestrial reporting conditions (25°C temperature, 1000 Wm^{-2} total irradiance and ASTM E892 global reference spectrum). The intensity of the Spectrolab X-25 solar simulator (30 cm square beam) is adjusted until the measured short-circuit current of a reference cell is equal to it's calibration value corrected for spectral mismatch. The current versus voltage characteristics are then measured using 4-terminal Kelvin connections to the PV device with a custom data acquisition system designed to give a random error of less than ±0.1% and a non random error of less than ±1%. The uncertainty in efficiency measurements with respect to standard reference conditions is ±2-5% depending on the sample size, geometry and number of junctions. These procedures have been shown to be valid for any given tabular reference spectrum including AM0 and the ASTM direct normal reference spectrum. The system is also used for dark I-V and tunnel diode measurements. For two-terminal multi-junction devices the spectrum of the Spectrolab model X25 solar simulator is adjusted, using a special filter plate developed at NREL, until each junction is producing the correct photo-current. The I-V system is also used for examining the effects of pre-measurement conditions, bias rate, maximum power versus illumination time, V_{oc} *vs*. time, and I_{sc} *vs*. time on the PV performance.

The filter spectral response system uses periodic monochromatic light directed through one of 68 10-nm bandwidth interference filters covering the spectral range from 280 to 1900 nm. The system is capable of providing steady-state light bias levels up to 200 mA and voltage bias levels from ±1 mV to ±40V. The uncertainty in the relative spectral response as a function of wavelength is less than ±5%. The grating monochrometer based system has a wavelength range from 300-5,000 nm with a 1-nm wavelength resolution and a 1-5 nm selectable bandwidth. The grating system was designed for accurate absolute spectral response measurements by illuminating a small 1-mm by 3-mm rectangular area and measuring the power of the entire beam. The system uses all reflective optics so chromatic aberrations and beam wander with wavelength are not present. The system is capable of broadband or filtered light bias for multi-junction or nonlinear devices. Both systems rely on accurate pyroelectric detectors or NIST calibrated semiconductor detectors for the measurement of the light power.

The efficiency versus concentration measurements are measured with a Spectrolab High Intensity Pulsed Solar Simulator (HIPSS). This system has been used to measure the performance as a function of concentration for GaAs, GaInP/GaAs, tandem, and

GaInP/GaAs/Ge triple junction concentrator cells. The concentrator lamp housing allows measurement from 1 to 2000 suns. The cell performance as a function of concentration can also be measured using an unfiltered 1000W Xe-arc continuous light source that is focused to a small area. The primary reference cell calibration procedure involves measuring the short-circuit current, the total irradiance with an absolute cavity radiometer, and the spectral irradiance at the same time outdoors with the same 5° field of view. Since the measured spectral irradiance does not encompass the limits of the reference spectrum, the measured spectrum is extended using a computer model developed by the group to encompass the range of the reference spectrum (300-4000 nm). This procedure has been shown to have a total uncertainty of less than ±1% by rigorous uncertainty analysis, intercomparison with the World Photovoltaic Scale, primary AM0 standards and other intercomparisons. In addition to recalibrating NREL's primary reference cells this system was used to recalibrate 15 WPVS reference cells and calibrate 6 new WPVS candidate cells.

The I-V characteristics of modules are routinely evaluated using the Spire 240A, Spectrolab model X200 Large-Area Continuous Solar Simulator and outdoors under clear sky conditions. The Spectrolab Large Area Pulsed Solar Simulator produces a one-sun beam of light, 2m by 2m in area was modified during FY99 to be able to adjust the spectrum to allow each junction in a multi-junction device to operate at the correct photo-current.

Status/Accomplishments:
During FY99 the team performed 5301 I-V and QE measurements on 1480 cells and modules (I-V under standard reporting conditions). The cell and module calibrations were performed for 68 different groups representing in-house activities, the U.S. PV industry, universities, and other groups in the U.S. and around the world.

The first recalibration of the World Photovoltaic Scale Reference cells from PV calibration laboratories around the world was conducted at NREL. All countries participated with the exception of India, which was barred because of sanctions. The Indian WPVS reference cells are scheduled to be recalibrated in early FY00.

Approximately 30 papers acknowledged the support of this group during FY99. This team has assisted nearly all module manufactures with their QA/QC programs by providing telephone consultations on measurement strategy, procedures, and a calibration tractability path for their cells and modules. The technology of PV I-V and spectral response measurements was transferred to a variety of university and manufacturing groups through phone conversations and visits. In support of international programs trips to China and India were made to transfer efficiency measurement technology. The team participated in the International intercomparison of calibration procedures for new technologies by performing extensive post-intercomparison analysis of the sample set. Former team member Halden Filed during FY99 formed the company PV Measurements, which specializes in custom PV data acquisition systems. Support has been given to this company by assisting in evaluating their equipment and providing calibrations.

A draft ASTM standard for concentrator module measurements was initiated during FY99.

Planned FY 2000 Milestones:
Complete a technical report documenting the 1999 World Photovoltaic Scale Recalibration held at NREL.
Enhance the quantum efficiency measurement capabilities for the maximum possible bias light for concentrator cells.
Continue to support the PV industry by providing, calibration, consultation, and performance verification services.

Major Reports Published in FY 1999:
B. Marion, B. Kroposki, K. Emery, J. delCueto, D. Myers, and C. Osterwald, "Validation of a Photovoltaic Module Energy Ratings Procedure at NREL," NREL/TP-520-26909, (August 1999).

Major Articles Published in FY 1999:
M.A. Green and K. Emery, K. Bücher, D.L. King, and S. Igari "Solar Cell Efficiency Tables (version 13)," Progress in Photovoltaics Research and Applications, vol. 7, pp. 31-37, 1999.

C. Osterwald and K. Emery, Spectroradiometric Sun Photometry," presented at the 22nd Atmospheric Transmission Review Conference, Hanscom Air Force Base, MA, June 8-10, 1999.

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M.A. Green and K. Emery, K. Bücher, D.L. King, and S. Igari "Solar Cell Efficiency Tables (version 14)," Progress in Photovoltaics Research and Applications, vol. 7, pp. 321-326, 1999.

C.R. Osterwald, S. Anevsky, K. Bücher, A.K. Barua, P. Chaudhuri, J. Dubard, K. Emery, B. Hansen, D. King, J. Metzdorf, F. Nagamine, R. Shimokawa, Y.X. Wang, T. Witchen, W. Zaaiman, A. Zastrow, and J. Zhang, "The World Photovoltaic Scale: An International Reference Cell Calibration Program," Progress in Photovoltaics Research and Applications, vol. 7, pp. 287-297, 1999.

K. Emery, "The Rating of Photovoltaic Performance," IEEE Transactions on Electron Devices, vol. 46, pp. 1928-1931, 1999.

Measurements and Characterization

Surface Analysis

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** S. Asher **Phone:** 303-384-6450 **Fax:** 303-384-6746 **E:mail:** sally_asher@nrel.gov	
Technical Monitor: P. Sheldon **Phone**: 303-384-6533 **Fax**: 303-384-6604 **E:mail**: pete_sheldon@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: \$767,400 1998: \$841,400 1999: \$916,700	**Cost Share Funding:**

Project Objective:
- To advance the understanding of photovoltaic materials and devices by using surface analytical techniques to investigate surface and interfacial properties.
- To advance the utility and understanding of surface analytical measurements by improving analytical methodology and instrument development.
- To support research activities planned through the work of other in-house and subcontracted researchers for all areas of the National PV program.
- To disseminate research results through publications, presentations, and regular interactions with researchers in the surface analysis and photovoltaic disciplines.

Approach/Background: Surfaces and interfaces are the boundaries between different phases and different types of materials. Interactions in these regions often determine the properties of PV materials and devices. The Surface and Interface Analysis Team uses a sophisticated array of techniques for the chemical and compositional analysis of surface, near surface, and interfacial regions of materials. The techniques utilized include scanning Auger electron spectroscopy (AES), X-ray photoelectron spectroscopy (XPS), ultra-violet photoelectron spectroscopy (UPS), and dynamic and static secondary ion mass spectrometry (SIMS). XPS and AES spectroscopies are related techniques for determining the composition and chemistry of surfaces. Dynamic SIMS is used to perform trace element analyses for contaminants and dopants. Static SIMS provides trace elemental and molecular information from the top surface monolayers.
Team members are Sally Asher (team leader), David E. King, Robert C. Reedy, Amy Swartzlander Guest, Matthew Young, and Alice Mason (10/98-7/99)

Status/Accomplishments: During FY99 the Surface and Interface Analysis Team collaborated with researchers in all areas of the National PV program. A summary of highlights is presented in the following section.
• We have conducted a series of studies with members of the Electro-optical characterization team and the NREL CdTe team leading to better fundamental understanding of the effects of post-deposition processing on surface properties of CSS CdTe. XPS measurements performed on films indicates a variation in stoichiometry at the CdTe back surface depending on treatment. We have also demonstrated that the back-surface composition of NREL grown material is Cd-rich, which deleteriously affects the ability to produce a good ohmic contact.
• Using a sample preparation method developed by the Analytical Microscopy team we were able to enhance depth profiling of CdTe/CdS devices by SIMS and other surface analysis techniques. This has allowed depth profile measurements to be made from the front side (SnO_2) of the device. Profiles from the SnO_2 side of the device led to the first clear evidence of Cu diffusion from the back contact through the CdTe layer. Cu levels are related to Cu in the back contact.

Contract #: DE-AC36-99GO10337

• We have used a combination of techniques to develop standardization procedures for determining Sn/O compositions in SnO_2 films. We have determined that surface composition can be quite different from the bulk in conducting oxide matrices. This has led to accurate measurements of Cd and Zn incorporation in SnO_2 films as well as the methodology for studying new materials such as CdO and $CdSnO_4$.
• We have used AES depth profiling to aid the ISET CI(G)S National Thin Film team in their study on the effect of Cu/In stoichiometry on S and Ga diffusion. Interpretation of the profiles shows that S diffusion is considerably higher in Cu-rich films. Estimates of the S diffusion constant were also made from the profiles, indicating that S diffusion in Cu-rich films is greater than two orders of magnitude faster than in the highly Cu-poor films. On the other hand, Ga diffusion was found to be higher in In-rich films.
• We have used dynamic SIMS, XPS, and AES to study new low band-gap alloys in collaboration with the NREL High Efficiency team. Compositional measurements were performed by all techniques. In addition, SIMS was used to study contamination by light elements and other trace impurities.

Planned FY 2000 Milestones:
Determine the origination and composition of surface defects on CIGS films
Determine the suitability of SbTe for back contacts on CdTe
Determine the role of back surface composition in the back contact of CdTe

Patent Applications:
"A Durable Corrosion and Ultraviolet-Resistant Silver Mirror," G. Jorgensen, R. Gee, D. King, Patent application, 8/99.

Major Articles Published in FY 1999:

Surface Analysis Team members authored or co-authored 9 papers published in 1999 from work presented at the NCPV review meeting held in October 1998.

Bertness, K. A.; Kurtz, S. R.; Asher, S. E.; Reedy, R. C., Jr. (1999). AlInP Benchmarks for Growth of AlGaInP Compounds by Organometallic Vapor-Phase Epitaxy. Journal of Crystal Growth. Vol. 196(1), January 1999; pp. 13-22; NICH Report No. 27004.

Branz, H. M.; Asher, S.; Gleskova, H.; Wagner, S. (1999). Light-induced D Diffusion Measurements in Hydrogenated Amorphous Silicon: Testing H Metastability Models. Physical Review. B, Condensed Matter. Vol. 59(8), 15 February 1999-II; pp. 5513-5520; NICH Report No. 27002.

Norman, A. G.; Olson, J. M.; Geisz, J. F.; Moutinho, H. R.; Mason, A.; Al-Jassim, M. M.; Vernon, S. M. (1999). Phase Separation and Facet Formation during the Growth of $(GaAs)_{1-x}(Ge2)_x$ Alloy Layers by Metal Organic Vapour Phase Epitaxy. 6 pp.; NICH Report No. CP-520-26319.

Crystalline Silicon

Low Cost Glass and Glass-Ceramics Substrates for Thin Film Silicon Solar Cells

Contract #: XAF-8-17607-06	**Contract Period:** 3/25/98 – 3/24/2001

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Cornell University Materials Science and Engineering Ithaca, NY 14853	
	Organization Type: CU	**Congressional District:** 26
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dieter G. Ast **Phone:** 607-255-4140 **Fax:** 607-255-2365 **e:mail:** dast@ccmr.cornell.edu	
Technical Monitor: Bhushan Sopori **Phone**: 303-384-6683 **Fax**: 303-384-6684 **E:mail:** bhushan_sopori@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Corning Incorporated, Corning, NY 14831
	DOE Funding Allocation: 1998: $105,000 1999: $135,000	**Cost Share Funding:** 1998: $127,050 1999: $ 53,420

Project Objective: The objective of the project is to develop a substrate for the economical and rapid fabrication of thin film solar cells. A substrate that is transparent and inert can do 'double duty' as the cell cover glass lowering cost. A substrate that can tolerate high temperatures (> 900 ^{o}C) during solar cell fabrication also lowers costs since the rate with which silicon and other semiconductors can be deposited by chemical vapor deposition increases exponentially with temperature. Thus high substrate temperatures are required to achieve high throughput. Furthermore, a high temperature during deposition promotes the formation of a more perfect solar cell material containing less crystalline defects and having a higher conversion efficiency. Currently, the most heat resistant glass substrates can tolerate only about 600 ^{o}C, which is too low to achieve either rapid deposition or low density of crystalline defects. Glass-ceramics are a class of material that can withstand high temperatures and are chemically extremely durable. They are generally non-transparent and are used commercially to fabricate the black, smooth stovetops found on electric ranges.

The goal of the project is i) to develop new, transparent glass-ceramic that use low cost ingredients, have a strain point in excess of 950 ºC, have a coefficients of thermal expansion matched to Si , and posses optical transmissions of greater than 90% and ii), to qualify these substrates for the production of solar cells.

Glass ceramics are low cost materials and hence their purity is not as high as that of fused quartz (a material used in optical fibers) or silicon used in integrated circuit. Many of these impurities will migrate during high temperature processing from the substrate into the solar cell material, decreasing both the conversion efficiency and contaminating the processing equipment. An important goal of the proposal, therefore is the task to develop a low cost substrate coating ('diffusion barrier') that will prevent out-migration of impurities at high temperatures.

Approach/Background: This project is a joint development between Corning Incorporated and Cornell University. The development of the substrate material is being conducted at Corning. The glass ceramics selected can be processed to > 900 ºC, is transparent, and matches the thermal coefficient of silicon.

The research encompasses four major technical components which are the i) the development of novel glass ceramics, ii) understanding the movement of impurities from glass ceramic substrate into the deposited semiconductors ('contamination') as well as the movement of impurities from the semiconductor to the substrate ('gettering') iii) evaluation of the effectiveness of barrier system to stop out-diffusion while minimizing interference with gettering and iv) verification of performance by fabricating thin film electronic and solar cell test structures on barrier coated glass ceramic substrates and comparing their device performance to reference specimens made on fused quartz and oxidized silicon wafers.

Status/Accomplishments: A glass ceramic, code name LGA-139 was developed at Corning that meets all the above requirements. The composition is SiO_2-Al_2O_3-ZnO-MgO-TiO_2-ZnO_2. The microstructure of this glass-ceramic consists of 10-15 nm-sized spinel crystals, dispersed uniformly in a siliceous glass matrix. The small size of the spinel crystals and the close match the refractive index of the SiO_2 ensures very high transparency of this glass-ceramic (over 90% of 2mm thick wafer, uncorrected for surface reflectivity). The strain point is over 950 ºC . The coefficient of thermal expansion is $38 \cdot 10^{-7}$ /ºC optimally matching that of Si at higher temperatures.

An intentionally over-designed barrier layer consisting of a triple stack of SiO_2/SiN_x deposited by Low Pressure CVD was used first.. After annealing this 7 layer system in N_2 at 900 ºC for 8 hour all elements contained in the glass ceramic were profiled by SIMS. The results shown that first SiO_2 layer did not prevent the out-diffusion of glass components. Concentration of all elements dropped in the first SiN_x layer and reach background levels in the following layers. Further studies showed that a simpler barrier layer consisting of 1000 Å SiN_x followed by 1000 Å of SiO_2, both deposited by Plasma Enhanced CVD (PECVD), had higher optical transparency and lower RMS roughness while still meeting all requirement.

Majority and minority carrier test devices fabricated on glass-ceramics, oxidized silicon, and fused silicon, to first order, exhibited similar performance. Second order differences in performances have been traced to differences in the thermal expansion coefficient of silicon and quartz, the different roughness of bare and barrier coated substrate. The density of states, N(E), was measured quantitatively in poly-silicon deposited on oxidized silicon, quartz, and glass ceramics, and was, within ½ order of magnitude, the same in all three materials.

Current work is concentrating on separating surface geometric effects (roughness) from chemical (impurity) effects, since both these properties of barrier layers influence the nucleation, growth, and structure of subsequently deposited thin silicon film. Deep level transient spectroscopy is being used to characterize the impurity content of these films.

To quantitatively measure the carrier mobility and density of mid-gap states in polysilicon.deposited on various substrates, we fabricated top gated thin film transistors (TFTs) at 900 ºC. The electron mobility (over 100 $cm^2/V\cdot sec$) and the leakage currents (below 30 pA) measured in devices fabricated on barrier layer coated glass-ceramics were similar to those measured in our controls, devices fabricated on oxidized silicon and fused silica.

In n-type poly-silicon, Na (and other alkali) impurities are of great concern since they accumulate in the negatively charged grain boundaries, attracted by both electrostatic and chemical forces (oxygen segregates to grain boundaries, forming SiO_x, which has a high affinity for Na). The presence of Na can be tracked electrically in TFTs, by investigating the stability of these transistors using the bias temperature stress test, to measure mobile charges in the gate oxide. Devices on glass-ceramics and fused silica were found to be more stable and could withstand high temperatures for longer times (200 ºC, 50 V, 10 minutes) than devices on oxidized silicon (100 ºC, 50 V, 1 minute). This finding is compatible with the model that low Na glass substrates can effectively getter mobile impurities from poly-silicon electronics. Gettering of impurities by P-glass or B-P-glass is well established in the IC industry, and low Na glass substrates seem to be similarly effective.

Solar cell and p-i-n junction diodes were fabricated on barrier layer coated glass-ceramic substrates and for comparison, on fused silica and oxidized silicon controls. The dark current-voltage characteristics of all cells were measured to evaluate the influence of the substrate on device performance. The low leakage current and high breakdown voltage observed in solar cells and p-i-n junction Diodes fabricated on glass-ceramic substrates had similar electrical characteristics to those fabricated on oxidized silicon controls. On both substrate types, the breakdown voltage was high and the leakage current was low. On the other hand, on fused silica substrates the junctions were leaky. The poor performance devices on fused silica substrates were traced to cracks in the polysilicon film, observed both with scanning electron microscope (SEM) and optical light microscope. Calculation showed that the cracks were caused by the mismatch in the thermal expansion coefficient of silicon and fused silica.

Planned FY 2000 Milestones:

- Separating geometric (surface roughness) and chemical (impurity diffusion) in barrier layers.
- Based on understanding acquired, further optimization of barrier layers
- Measuring the density of states in hydrogenated poly-Si device layers deposited on barrier layer covered glass ceramics and control substrates (fused quartz, oxidized silicon)
- Quantitative tracking of low concentrations of impurities by deep level transient spectroscopy.
- Collaboration with Professor M.Green (UNSW, Australia), and Drs. Sopori and Ciszek (NREL) on the fabrication of thin film solar cells on glass ceramic substrates.

Major Reports published in FY 1999

Annual Progress Report, Photovoltaic Program, FY 1998

Major Articles Published in FY 1999:

Nemchuk, N.I.; Krasulya, S.M.; Couillard, J.G.; Ast, D.G.; Pinckney, L.R.. "Novel Glass-Ceramic Substrates for Thin Film Polycrystalline Silicon Solar Cells," *Ninth Workshop on Crystalline Silicon Solar Cell Materials and Processes, Extended Abstracts and Papers; Beaver Run Resort, Breckenridge, CO, August 9-11, 1999. NREL/BK-520-26941, pp. 90-93.*

Nemchuk, N.I.; Couillard, J.G.; Ast, D.G.; Fehlner, F.P.; Pinckney, L.R.. "High-Temperature Glass-Ceramic Substrates for Thin Film Electronics," Presented at *1999 International Semiconductor Device Research Symposium, Charlottesville, VA, December 1-3, 1999.*

Investigation of Gettering Mechanisms in Crystalline Silicon

Contract #: XAF-7-17607-01	**Contract Period:** 7/21/97–3/31/00

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None.</td></tr>
<tr><td>DOE Funding Allocation:
1997: $145,000
1998: $ 30,000
1999: $148,500</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

The objective of this work is to model gettering processes in single- and multi-crystalline Si so as to predict gettering performance and design optimum gettering processes. Physically correct mechanisms and numerically accurate simulation results are sought after. It is necessary to perform experiments to verify the models and improve accuracy of the modeling parameters as well as to demonstrate practical application of the insights obtained from modeling.

Approach/Background:

The role of metallic impurities as efficiency limiting factors in solar cells fabricated using crystalline Si substrates is well established. In multi-crystalline Si, a large fraction of the impurities is in the form of precipitates and large numbers of dislocations and grain boundaries also exist. Various processes, including precipitate formation and dissolution, impurity atom diffusion, native point defect diffusion, clustering and dissociation of defects and dislocations etc., can affect the gettering of impurities and the minority carrier diffusion length. For complete understanding and control of the gettering process, it is necessary to have physically sound models of all the involved processes and accurate values of the modeling parameters. It is also necessary to evaluate the electrical performance of solar cells as a result of gettering.

Status/Accomplishments:

- Al gettering process with simultaneous monitoring of resultant solar cell efficiency. - Our previous modeling demonstrated that the limitations of the Al gettering, viz., process duration and residual impurity concentration., can be overcome by implementing variable temperature process, which increases the lifetime improvement and requires much shorter time. In the further work, the process model has been combined with solar cell device model. It predicts the efficiency of solar cells obtained as a result of gettering. In addition, Al indiffusion and formation of the back surface field have been taken into account. This helps optimize the Al gettering/indiffusion process with respect to both gettering and the back surface field and provides an insight into the role of each of the effects. In order to correctly predict the efficiency of solar cells made of Si with a certain distribution of impurities in solid solution and precipitates, it is necessary to know how electrically active the precipitates are. Since their electrical activity is controlled by multiple factors, such as Schottky barrier at the surface and carrier diffusion, generation and recombination in Si bulk, a model of recombination process has been developed. It allows us to calculate effective capture cross-section of impurity precipitates in Si. As our preliminary results show, the capture cross-section is dependent on the generation rate and precipitate size and concentration and is generally greater than predicted by simplified models.

- Modeling of Al gettering of Au in Si - Earlier experiments had consisted of deliberately contaminating single crystal Si by indiffusion of Au followed by Al gettering of the Au in Si. Characterization by Spreading Resistance Profiling (SRP) had shown that the gettering of Au proceeded from both wafer surfaces to progressively greater depths even though the Al layer was present only on one surface. The SRP profiles were converted to Au profiles by accounting for the increase in resistance due to the compensation of the dopant shallow level by the Au deep levels. Modeling of the Al gettering process using the kickout(KO) mechanism for Au diffusion could qualitatively reproduce the features of the experimental profiles, but the rate of removal of gold was too slow. Instead, if the Frank-Turnbull(FT) mechanism was invoked for Au diffusion, the rate of removal of gold was found to be satisfactory, but the profile shape in the surface region was found to not fit the experimental results. Preliminary results indicate that by using both the KO and FT mechanisms simultaneously for Au diffusion and also accounting for the reaction between self-interstitials and vacancies in Si, satisfactory fits may be obtained to the experimental results. The fitting is expected to provide some bounds on the values of self-interstitial and vacancy diffusivities and solubilities. Reliable values of these parameters are essential for accurate predictions of gettering efficacy for substitutional-interstitial impurities.

Planned FY 2000 Milestones:

- Completion of the modeling of recombination processes due to impurity precipitates in Si.
- Finding dependencies of electrical activity of precipitates on various factors.
- Incorporating the results of precipitate electrical activity calculations into the solar cell device model.
- Comparing the role of gettering and back surface field in the improvement of the solar cell efficiency.
- Working out recommendations regarding Al gettering/indiffusion process parameters leading to the highest cell efficiency.
- Fitting of experimental profiles of gettering of Au in Si by Al using KO & FT mechanisms simultaneously for Au diffusion.
- Establish bounds on vacancy and self-interstitial diffusivity and solubility values at experimental temperature.

Major Reports Published in FY 1999:

NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Tan, T. Y., Gosele, U. M., et al. (1999) “Investigation of Gettering Mechanism in Crystalline Silicon,” Second Annual Report, 31 pp. Available from Duke University, Durham, NC 27708-0300.

Major Articles Published in FY 1999:

Tan, T. Y., et al., "Effects of Al gettering and Al Indiffusion Induced Back-Surface-Field on the Efficiency of Si Solar Cells," *Ninth Workshop on Crystalline Silicon Solar Cell Materials and Processes. Extended Abstracts and Papers, Breckenridge, CO, August 9-11, 1999*, pp. 46-49 (1999).

Joshi, S. M., et al., "Enhancement of Diffusion Length in Multicrystalline Silicon by Extended High Temperature Aluminum Gettering,” *Ninth Workshop on Crystalline Silicon Solar Cell Materials and Processes. Extended Abstracts and Papers, Breckenridge, CO, August 9-11, 1999*, pp. 202-205 (1999).

Plekhanov, P. S., et al., "Modeling of gettering of precipitated impurities from Si for carrier lifetime improvement in solar cell applications," *J. Appl. Phys.* **86**, 2453 (1999).

Joshi, S. M., et al., "Extended High Temperature Al Gettering for Improvement and Homogenization of Minority Carrier Diffusion Lengths in Multicrystalline Si," submitted to *Appl. Phys. Lett.*

Crystalline Silicon Research Center of Excellence

Contract #: AA-1638 and AO-6162	**Contract Period:** 6/11/92–6/30/2000

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<tr><td>DOE Funding Allocation:
1995: $525,000
1996: $500,000
1997: $548,000
1998: $567,000
1999: $599,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Improve the state of the art in crystalline-silicon solar cells through research on high-efficiency, one-sun, single- and multicrystalline silicon solar cells; improve fundamental understanding of efficiency-limiting defects and mechanisms; develop low-cost manufacturable processes; train future professionals in photovoltaic technology; and transfer new technology to industry through collaborative research.

Approach/Background: Conduct collaborative research with students from other universities and industry. Develop high-efficiency float-zone (FZ) and multicrystalline silicon solar cells in order to demonstrate new device concepts. Develop new processes for fabricating solar cells, including Rapid Thermal Processing (RTP). Develop characterization and modeling tools for high efficiency silicon solar cells.

Status/Accomplishments:

- Developed effective stack surface passivation and screen-printed Al BSF to achieve 4 cm^2 19-20% efficient FZ and ~ 18.5% CZ and 42 cm^2 18.3% CZ cells with Photolithography contacts
- Fabricated record high efficiency 4 cm^2 16.2% string ribbon cells with photolithography contacts
- Pioneered the field of RTP and BLP to reduce cell processing time to ≤ 2 hours with screen printed contacts
- Developed a belt line and screen printing process to achieve high fill factors of ~ 0.798 on single crystal CZ and FZ silicon
- Developed screen printing process that can produce high fill factors ~ 0.77 and efficiency of ~ 15% on cast multi-crystalline
- Fabricated record high 14.9% efficient 4 cm^2 screen-printed string ribbon cells using belt line processing
- Fabricated record high efficiency screen-printed 100-µm thick 14.2% 4 cm^2 solar cells on n-type dendritic web silicon ribbon
- In collaboration with an equipment vendor, designed a novel belt line furnace which can reduce the cell processing time, enhance the cell performance, and bridge the gap between RTP and belt line processing
- Successfully maintained and monitored 342 kW Georgia Tech PV system which has thus far produced one billion kWh of electrical energy

Contract #: AA-1638 and AO-6162

FY 2000 Milestones:

- Fabricate large area cells on PV-industry CZ silicon with target efficiency of 20%
- Fabricate large area cells on multi-crystalline silicon with target efficiency of 19%
- Fabricate large area RTP/PECVD/SPC cells on CZ silicon with target efficiency of 17%
- Fabricate large area RTP/PECVD/SPC cells on CZ silicon with target efficiency of 16% multi-crystalline silicon
- Reduce cell processing time to less than 2 hours/batch using screen-printed contacts
- Investigate light trapping in silicon cells by porous silicon and RIE texturing
- Teach a course on Solar Cells and provide hands-on training to students in the area of design and fabrication of solar cells
- Publish at least five papers on current research involving RTP, screen printing, belt line processing and high efficiency cells on low-cost materials
- Train about 10 Ph.D. students in the area of modeling, design, and fabrication of low-cost high-efficiency silicon solar cells
- Serve as General Chair of the 28th IEEE PVSC Conference in Alaska
- Maintain several different cell process lines including RTP, CFP, BLP at Georgia Tech

Major Reports Published in FY 1999:

J. B. Lee, M.G. Allen, and A. Rohatgi, " Photovoltaic On-Demand Pulse Generator as an On-Board Power Source for Electrostatic Actuator Array", SPIE Symposium on Micromachining and Microfabrication, Santa Clara, California, September 19-23, 1999

Major Articles Published in FY 1999:

T. Krygowski, A. Rohatgi, and T. Selzer. "A Novel Processing Technology for High-Efficiency Silicon Solar Cells," J. Electrochemical Soc., vol. 146, no. 3, March 1999.

Rohatgi, A. et al., "Rapid Thermal Processing and Screen-Printing for Low Cost Silicon Solar Cells," American Institute of Physics, NCPV Photovoltaics Program Review, eds. M. Al-Jassim, J.P. Thornton and J.M. Gee, pp. 354-360, March 1999.

S. Narasimha, A. Rohatgi and A.W. Weeber, "An Optimized Rapid Aluminum Back Surface Field Technique for Silicon Solar Cells," IEEE Transaction on Electron Devices, vol. 46, no. 7, pp. 1363-1370, July, 1999.

A. Rohatgi et al., "Rapid Processing of Low-Cost, High-Efficiency Silicon Solar Cells," Proceedings of the IUMRS-ICA International Conference in Asia, October, 13-16, 1998.

A. Ebong, J. Brody, A. Rohatgi and T. Williams, "Optimization of Front Metal Contact Firing Scheme to Achieve High Fill Factors on Screen Printed Silicon Solar Cells," Proceedings of the 11th International Photovoltaic Science and Engineering Conference (PVSEC-11), September 20, 24, 1999.

A. Rohatgi, "Rapid Thermal Processing of High Performance Dielectrics and Silicon Solar Cells," Proceedings of the ECS Symposium, PV for the 21st Century, Seattle, Washington, May 3-6, 1999.

High Efficiency Solar Cell Fabrication on Commercial Si Substrates

Contract #: XAF-8-17607-05	**Contract Period:** 2/4/98–2/3/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: CU	**Congressional District:** 5
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Technical Monitor: Bhushan Sopori **Phone**: 303-384-6683 **Fax**: 303-384-6684 **E:mail:** bhushan_sopori@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $105,000 1999: $126,300	**Cost Share Funding:**

Project Objective: The project objective is two-fold: (a) minimize electrical activity of performance limiting defects in promising low-cost Si materials through fundamental understanding and optimization of low-cost gettering and passivation techniques, and (b) develop cell process sequences to incorporate the best gettering and passivation techniques to fabricate record high efficiency cells on low-cost materials.

Approach/Background: Silicon material accounts for about 40% of the cost of current Si photovoltaic modules. In an attempt to reduce cost, most cell manufacturers use low-cost defective Si materials. Unfortunately, this comes at the expense of cell efficiency because low-cost materials contain defects and defect clusters involving carbon, oxygen, transition metals, grain boundaries and dislocations which severely degrade bulk lifetime. The goal of this project is to minimize the harmful effects of the above defects by implementing appropriate combination and sequence of gettering and passivation techniques. This will lead to high-efficiency cells on low-cost materials and a significant cost reduction of Si photovoltaic modules.

The approach to realize the above objective is outlined below.

- Characterize and identify lifetime limiting defects and defect clusters in low-cost materials
- Optimize and enhance the synergistic effect of gettering and passivation techniques such as phosphorus and Al gettering and SiN and forming gas induced hydrogenation of defects
- Implement RTP to enhance gettering and passivation of defects and defect clusters
- Integrate gettering and passivation techniques in proper order to achieve record high efficiency cells on low-cost materials

Status/Accomplishments:

- Successfully optimized and integrated phosphorus and Al gettering and PECVD SiN and forming gas induced hydrogenation to raise the as-grown bulk lifetime of (a) string ribbon silicon from 3-8 µs to 15-50 µs; (b) EFG silicon from 1-3 µs to 15-40 µs; (c) dendritic web silicon from 1 µs to $\geq$ 20 µs; and (d) cast Eurosolare and Bayer mc-Si from 10 µs to 50 µs.

- Demonstrated on various low-cost materials that simultaneous Al gettering and SiN hydrogenation amplifies the defect passivation, i.e. the positive synergistic effect of the two steps in a single firing cycle is much greater than the sum of the individual effects. This finding not only reduces the processing time and number of processing steps but also gives higher bulk lifetime and cell efficiency.

- Improved fundamental understanding of hydrogenation of defects from SiN by showing that maximum defect passivation requires balancing the vacancy generation from Al alloying and retention of hydrogen at the defect. Higher temperature, shorter hold time, and faster cooling rate can achieve this goal.

- Proposed a model to explain Al enhanced SiN-induced hydrogen of defects. According to this model, vacancy generation due to the simultaneous Al alloying process increases the flux of atomic hydrogen from SiN into the bulk Si by providing a chemical potential gradient and also raises the bulk content of atomic hydrogen by dissociating molecular hydrogen.

- Developed and optimized process sequences for low-cost screen printed Al BSF Ag ohmic contact on the front. It was shown that time and temperature of the firing cycles are crucial for achieving best defect passivation.

- Fabricated record high efficiency cells on low-cost ribbon materials by integrating the gettering and passivation techniques. Using the furnace processing and photolithography contacts, we achieved 16.2% on string ribbon, 16% cells on EFG, and 16.8% cells on dendritic web silicon. More manufacturable belt line processing and screen printing gave 14-15% efficient cells on these ribbon materials.

Planned FY 2000 Milestones:

- Continue the optimization and integration of gettering and passivation techniques to achieve higher lifetimes and cell efficiency
- Use RTP to dissociate defect clusters to improve uniformity and reduce electrical activity in localized areas
- Investigate the impact of cooling rate after the co-firing of Al BSF and SiN to enhance defect passivation
- Understand the role of dopant-defect interaction to provide guidelines for selecting optimum bulk resistivity for highest cell efficiency
- Develop low-cost process sequences which incorporate best gettering and passivation cycles to fabricate record high efficiency cells on low-cost materials

Major Articles Published in FY 1999:

Rohatgi, A., et al., "Rapid Thermal Processing and Screen-Printing for Low Cost Silicon Solar Cells," *American Institute of Physics, NCPV Photovoltaics Program Review*, edited by M. Al-Jassim, J.P. Thornton and J.M. Gee, pp. 354-360 (1999).

Ebong, A., et al., "The Effect of Low and High Temperature Anneals on the Hydrogen Content and Passivation of Si Surface Coated with SiO_2 and SiN Films," *J. Electrochem. Soc.*, **146**, 5 (1999).

Rohatgi, A., et al., "Understanding and Implementation of Rapid Thermal Technologies for Low-Cost High-Efficiency Silicon Solar Cells," *IEEE Trans. Elec. Dev*., **46**, 10 (1999).

Ebong, A., et al., "Gettering, Hydrogenation and Resistivity Dependence of Minority Carrier Lifetime in Dendritic Web Ribbon Silicon," *9th Workshop on Crystalline Silicon Solar Cell Materials and Processes; August 9-11, 1999, Breckenridge, Colorado*, pp. 189-192 (1999).

Jeong, J., et al., "Aluminum-Enhanced PECVD SiN Hydrogenation of Defects in Edge-defined Film-fed Grown (EFG) Multicrystalline Silicon," *9th Workshop on Crystalline Silicon Solar Cell Materials and Processes; August 9-11, 1999, Breckenridge, Colorado*, pp. 193-197 (1999).

Yelundur, V., et al., "Understanding and Optimization of Manufacturable Defect Gettering and Passivation Treatments on String Ribbon Silicon," *9th Workshop on Crystalline Silicon Solar Cell Materials and Processes, August 9-11, 1999, Breckenridge, Colorado*, pp. 223-227 (1999).

Hydrogen-Defect Interactions Relevant to Si Solar-Cell Fabrication Studied by Vibrational Spectroscopy

Contract #: XCE-8-18684-01	**Contract Period:** 8/1/98–10/ 31/99

<table>
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $29,990
1999: $0</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:

The objective of this project is to elucidate the basic mechanisms and defect reactions that have an impact upon the hydrogen passivation of defects and impurities in Si.

Approach/Background:

Hydrogen plays an important role in semiconductors where it forms defect complexes with many impurities and defects and has a pronounced effect on electrical properties. The ability of hydrogen to passivate defects in solar-grade Si materials is often exploited to improve the properties of solar cells. The goal of this project is to provide detailed microscopic information about hydrogen-containing defects to help elucidate the mechanisms that either assist or impede defect passivation in Si. In our experiments we have focused on two important H-containing defects in Si, the H_2 molecule and the transition-metal-H complexes. The hydrogen-stretching vibrations of these defects are studied by infrared spectroscopy in conjunction with additional perturbations in order to probe microscopic structures, defect reactions, and electronic properties.

Status/Accomplishments:

Hydrogenation of transition-metal impurities in Si

In pioneering studies of the hydrogen passivation of deep-level defects in semiconductors, it was discovered that exposure of Si samples to a hydrogen-containing plasma can eliminate many of the electrical levels associated with transition metal impurities. Until recently, little was known about the microscopic properties of the hydrogenated transition metals in Si or the mechanism of passivation. In our experiments, H is introduced throughout bulk samples at high temperature (1250°C) that can then be studied with structure-sensitive methods like EPR and vibrational spectroscopy. Several hydrogenated transition metals (PtH, PtH_2, AuH and AuH_2) have been identified and their structures determined.

Surprisingly, these hydrogenated metal impurities remain electrically active. To probe the electronic properties of transition-metal-hydrogen complexes whose structures we have determined, we have prepared samples with their Fermi levels located at several different positions in the Si band gap. Vibrational spectroscopy was then used to determine the charge states of the transition-metal-H complexes for the various known Fermi-level positions. In these experiments, the positions of the electronic levels of the PtH, PtH_2, AuH, and FeAuH complexes have been approximately located. These experiments allow the results of vibrational spectroscopy for these defects to be correlated with the results of electrical measurements such as DLTS.

Contract #: XCE-8-18684-01

Structure of the H_2 molecule in Si

The hydrogen molecule is one of the simplest hydrogen-containing defects in semiconductors and has been suggested, beginning in 1983, to play an important role during hydrogen indiffusion and in a variety of hydrogen reactions. In spite of its proposed importance, the H_2 molecule in a semiconductor was observed directly by vibrational spectroscopy only recently. In our experiments, we have used uniaxial stress in conjunction with IR absorption to probe the stress dependence of the H-stretching vibrational line. These experiments provide information about the symmetry of the H_2 defect in Si so that its configuration in the lattice might be determined. Our experiments have revealed the surprising result that H_2 in Si has C_1 symmetry, lower than has been suggested previously by several theoretical calculations. The form of the tensor that describes the response of the H_2 vibrational frequency to uniaxial stress has led us to suggest a structure with the H_2 molecular axis aligned close to a <100> direction in the Si lattice.

Planned FY 2000 Milestones: Not applicable. Subcontract period ended on October 31, 1999.

Major Reports Published in FY 1999:

M. Stavola, M. Weinstein, and J.A. Zhou, "Hydrogen-Defect Interactions Relevant to Si Solar-Cell Fabrication Studied by Vibrational Spectroscopy," in *NCPV FY 1998 Annual Report* (NREL/BK-210-25626)*,* eds. R.D. McConnell and A. Hansen (NREL, Colorado, 1999), p. 43.

Major Articles Published in FY 1999:

M. Stavola, "Hydrogen-Containing Point Defects in Silicon," in: *Defects in Silicon III*, eds. T. Abe, W.M. Bullis, S. Kobayashi, W. Lin, and P. Wagner, (ECS, Pennington, 1999), p. 227.

J.A. Zhou and M. Stavola, "Symmetry of Molecular H_2 in Si from a Uniaxial Stress Study of the 3618.4 cm^{-1} Vibrational Line," *Phys. Rev. Lett.* **83**, 1351 (1999).

J. A. Zhou, E. Chen, and M. Stavola, "Microscopic Properties of H_2 in Si from the Dependence of the 3618.4 cm^{-1} Line on Temperature and Stress," *Proc. 20th Int. Conf. on Defects in Semiconductors*, Berkeley, July, 1999, to be published.

Advanced Device Process Development

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/98 – 09/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Boulevard Golden, Co 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator** Bhushan Sopori **Phone:** 303-384-6683 **Fax:** 303-384-6684 **E:mail:** bhushan_sopori@nrel.gov	
Technical Monitor: John Benner **Phone**: 303-384-6496 **Fax**: : 303-384-6531 **E:mail**: john_benner@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $370,000	**Cost Share Funding:**

Project Objective:
- Investigate and apply impurity and defect interactions to develop processing techniques for fabrication of low-cost silicon solar cells
- Develop methods to rapidly analyze and characterize solar-cell materials and devices.
- Provide technical assistance to industry in characterization, and process and device modeling.
- Coordinate national laboratory, university, and industry c-Si materials/device research through hosting a workshop on defects and impurities in c-Si.

Approach/Background: The work in this area has several tasks:
- Development of high speed equipment to map impurities and defects in solar cells and a solar-cell substrates
- Theoretical studies of recombination effects of impurities and defects on the PV properties of the substrate and effect on the cell performance
- Development of low-cost solar cell processing techniques
- Development of a low-cost thin film Si solar cell

Status/Accomplishments:
Recombination in nonuniform devices: We have continued further development of the previous software package for modeling "non-uniform" solar cells. This extension involves inclusion of minority carrier recombination in a non-uniform substrate. We have completed writing the first version of a finite-element code to determine time-dependence of the genration/recombination of the minority carriers. This analysis will provide an input to our Non-uniform Solar Cell model. This code is applicable to both uniform and non-uniform materials. Our current interest is to pply this analysis to understand issues of making lifetime measurements in PV-Si wafers. This work is complementary to our earlier analysis that used a phenomenological methodology to solve diffusion and continuity equations. The analysis gives an insight into the meaning of the experimental results on the minority-carrier lifetime/diffusion length that are typically obtained on commercial, single and multi-crystalline PV-Si wafers by various techniques such as PCD, SPV, and LBIC.
***PV Optics* upgrade** : The *PV Optics(*version 2) is now ready for release. This version incorporates a number of improvements to the Version 1. These include — reduced calculation time for multijunction cells (approx. a factor of 4), capability to input user defined material parameter files, and capability to change the incident angle of illumination (we received many requests to make this improvement).
Emissivity modeling package was completed. This software generates reflectance, transmittance, and emissivity of a silicon sample of any surface morphology, at different temperatures. The model uses a theoretical simulation of the refractive index and absorption coefficient for different resistivities and temperatures. A further extension of this package is to determine temperature profiles of a wafer during rapid thermal and Optical Processing.

Fiber Optic Solar Simulator): The basic design of a new Fiber Optic solar Simulator was developed in collaboration with III-V group. The simulator will have four incoherent light sources and four coherent (laser) sources. The output of the light sources will be combined through an optical fiber to produce an output light beam whose spectrum can be adjusted. This will allow measurement of the I-V characteristics of a multijunction device as well as that of the each individual cell. A breadboard model of the system is expected to be completed in FY2000.

New Reflectometer: Further work has been done on the reflectometer to improve S/N ratio, and make it operator-friendly. In addition, the software has been improved to eliminate most operator errors. One of the limitations of the current system is its lower sensitivity for polished wafers (the primary purpose of the system is to overcome the inability of conventional methods to make measurements on the rough and textured surfaces). A newer design will overcome this limitation. This design will be able to switch conditions for different wafer morphologies. The reflectometer was also used to successfully detect very small changes in the front metallization of commercial silicon solar cells. Many test runs were made for the samples supplied by BP Solarex, Siemens Solar, and ASE Americas.

Optical Processing/Thin Film Si Cell: We have carried out detailed experiments to quantify differences in the mechanisms involved in Optical Processing Vs thermal processing. Major emphasis is on the study of interdiffusion of Si and Al, and controlled formation of texture as a result of point defect injection. Experiments were also performed to make large-grain Si films at low temperatures using metal induced crystallization and subsequent grain enhancement by Optical Processing. We have obtained thin films, ranging in thickness between 2 and 10□m, highly preferred grain orientation. These films, deposited on metal-coated glass, show little or no residual stress and an excellent adhesion.

PVSCAN: Because of the termination of the licensing agreement with Labsphere, PVSCAN is no longer available to customers. We are building PVSCANS for a number of institutions, while there is a search for a new licensee. We are also investigating higher scanning speeds to accommodate large (8-in x 8-in) cells and wafers, without increasing scanning time. In our laboratory tests we have been able to do the following:

- increase in the scan speed from 1- to 4-ips with a comparable resolution
- increase the data taking capability (4X)
- identify method to increase data storage by increasing the buffer size (buffer size is limited by the interface card)
- eliminate sources of image distortion (which are very forgiving at low scanning but become prominent at high scanning speeds).

Workshop: The 9th Workshop on Crystalline Silicon Solar Cell Materials and Process was held on Aug. 9-11, 1999 in Breckenridge, CO. The theme of the workshop was "R&D Challenges and Opportunities in Si Photovoltaics." It was attended by 102 scientists and engineers working in the photovoltaic and microelectronics fields, and included topics that are of immediate concern to the PV community.

Planned FY 2000 Milestones:
- Complete fabrication /upgrade of four PVSCAN systems
- Complete fabrication of high-speed reflectometer, reducing the measurement and analysis time to less than one second per wafer
- Investigate possibility of combining PV Optics and an electronic model for solar cell design and analysis
- Upgrade Module Laser Scanner

Major Reports Published in FY 1999: (Examples below)
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Major Articles Published in FY 1999:

Bhushan Sopori, Wei Chen, Teh Tan and Pavel Plekhanov, "Overcoming the Efficiency-Limiting Mechanisms in Commercial Si Solar Cells," NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 341-347 (1999)*

Bhushan L. Sopori, Wei Chen, N. M. Ravindra, "*Calculation of the Emissivity of Si Wafers,*" J. Electronic Materials, Dec. 1999.

Bhushan L. Sopori, Wei Chen, and Marta Symko, "Spatial Nonuniformities in the Minority Carrier Diffusion Length/Lifetime: Measurement and Implication" *Silicon Recombination Lifetime Characterization Methods*, ASTMSTP1340, Eds. D. C. Gupta, F. Batcher, and W. H. Hughes, American Society for Testing and Materials, pp 328-346,1999.

Bhushan Sopori, Jamal Madjdpour, Yi Zhang, Wei Chen, Subhendu Guha, Jeff Yang, Arindam Banerjee, Steven Hegedus, "Optical Modeling of a-Si Solar Cells," Procd. MRS Spring '99.

Wei Chen and Bhushan Sopori, "A Thin Silicon Solar Cell on Glass: Cell Design and Process Physics," Procd. **99-11**, Electro-Chemical Soc. Meeting, May '99, Symposium on Photovoltaics for the 21st Century, pp 145-152.

Bhushan Sopori, Wei Chen, Yi Zhang and Jamal Madjdpour, and N. M. Ravindra, "Emissivity Of Bare And Coated Si Wafers: Theoretical Studies," Procd. **99-10**, Electro-Chemical Soc. Meeting, May '99, Symposium on Advances in Rapid Thermal Processing, pp 427-434.

Bhushan Sopori, Jamal Madjdpour, Yi Zhang, and Wei Chen, "*PV Optics*: an Optical Modeling-Tool for Solar Cell and Module Design," Procd. **99-11**, Electro-Chemical Soc. Meeting, May '99, Symposium on Photovoltaics for the 21st Century, pp 138-144.

Crystalline Silicon

Characterization and Ti Gettering of PV Substrates

Contract #: XAF-8-17607-03	**Contract Period:** 1/29/98–1/18/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148	North Carolina State University Department of Materials Science and Engineering Raleigh, NC 27695-7514	
	Organization Type: CU	**Congressional District:** 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** G. Rozgonyi **Phone:** 919-515-2934 **E:mail:** rozgonyi@ncsu.edu	
Technical Monitor: Bhushan Sopori **Phone**: 303-384-6683 **Fax**: 303-384-6684 **E:mail**: bhushan_sopori@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $80,000 1999: $98,400	**Cost Share Funding:**

Project Objective: (i) lifetime measurement of Ni and Fe contaminated p-type silicon wafers using a contactless frequency resolved photoconductance (FR-PC) technique, (ii) Ti thin film external gettering (EG), and (iii) variable wavelength excitation source of the new μ-PCD system JANUS 300.

Approach/Background: 1. Wafer characterization using frequency resolved photoconductance has been investigated in this report. The spectra have been measured at elevated temperatures to: (i) dissociate weak recombination centers, (ii) reduce the surface recombination velocity due to surface potential deterioration, (iii) enhance detection sensitivity of the midgap levels. Five parameters; surface recombination velocity v_s, deep level concentration N_r, electron/hole capture cross section σ_n, σ_p and activation energy E_r, are used for spectra simulation and determination of the material properties. The set of wafers with low Fe or Ni concentration was prepared at Mitsubishi-Silicon-America. The wafer spectra were measured using FR-PC and recombination parameters were evaluated using procedures described in [1].

2. The gettering strategy using a thin Ti film, as well as μ-PCD lifetime data have been described in our previous report [1]. The CZ and FZ wafers were contaminated with Fe and Ni and gettered using a thin Ti film deposited by magnetron sputtering. Gettering was done for two annealing temperatures (500^0C, 700^0 C) in a N_2 atmosphere using one of four thin films: Ti(Ar), Ti(Ar+N_2), Ti/Al alloy Ti/Al stock or Al (reference) [1].

3. A new μ-PCD lifetime system, JANUS 300, has been installed at NCSU. The advantages of the system are as follows: (i) mapping area up to 300 mm, (ii) automatic injection level control, (iii) variable wavelength excitation source, (iv) internal solid state IR laser with λ = 904nm, external dye laser with λ = 400 nm to 960 nm, (v) enhanced optical focusing system with beam spot of 0.1 mm and scan step of 0.1 mm, (vi) temperature range: RT to 200^{o}C.

Status/Accomplishments: 1. P-type CZ silicon containing Fe impurities was found to have an activation energy of 0.42±0.01eV, which was identified as a Fe-B pair by DLTS. The concentration of the Fe impurities matched the Fe-B impurity concentration for the highly contaminated wafers. In the case of low level Fe, Ni, or Ni+Fe contamination, N_r was found to be weak parameter, while E_r, $\eta = \sigma_n E_r$ and $\chi = \sigma_p/\sigma_n$ proved to be robust parameters. E_r and χ can be treated as characteristic material parameters. For example, it has been shown that the Ni contaminated wafers had the same E_r and χ values as the reference wafer, indicating operative residual impurities. The wafer contaminated with both Fe and Ni impurities had different E_r, χ values than the wafers containing Fe or Ni atoms separately.

<u>*Conclusions:*</u> E_r and χ can be treated as characteristic material parameters and they can be evaluated using frequency resolved photoconductance (FR-PC). Other parameters, such as concentration and electron/hole capture cross sections, can be evaluated only for highly contaminated wafers ($N_r > 10^{12}$ cm^{-3}).

2. The lifetime data is explained by using DLTS and SEM measurements. We have reported [1] the highest lifetime rate of $\kappa \approx 13$ for the Al getter, and the lowest lifetime rate of 3 for the Ti getter for low temperature annealing (500^0 C) of p-type CZ wafers. The lifetime rate is defined by $\kappa = \tau_G / \tau_{IN}$, where τ_{IN}, τ_G are initial and final sample lifetimes measured before and after gettering using μ-PCD. This gettering procedure was ineffective for the FZ wafers and no lifetime improvement was observed for n-type CZ wafers. In order to explain the low lifetime, DLTS measurements were performed and two peaks were detected for the Al

getters (p-type CZ wafers). These peaks corresponded to Fe-B and Fe-2 iron ($8x10^{11}$ cm^{-3} and 10^{12} cm^{-3} respectively) and were lower than the initial Fe-B concentration of $2x10^{13}$ cm^{-3}. In the case of the Ti getter, the Fe-B concentration was one order lower than for the Al getter, but a prominent Au-Fe complex peak accompanied by a donor-Fe peak was also observed. The Au atoms had been introduced into the samples during the Ti sputtering. It can be seen that the donor-acceptor pairing between Au_s and Fe_I has a stronger affinity than Fe-B, which is in accordance with Brotherton et al [2] data. The presence of Au explains the low lifetime enhancement for Ti gettering and reveals that Au-Fe and d-Fe levels are more operative recombination centers than the Fe-B and Fe-2 centers that are present in the Al gettered samples. The Au-Fe concentration of 10^{13} cm^{-3} was three times lower than the initial Fe-B concentration of $3x10^{13}$ cm^{-3}, and this was responsible for the low lifetime rate $\kappa \approx 2$ of the Ti gettered sample. One can also expect that the Fe atoms may precipitate during the oxygen nucleation process. This process was absent in the FZ samples resulting in their low lifetime rate of $\kappa < 2$. The moderate temperature gettering at 700^0C revealed more homogenous lifetime distributions than for the 500^0C anneal, with the exception of p-type CZ wafers containing Fe. These wafers had a high lifetime rate of $\kappa \approx 35$ for the Al and Ti/Al alloy getters. The lifetime enhancement was also seen for the Ti getter (with κ of 30), showing almost the same gettering efficiency as the Al getter. The external gettering (EG) process is shadowed by the internal gettering (IG) process during oxygen precipitation, which was confirmed by the low lifetime rate of 3 for p-type FZ wafers. The DLTS spectrum of the Ti getter shows separating peaks due to the donor-Au, the Au-Fe complexes, and the Fe-4 level. The Al gettered wafer has two separate peaks, the Fe-B pairs and the donor-Fe. The Al getter spectrum varies continuously, indicating continuous distribution of the deep levels in the lower Si bandgap. In the case of Ti and Al getters the Fe concentration did not surpass $3x10^{11}cm^{-3}$, which was ~100 times lower than the initial Fe-B concentration. However, the iron precipitation process can mask measured iron concentration. For the Ti gettering, low lifetime enhancement of the FZ samples was due to the presence of the Au atoms (Au-d and Au-Fe), or uniformly distributed non-identified deep levels for Al gettering. The concentration of the electrically active Au-Fe and donor-Au levels did not exceed $2x10^{12}$ cm^{-3} and were lower than the initial Fe-B concentration of $2x10^{13}$ cm^{-3}, demonstrating an operative gettering process. This concentration was higher than the Fe concentration in the CZ wafers indicating an IG process. The lowest lifetime rate of $\kappa = 14$ for the p-type CZ wafer was found for Ti getter with the Ar + N_2 plasma. The DLTS spectrum revealed five peaks: the Fe-B pair, the donor/acceptor Au, the Au-Fe complex and the Ni peaks. The peaks were not overlapping as in the case of the Ti(Ar) and Al getters. The dominating donor-Au peak is responsible for the lifetime deterioration. We believe the high concentration of Au related defects is caused by vacancy injection during surface nitridation processes and the formation of the nitride-oxygen complexes. An aggressive solution CP-4 was used for stripping metal thin layers after annealing. Different etching times were used for each four getters, the longest for the Ti(Ar) and the shortest for the Al getter. The etching times were chosen to correspond to the chemical bonding between Ti-Si-N and Al-Si atoms. The SEM-EBIC images revealed surface patterns which are largest for the Ti(Ar) getter, reduced for the Ti(Ar+N_2) getter, and the smallest for the Al getter.
Conclusions: (i) Efficiency of Ti thin film gettering is almost the same as Al gettering for moderate temperature of 700^0C, (ii) 700^0C Ti and Al gettering processes are more efficient than low temperature gettering (500^0C), (iii) Au atoms are not gettered by Ti film getter, (iv) IG sites compete with the metal film EG, (v) Au atoms are introduced during Ti deposition and they deteriorate carrier lifetime, (vi) Formation of Ti-N-Si complexes reduces impurity segregation, (vii) Nitrogen enhances the removal of Ti silicide, revealing a smooth surface after etching, (viii) the presence of surface vacancies deteriorates impurity segregation (this effect can be reduced by self-interstitial injection during the sputtering process, for example by adding O_2 gas into Ar plasma)

References

[1] *NCPV FY 1998 Annual Report,* NREL/BK-210-25626, (June 1999).
[2] Brotherton S.D, Bradley P., and Gill A., Weber E.R, J.Appl.Phys. 55, 952(1984).

Planned FY 2000 Milestones: 1. (i) Double wavelength excitation source for surface/bulk separation of recombination centers, (ii) AC analysis of the microwave reflection coefficient with surface recombination parameters, simulation and recovery procedure.
2. (i) Formation of TiO_x thin layer, (ii) Influence of N_2 gas on TiO_x formation, investigation of TiNO as well as TiO_x interfaces and their gettering ability, (iii) Electrical and optical characterization of the TiNO and TiO_x thin metal films.

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Major Articles Published in FY 1999:
A. Romanowski, et al, "Contactless Characterization of Fe and Ni Contaminated Silicon Wafers Using Frequency Resolved Microwave Photoconductance," 9th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Beaver Run Resort, Breckenridge, Colorado, pp. 142, 1999.
A. Romanowski, et al, Gettering of p-type Silicon Using Ti Thin Film, 9th Workshop on Crystalline Silicon Solar Cell Materials and Processes, Beaver Run Resort, Breckenridge, Colorado, pp. 218, 1999.
A. Romanowski, at al, "Contactless Characterization of the Silicon Contaminated Wafers Using Frequency Resolved Microwave Photoconductance," paper submitted to J. Appl. Phys.

Crystalline Silicon Device Research

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/98 – 9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic System Components Department	
	Organization Type: FF	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Douglas Ruby **Phone:** 505-844-0317 **Fax:** 505-844-6541	
Technical Monitor: James M. Gee **Phone:** (505) 845-7812 **Fax:** (505) 844-6541 **E:mail:** ljmgee@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $1,211,000	**Cost Share Funding:**

Project Objective: The objective of this research is to improve commercial photovoltaic crystalline-silicon (c-Si) module performance--including cost, efficiency, and reliability--through development of improved device structures and processes. The work is closely coordinated with c-Si PV industry through collaborative research, through CRADAs, and through work-for-others projects. The work emphasizes near-term impacts. A world-class PV device characterization laboratory is part of the effort. Specific emphasis is placed on development of self-aligned, selective emitter cells; plasma texturization processes; and simplified module assembly using back-contact c-Si solar cells.

Approach/Background:

The Crystalline Silicon Research Cooperative (CSRC) coordinates national laboratory c-Si research with the needs of the domestic PV industry. It promotes early dissemination of research results to US Si PV manufacturers, assists with the setup of joint experiments, and incorporates the research needs of industry into the national PV program. Concepts identified as high-priority by the CSRC include: plasma-texturization of mc-Si cells, development of self-doping metallizations, and low-cost polysilicon feedstock purification techniques.

The quality of the best mc-Si wafers has increased to the point where cell performance is approaching that of single c-Si cells, with the major difference due to the inability to texture mc-Si affordably using standard wet chemical etches. Ion etching (RIE) for texturing entire wafers at once was examined. The physics of texture formation by reactive ion etching, the optics of nanometer-scale surface texture, and the performance of RIE-textured cells were also examined.

Previous work on self-aligned, selective-emitter (SASE) cells used plasma etching and plasma-enhanced CVD of silicon nitride to form high-performance emitter structures on commercial screen-printed cells. Improvements of 0.8% absolute in efficiency using commercially processed cells were demonstrated.

The Emitter-Wrap Through, or EWT cell has been the focus of back contact cell development in past fiscal years. In FY98 the device demonstrated the potential for high efficiency with the fabrication of an 18.2%-efficient cell using photolithography. The focus in FY99 has been the conversion of this device structure to the use of industrially applicable techniques such as screen-printed metallizations.

Work was begun on new metal compositions that have the potential to form self-aligned selective-emitters and back-surface fields using low-cost deposition and simple firing conditions. This work is closely coordinated with the back-contact cell effort, because self-aligned, self-doping metals would be ideal for back-contact cells.

Contract #: DE-AC04-94AL85000

Status/Accomplishments:

- Performance of self-aligned, selective-emitter cells was improved by 7% relative (or 0.8% absolute) on 130-cm^2 production-line cells; grid pull tests indicated potential reliability problem, so efforts were redirected toward the fire-through process
- Demonstrated a 15.2% screen-printed EWT cell, using two metal pastes and single fire for both n and p contacts, exceeding the 14% target for using this process
- Demonstrated low contact-resistance of metal compound to p-type grown layer; total series resistance of p/n junction diode less than 20 mohm-cm^2; p-contact consisted of silver/dopant compound
- Demonstrated good I-V characteristics with new metallizations; optimum diode ideality factor of unity obtained over two decades of current for p/n diode; the p-type Si layer was grown from the self-doping metal compound
- RIE-textured cells on Solarex mc-Si wafers fabricated on production line with 0.54% current gain; potential for significant efficiency boost exists if shunting and loss of texture are reduced
- Initiated an LDRD project to examine solar-grade Si production, which is a topic of emerging importance to the PV community
- Successfully completed a work-for-others project with TerraSun for the commercialization of EWT solar cell technology for concentrator applications
- Increased productivity, quality, and usefulness of cell diagnostic measurements (58% increase) in the PDML; upgrades at the PDML included improved ability to measure MJ and Si cells with increased accuracy, and new internationally recognized reference cell calibration for better intercomparison

FY 2000 Milestones:

- Demonstrate plasma-textured solar cells with increased current generation compared to planar cells
- Provide plasma-nitride films and cell analysis to PV industry to speed development of passivating fire-through process
- Demonstrate EWT cell on multicrystalline silicon using screen-printed contacts
- Demonstrate self-doping metal compound with N-type dopant
- Measure dopant and silver concentration in epitaxial layers grown from silver-based self-doping metals; determine impact of silver on minority-carrier lifetime
- Fabricate self-aligned, selective-emitter solar cell using self-doping metals for both contacts, with at least 10% efficiency.

Major Reports Published in FY 1999:

Gee, James M., Saleem H. Zaidi, and Douglas S. Ruby, Advanced Silicon Space Solar Cells Using Nanotechnology, Micro- and Nano-Satellite Technology Conference 99.

Ruby, Douglas S., Pin Yang, Saleem Zaidi, Madhu Roy, S. Narayanan, "Plasma Texturing, Etching and Passivation of Multicrystalline Silicon Solar Cells," Renewable and Advanced Energy Systems for the 21st Century, Maui, Hawaii, April 1999. [Winner of 1999 Best Paper Award]

Saleem H. Zaidi, James M. Gee, Douglas S. Ruby and S. Brueck, "Characterization of Si Nanostructured Surfaces," 44th SPIE Annual Meeting, July, 1999.

R. J. Buss, D. S. Ruby, G. A. Hebner and P. Yang, "Modeling a Dry Etch Process for Large-Area Devices," 9th Workshop on Crystalline-Silicon Solar Cell Materials and Processes, Breckenridge, August 1999, pp. 175-178.

Keith Matthei, Ghazi Darkazalli, and Douglas S. Ruby, "Design of a High-Throughput Plasma-Processing System," 9th Workshop on Crystalline-Silicon Solar Cell Materials and Processes, Breckenridge, August 1999, pp. 183-188.

Douglas S. Ruby, Saleem H. Zaidi, Madhu Roy and Mohan Narayanan, "Plasma Texturing of Silicon Solar Cells," 9th Workshop on Crystalline-Silicon Solar Cell Materials and Processes, Breckenridge, Colorado, August 1999, pp. 179-182.

Major Articles Published in FY 1999:

Smith, David D., James M. Gee, Michel D. Bode, and Juan Carlos Jimeno. "Circuit Modelling of the Emitter-Wrap-Through Solar Cell," IEEE *Trans. El. Dev*., October 1999, Vol. 46, No. 10., p. 1993.

Crystalline Silicon

Theoretical Analysis of Hydrogen Passivation of Impurities and Defects

Contract #: XAX-5-15230-01	**Contract Period:** 6/29/95–6/14/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	Texas Tech. University Lubbock, TX 79409 **Organization Type:** CU	**Congressional District:** 19
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Stefan Estreicher **Phone:** 806-742-3723 **Fax:** 806-742-1182 **E:mail:** stefan.estreicher@ttu.edu	
Technical Monitor: Bhushan Sopori **Phone**: 303-384-6683 **Fax**: 303-384-6684 **E:mail**: bhushan_sopori@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1995: $17,000 / 1997: $49,900 1996: $26,998 / 1998: $49,900	**Cost Share Information:** None. **Cost Share Funding:**

Project Objective: Poly-Si solar cells often benefit substantially from the passivation by hydrogen at defects (native defects, impurities, and complexes). However, in all materials, some defects resist hydrogenation. This project deals with theoretical studies of H interactions with native defects and with transition metal related defects.

Approach/Background: The fundamental properties of point defects and small complexes are obtained in molecular clusters using ab-initio Hartree-Fock (HF) and/or periodic supercells using first-principles, density-functional based, molecular-dynamics (MD) simulations. Typical clusters contain a 60 to 80 atoms, and typical supercells contain 64 to 216 atoms. All the calculations solve the Schrodinger equation with atomic-like basis sets (localized orbitals).

The defects range in size from an isolated point defect (monovacancy, interstitial copper, etc.) to complexes such as vacancy clusters, multiple Cu's trapped at a precipitation site, etc.

In all cases, the geometries are energy-optimized with no symmetry assumptions, the electronic structure and chemical details calculated, and the classical dynamics studied at the MD level.

Status/Accomplishments:

1. H TRAPPING AT VACANCY AGGREGATES (Vn)

We have obtained the configurations, structures, and properties of H trapped at the most stable V_n's and predicted systematic properties of the resulting complexes. Among the key results are that the binding energy of H to V_n (with n=1,…,7) does not correlate with the stability of the V_n's but only with their size. The binding energies range from 2.5eV to 3.5eV. Hydrogen always forms a single strong Si-H bond, and is never found in a weaker (e.g., bond-centered) configuration. The entire {Vn,H} defect reconstructs around the strong Si-H bond.

2. DEFECT-INDUCED TRANSFORMATION OF THE (INVISIBLE) H_2 INTO ACTIVE SPECIES

We now finished the work begun during the last funding period dealing with the dynamics of the interactions of the "hidden" interstitial H_2 molecules with rapidly-diffusing defects such as the vacancy (V) or self-interstitial (I). These defects are injected into the material during a number of common processing steps, and their presence affects the electrical and optical properties of the H present in the sample. We have shown how V's or I's dissociates H_2, and that V-1 recombination at H_2 can lead to the formation of H_2*, a defect only seen in irradiated material.

3. C-C PAIRS

In collaboration with an experimental group at the University of Aarhus (Denmark) we have identified a new carbon-carbon pair, generated by radiation damage, consisting of two substitutional C impurities at adjacent crystal sites. This defect is electrically, optically, and EPR-active in the –1 charge state.

Contract #: XAX-5-15230-01

4. COPPER IN SILICON

The properties of interstitial Cu, substitutional Cu, Cu-acceptor pairs, and Cu precepitates at the ring-hexavacancy (V_6) have been obtained from total-energy, ab-initio Hartree-Fock calculations in molecular clusters. All the geometries have been energy-optimized and many details about the chemistry of copper in Si uncovered.

The key result is the Cu^+ is never in the closed-shell (3d10) configuration but promotes several electrons into its 4sp shell. This allows Cu^+ to interact in a variety of ways with the host crystal as well as with defects and impurities in it. The origin of the electrical activity of Cu-defect complexes in Si is found to reside in the tendency of copper to form multiple weak Cu-Si bonds rather than just a few strong bonds. The bonding and antibonding levels remain in the gap, and become traps for charge carriers. Hydrogen displaces the trapped Cu's by replacing the weak Cu-Si bonds by strong H-Si ones.

Planned FY 2000 Milestones: Research continues on several fronts (dependent on new contract funding):
1. The dynamics of interstitial precipitation and the electronic properties of the most stable self-interstitial aggregates,
2. hydrogen interactions with vacancy clusters and self-interstitials,
3. dynamics of interstitial H_2 molecules,
4. copper interactions with isolated impurities such as O or C,
5. copper interactions with O and/or C in small voids,
6. time permitting, we will begin to study the statics and dynamics of Fe-related defects in Si.

Major Reports Published in FY 1999:

Estreicher, S.K., *NCPV FY 1998 Annual Report*, NREL/BK-210-25626, (June 1999), p. 55

Estreicher, S.K., "Theoretical Analysis of Hydrogen Passivation of Impurities and Defects," Final Technical Report, available from S.K. Estreicher at Texas Tech. University.

Major Articles Published in FY 1999:

Estreicher, S.K. and Fedders, P.A. "Molecular Dynamics Studies of Defects and Impurities in Semiconductors" in Computational Studies of New Materials," ed. D.A. Jelske and T.F. George *(World Scientific, Singapore; AIP Conference Proceedings,* **462**, pp. 27-73 (1999).

Estreicher, S.K., et al., "Hydrogen-Defect Ineractions in Si," *Mater. Sci. Engr.* **B 58,** pp. 31-35 (1999).

Estreicher, S.K., et al., "Radiation-Induced Formation of H_2* in Si," *Phys. Rev. Lett.,* **82,** pp. 815-818 (1999).

Estreicher, S.K., et al., "Rich Chemistry of Copper in Silicon," *Phys. Rev. B***, 60,** pp. 5375-5382 (1999).

Impurity Precipitation, Dissolution, and Gettering in PV Silicon

Contract #: XAF-8-17607-04	**Contract Period:** 1/30/98–1/29/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	University of California at Berkeley Department of Material Sciences Berkeley, CA 94720	
	Organization Type: CU	**Congressional District**: 9
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** E.R.Weber **Phone:** 510-642-0205 **Fax:** 510-642-2069 **E:mail:** weber@socrates.berkeley.edu	
Technical Monitor: Bhushan Sopori **Phone**: 303-384-6683 **Fax**: 303-384-6684 **E:mail**: bhushan_sopori@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $105,000 1999: $138,130	**Cost Share Funding:**

Project Objective: To improve the carrier collection efficiency of large area solar cells, limited by regions of high recombination activity which contain defect clusters. This is to be accomplished by a) gaining an understanding of the nature of diffusion of transition metals to sinks, formation of precipitates and clusters of these metals, particularly in the regions of defect clusters, and their dissolution; b) analysis of recombination activity of precipitates with different morphology to characterize quantitatively the impact of transition metals in different chemical states on recombination of minority carriers; c) using this knowledge to design efficient gettering and passivation processes to improve the regions in silicon containing defect clusters, or to develop recommendations how to modify growth process to avoid formation of gettering-resistant defect clusters or to decrease their recombination activity

Approach/Background: PV-grade silicon is known to contain higher concentrations of transition metals than FZ or CZ-grown silicon for integrated circuit applications. This is because growth techniques used in photovoltaics cannot benefit from the segregation effects of transition metals (for example, the segregation coefficient of iron between the crystalline phase and the melt is 10^{-5}) to the same extent as CZ or FZ growth techniques do. Since mc-Si growth technologies use rapid solidification of silicon, metal impurities are trapped in the solid phase before they can segregate in the melt.

While *interstitial* transition metals or metal-acceptor pairs are generally very efficient lifetime killers, they usually have only weak detrimental effect on solar cell performance since they can be easily gettered. For instance, our NREL-supported research in 1994-1998 has clearly shown that intentionally contaminated FZ materials, containing metals in the form of interstitial species or metal-boron pairs, can be successfully gettered via aluminum gettering. The latter can be easily incorporated into the PV technological process. However, it was found that gettering is not entirely effective for the improvement of the minority carrier lifetime in PV materials, especially in regions of high dislocation densities. Studies on structural defects indicate that the recombination activity of structural defects is greatly enhanced by the precipitation and/or decoration of impurities at the defects. This suggests that the low lifetimes of the regions with defect clusters are a result of impurity precipitation/decoration in these regions.

Using computer modeling, we have shown that it is unlikely that simple diffusion kinetics alone can account for inefficiency of gettering of impurities from those regions. We have thus speculated that there exist barriers to dissolution of precipitates in PV silicon materials, which may be associated either with local lattice strains, or more likely with the formation of a crystalline phase other than metal-silicides. Hence, this project is focused on studies on physics of precipitation and dissolution of transition metals in silicon, and on understanding of the possible nature of gettering-resistant defect clusters. The approach to solve this problem is, on the one hand, to study the diffusion of transition metals to well-defined defects, their precipitation, recombination activity of these precipitates, and their dissolution using well-characterized crystalline silicon materials, and, on the other hand, to study the location and the nature of gettering-resistant metal clusters in PV-grade mc-Si by using a combination of advanced X-ray microprobe techniques, available at the Advanced Light Source at Lawrence Berkeley National Laboratory, lifetime characterization techniques, electrical measurement techniques, and scanning and transmission electron microscopy.

Contract #: XAF-8-17607-04

Status/Accomplishments:

- It is demonstrated that copper precipitates in silicon form a defect band between approximately 0.15 eV and 0.35 eV below the conduction band edge. Since this band is located close to the midgap position, it can be expected to provide an efficient recombination channel for minority charge carriers. It is shown that the precipitates are positively charged in p-type silicon, and become negatively charged or neutral in n-type silicon. Thus, local band bending formed around the precipitates in p-type silicon facilitates the capture of minority charge carriers (electrons) in p-Si. It is shown experimentally that copper-precipitates are several orders of magnitude more efficient as recombination centers than interstitial Cu or CuB pairs.
- Precipitation behavior of Cu is studied in n-Si and p-Si. A model is suggested and confirmed by experimental results that electrostatic repulsion between positively charged interstititial copper ions and growing Cu precipitates retards the growth of Cu precipitates in the bulk and stimulates diffusion of Cu to the surface sink. Efficient formation of Cu precipitates is possible only under the condition when Cu precipitates become neutral or negatively charged, which is possible if the Fermi level in the sample lies at or above the level of E_C-0.2 eV. This is feasible in either n-type silicon, or at high concentrations of Cu. This model enabled us to explain, for the first time, the weak effect of Cu contamination of solar cell efficiency, and the drastic difference of the dependencies of minority carrier diffusion length on Cu contamination in n-Si and p-Si.
- Fundamental physical properties of iron and its complexes in silicon are reviewed in detail, and presented in the form of two invited reviews. In particular, it is shown that a number of literature reports indicate that under certain conditions (which seem to be sufficiently high temperature (over 900^0C) and high concentration of oxygen), iron may form chemical bonds to oxygen with the formation of iron oxides or iron silicates, bound in the silicon lattice. According to the available thermodynamical data, these oxides and silicates bind iron much stronger than iron-silicides, and thus are very difficult to dissolve. Studies of metal contamination of mc-Si, conducted at the Advanced Light Source by S.A.McHugo, provided a direct evidence that iron clusters in the bulk of EFG material are iron silicates.
- As a part of our program of involvement of the Advanced Light Source user facilities into our NREL-sponsored research, we developed a novel technique for in-situ location of impurity clusters. This technique was called XBIC (X-ray beam induced current) and is essentially similar to EBIC or LBIC, with the difference that minority carriers are injected by X-ray beam from the synchrotron. We are presently exploiting the possibilities of application of this technique for rapid identification of the chemical state of the impurities.

Planned FY 2000 Milestones:

- Analysis of chemical state of copper and iron in the silicon oxide, bound during oxidation (iron) and outdiffusion (copper), using beamline 7.3.1.2 (micro-XPS) of the Advanced Light Source.
- Test of viability to apply the knowledge and experimental tools, developed for copper in silicon, to the third major metal contaminant in silicon, nickel. Nickel is expected to be positively charged in p-Si, and behave similarly to copper.
- Detailed studies of precipitation of copper at silicon oxide precipitates and dislocations in CZ and mc silicon, of enhancement of recombination activity of copper-contaminated precipitates, and of the thermal stability of these precipitates, by combination of transient ion drift and X-ray microprobe technique.
- Continued studies of the effect of iron clusters and precipitates at extended defects on minority carrier diffusion length, and quantitative studies of dissolution kinetics of iron clusters in crystalline and polycrystalline silicon substrates.

Major Reports Published in FY 1999:

E.R.Weber, C.Flink, H.Hieslmair, and A.A.Istratov, "Impurity precipitation, dissolution, gettering and passivation," in PV silicon NCPV FY 1998 Annual Report, NREL/BK-210-25626 (June 1999).

Major Articles Published in FY 1999:

1. A.A.Istratov, H.Hedemann, M.Seibt, O.F.Vyvenko, W.Schröter, T.Heiser, C.Flink, H.Hieslmair and E.R.Weber, "Electrical and recombination properties of copper-silicide precipitates in silicon," J. Electrochem. Soc. **145**, no.11, 3889-98 (1998).
2. H.Hieslmair, A.A.Istratov, S.A.McHugo, C.Flink, E.R.Weber, "Analysis of iron precipitation in silicon as a basis for gettering simulations," J. Electrochem. Soc. **145**, 4259-64 (1998).
3. S.A. McHugo, A.C. Thompson, G. Lamble, A. MacDowell, R. Celestre, H. Padmore, M. Imaizumi, M. Yamaguchi, I. Perichaud, S. Martinuzzi, M. Werner, M. Rinio, H.J. Moller, B. Sopori, H. Hieslmair, C. Flink, A. Istratov, E.R. Weber, "Direct correlation of solar cell performance with metal impurity distributions in polycrystalline silicon using synchrotron-based X-ray analysis," in "Application of Synchrotron Radiation Techniques to Materials Science IV," Eds: S.M. Mini, S.R. Stock, D.L. Perry, L.J. Terminello, (Mat.Res.Soc., Warrendale, PA), MRS Symp.Proc. **524,** p. 297-302 (1998).
4. T.Heiser, A.A.Istratov, C.Flink, and E.R.Weber, "Electrical characterization of copper related defect reactions in silicon," Material Science and Engineering B **58,** 149-154 (1999).
5. A.A.Istratov, H.Hieslmair, and E.R.Weber, "Iron and its complexes in silicon," Applied Physics A **69**, 13-44 (1999).

Optimization of Gettering Processes for PV Silicon

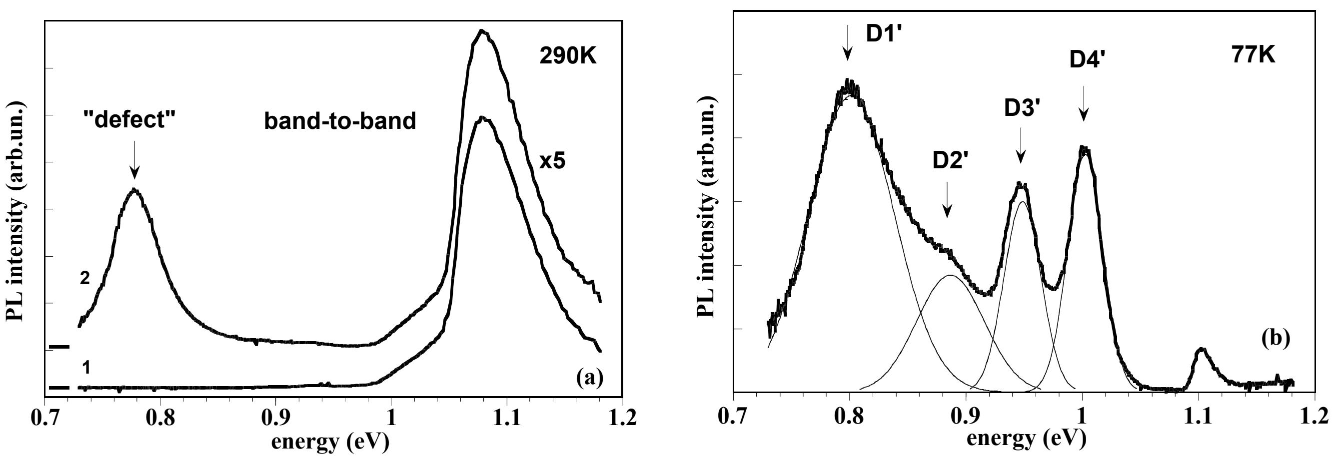
Contract #: XAD-2-11004-05	**Contract Period:** 5/12/92–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	University of South Florida Center for Microelectronics Research Tampa, FL 33620-5350 **Organization Type:** CU	**Congressional District:** 11
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Sergei Ostapenko **Phone:** 813-974-2031 **E:mail:** ostapenk@eng.usf.edu	
Technical Monitor: Bhushan Sopori **Phone:** 303-384-6683 **Fax:** 303-384-6684 **E:mail:** bhushan_sopori@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1994: $129,994 1997: $20,000 1995: $ 95,173 1998: $30,000 1996: $197,785 1999: $25,120	**Cost Share Information:** None. **Cost Share Funding:**

Project Objective: The effort was focused on a characterization of 'bad" regions in bulk polycrystalline silicon (poly-Si) wafers and solar cells with enhanced recombination activity and reduced minority carrier lifetime using a scanning room-temperature photoluminescence (PL). We developed this new spectroscopic technique to monitor defects attributed to lifetime killers. The ultimate goal is reducing of a detrimental role of such defects to poly-Si solar cell efficiency by adjusting solar cell processing steps.

Approach/Background: As we reported previously [1], PL mapping in photovoltaic silicon revealed a clear correlation between minority-carrier lifetime (or diffusion length) and intensity of the band-to-band PL. This was demonstrated in EFG and cast poly-Si wafers. In the regions with low lifetime, the room-temperature PL spectrum revealed an additional "defect" band, with the maximum at about 0.8 eV. PL mapping of the band-to-band and 0.8-eV PL intensity revealed a reverse correlation of both bands. This result suggested to us that the 0.8-eV PL band is a luminescence benchmark of a recombination center created during wafer growth and subsequent solar-cell processing. It is important to note that the 0.8-eV band is clearly observed in EFG and cast solar cells, indicating bad regions with enhanced recombination activity. To gain deeper insight into the origin of the "defect" PL, we performed a comprehensive study using a set of scanning techniques, such as SPV, μ-PCD, PL, and dislocation density mapping. Together with low-temperature PL spectroscopy, this allowed us to identify the "defect" PL as a dislocation D1 line modified by interaction with contamination centers.

Status/Accomplishments: In figure 1a we present two typical PL spectra measured in EFG wafer after solar cell processing including P-diffusion, anti-reflected coating, and Al backside firing. The spots for PL measuring are attributed to regions with minority carrier diffusion length L=250μm (curve 1) and L= 50μm (curve 2). Besides of band-to-band PL with the maximum at 1.09eV, the intense "defect" band at 0.78eV is observed in the low lifetime PL spectrum.



The following is a list of major features characterizing the “defect” PL band.

1. A distribution across the wafer of the “defect” band intensity correlates to a map of dislocation density. It is observed in areas with high dislocation density of 1-8 $\times 10^6$ cm^{-2}.
2. The PL maximum can vary from 0.76 to 0.80eV along the grain boundary, however its position does not shift by scanning the excitation laser spot perpendicular to a grain boundary. This may imply that additional PL bands contribute to the “defect” PL.
3. By measuring PL intensity in EFG and cast wafers using polarized light, we have found a substantial linear polarization of the defect PL band. The value of polarization degree is changed across a wafer approaching in some spots 70%. Polarization maximum is perpendicular and the minimum is parallel to grain boundaries. This strong polarization is attributed to thermo-elastic stress fields in poly-Si.
4. At low temperatures, between 4.2 and 77K, we have found additional spectral features in regions with low lifetime (Fig. 1b). The entire spectrum was numerically decomposed at four individual Gaussian peaks, assigned as D1’ to D4’. Corresponding maxima are very close to well-known D1 – D4 dislocation lines observed previously in plastically deformed Cz-Si wafers. Important that D1’ band is traceable to the “defect” PL at room temperature.
5. By comparing recombination properties of the D1-band in Cz-Si with D1’-band in poly-Si wafers, we have found that in Cz-Si it is much narrower (by a factor of three) and quenched at room temperature contrary to the D1’ band observable at room-T. We assigned this difference to interaction between dislocations and precipitates of point defects due to a process of dislocation gettering.

At this stage we have a strong support of the idea that contaminated dislocations are major recombination defects contributing to “bad” regions of solar cells.

Planned FY 2000 Milestones: In a follow-up study, we intend to determine at what stage of solar cell processing “defect” centers are created and how they are modified from a bare wafer to solar cell. Room-temperature PL mapping of the band-to-band and “defect” PL is offering a unique spectroscopic tool to <u>quantitatively</u> monitoring the electrically active dislocation centers in EFG, cast and ribbon polycrystalline Si.

Major Reports Published in FY 1999:

[1] NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999), pp.63-66.

Major Articles Published in FY 1999:

Koshka, Y., Ostapenko, S., Tarasov, I., McHugo, S., and Kalejs, J.P. “Scanning Room-Temperatures Photoluminescence in Polycrystalline Silicon,” Appl. Phys. Lett. (1999), v. **74**, 1555-57.

Tarasov, I., Ostapenko, S., Feifer, V., McHugo, S., Koveshnikov, S.V., , Weber, J., Haessler, J., and Reisner, E.-U. “Defect Diagnostics Using Scanning Photoluminescence in mc-Si,” Physica B, (1999) in press.

Tarasov, I., Ostapenko, S., Haessler, J., and Reisner, E.-U. “Spatially Resolved Diagnostics in Multicrystalline Si for Solar Cells Using Room Temperature Photoluminescence Spectroscopy ,” (ECS Meeting, Honolulu, October 1999), Proceedings v. 99-16, pp. 433-440.

Ostapenko, S., “Defect Engineering in Polycrystalline Silicon Using Ultrasound,” in Polycrystalline Semiconductors V, ed. J.H. Werner, H. P. Strunk, and H. W. Schock (1999), pp. 485-495.

Ostapenko, S., “Defect Passivation Using Ultrasound Treatment: Fundamentals and Application,” Applied Physics A, v. 68, 1999, pp.1-8.

PV Electronic Materials and Devices

Amorphous Silicon

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/98–9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King   Jeffrey Mazer
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E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">National Renewable Energy Laboratory
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<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
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None</td></tr>
<tr><td>DOE Funding Allocation:
1997: $1,072,600   1999: $1,189,400
1998: $1,145,300</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The NREL Amorphous Silicon Team pursues breakthrough advances in materials and devices in order to improve the stabilized efficiency of amorphous-silicon-based PV cells and meet DOE PV cost goals. We also aim to collaborate closely with the PV industry and academic researchers through participation and direction of the National Amorphous Silicon Teams.

Approach/Background: During FY1999, we focussed on several research areas with the potential to dramatically increase the efficiency or reduce the cost of a-Si:H PV. These were improvement in the stabilized efficiency of our high-deposition rate PV devices with hot-wire chemical vapor deposition (HWCVD) i-layers deposited at 10-20Å/s, incorporation of high-deposition-rate HW into tandem devices, and completion of experiments testing key predictions of our new metastability model. To improve the rate of our research progress, we constructed a third HWCVD deposition system and developed combinatoric research techniques.

Status/Accomplishments:
We completed construction of our new a-Si:H deposition system: the "L" System. This system has a plasma-enhanced (PE) CVD chamber, a hot-wire CVD chamber, and a load lock. The load lock increases throughput by keeping the main chambers clean and under vacuum. We deposited our first a-Si:H films by PECVD in the new System in February, 1999 and our first a-Si:H films by HWCVD in March, 1999. The system has performed extremely well to-date. The first five HWCVD films we grew also had excellent photosensitivity and low dark conductivity, with a photo-to dark-conductivity ratio of about 10^6 and a dark conductivity below 10^-11 S/cm. These films were grown between 10 and 17 Å/s.

Using a new combinatoric HWCVD technique, we deposited up to 12 different samples on a single substrate without breaking system vacuum. This saves significant amounts of time normally spent on cleaning, loading, heating and cooling samples and also avoids lengthy chamber evacuations. A series of samples that normally requires a week of deposition can now be deposited in less than a day. For example, thin-film materials that gradually transition from amorphous to microcrystalline silicon have been successfully deposited on a single substrate. This sample series is designed to help us discover and characterize new Si materials with medium range ordering. We have also demonstrated a combinatorial approach to fabricating solar cells that permits rapid optimization of p-type, intrinsic, and n-type layers within the device structure. It is possible to study the single layers as well as the combinations of each layer on a single substrate.

Through a collaboration with our partners from the National Amorphous Silicon Teams, United Solar Corp. (USSC) and Colorado School of Mines we find that infra-red (IR) absorption provides a rapid, simple technique for identifying a-Si:H with enhanced medium-range ordering. USSC uses a-Si:H deposited on the "edge" of crystallinity because enhanced ordering improves the stabilility of their PV modules. This innovation has led to USSC's recent record a-Si:H solar cell efficiencies. Their "edge" material is deposited by plasma-enhanced chemical vapor deposition (PECVD) by increasing the H-dilution of the source gases to near the threshhold of microcrystalline Si growth. Until now, only time-consuming x-ray linewidth and H evolution temperature measurements have been available to characterize the improved material ordering. We have found that the peak frequency of the IR absorption due to Si-H wagging modes downshifts as a function of increasing H dilution, and that the frequency can be correlated with x-ray-linewidth characterization of the ordering. The measurement requires less than 10 minutes.

Contract #: DE-AC36-99G010337

We have designed, fabricated and tested an a-Si:H tandem SS/nipnip/ITO solar cell on a flat stainless steel (SS) substrate using the HWCVD technique in a single chamber system. The intrinsic (i) layers are a-Si:H grown at about 8 Å/s but differ in thickness. All dopant layers (n,p) are deposited from a mixture of silane, dopant and hydrogen gases; the H-dilution promotes growth of microcrystalline and near-microcrystalline dopant layers. Between each of the 6 Si layers, we perform a hydrogen gas flush of the chamber. Indium-tin oxide (ITO) is used as the top contact and the area of each cell is 0.05 cm^2. The solar cell has an efficiency of 3.7%, with an open-circuit voltage of 1.56 V, a fill factor of 0.67, and a short-circuit current of 3.6 mA/cm2. The high voltage and and fill-factor indicate that we made a working all-HWCVD pn tunnel juction between the two cells; this is the key to multi-junction solar cells. We believe that the poor current is due to photocurrent mismatch between our unmatched top and bottom cells. Current matching can be achieved by tuning the intrinsic layer thicknesses or optical band gaps.

We obtained experimental confirmation of an important prediction of the "H collision" model of light-induced metastability in hydrogenated amorphous silicon (a-Si:H) . We showed previously that the model we proposed for defect production can account for a great many experimental facts about the Staebler-Wronski effect. In the experiment, we degraded hydrogenated amorphous silicon (a-Si:H) using light pulses of 40 microsec to 2 millisec. Metastable photoconductivity degradations from pulsed light were compared to degradation with continuous light of the same intensity and same accumulated exposure time. Pulses were obtained by mechanically or electrically chopping a red laser beam of 150 mW/cm2 intensity. Careful measurement of film temperature shows that it rises less then 2°C. Remarkably, for a given integrated exposure time, we observe higher photoconductivities (by up to 50%), as we shorten the pulses. For example, to obtain the same amount of degradation with 100 microsec pulses as with continuous illumination, the integrated sample exposure time to the pulses must be doubled.

Our experiments show that light induced degradation of a-Si:H involves a second timescale of about 1 ms, never before measured. Our result cannot be explained with a simple carrier-driven, degradation mechanism (as dominated previous metastability theories) because electron and hole populations rise and fall to steady-state values in less than 2 ms. In the hydrogen collision model, the newly observed timescale would be the time to reach a steady-state population of mobile hydrogen, precursors to defect creation. During illumination with pulses shorter than the mobile hydrogen rise time, the average mobile hydrogen population is lower than during continuous illumination, so defect creation is suppressed. In short, our theory predicted the existence of an unsuspected timescale associated with the mobile H and we did the experiment to detect and measure this timescale. Of course, alternative models of metastability could still be formulated - but they must be consistent with our new experiment and timescale.

Planned FY 2000 Milestones:

- Increase a-Si:H deposition rate to 0.5 mm/min while maintaining state-of-the-art stabilized defect density (<4 x 1016 cm-3)
- In partnership with USSC, improve hot-wire device efficiencies to >10% initial and >8% stabilized for i-layers grown at >17Å/s.
- Complete experiments using time resolved light-soaking to determine key parameters of the hydrogen collision mechanism of the Staebler-Wronski metastability
- Complete development of processes for making n-i-p PV cells, including the hot-wire p-layers and TCO layers in-house

Major Reports Published in FY 1999:

NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Refereed Journal Articles Published in FY 1999:

H.M. Branz, "The hydrogen collision model: Quantitative description of metastability in amorphous silicon," Phys. Rev. B , 59, 5498-512 (1999)

H.M. Branz, S. Asher, H. Gleskova, and S. Wagner, "Light-induced deuterium diffusion measurements and metastability in hydrogenated amorphous silicon," Phys. Rev. B, 59, 5513-20 (1999)

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W. Gao, S.H. Lee, J. Bullock, Y. Xu, D.K. Benson, S. Morrison and H.M. Branz, "First a-SiC:H photovoltaic-powered monolithic tandem electrochromic smart window device," Solar Energy and Solar Energy Materials,59, 243-54 (1999)

Guozhen Yue, J. D. Lorentzen, Jing Lin, Daxing Han and Qi Wang "Photoluminescence and Raman studies in thin-film materials: Transition from amorphous to microcrystalline silicon," Appl. Phys. Lett., 75, 492-4 (1999)

J. Thiesen, E. Iwaniczko, K.M. Jones, A. Mahan and R. Crandall, "Growth of epitaxial silicon at low temperatures using hot-wire chemical vapor deposition," Appl. Phys. Lett., 75, 992-4 (1999)

H. M. Branz, "Hydrogen diffusion and mobile hydrogen in amorphous silicon," Phys. Rev. B-Brief Reports, 60, pp. 7725-7 (1999)

R. O. Pohl, X. Liu and R.S. Crandall, "Lattice vibrations of disordered solids," Current Opinion in Solid-State Materials Science, 4, 281-7 (1999)

PV Electronic Materials and Devices

Cadmium Telluride Research

Contract #: DE-AC36-98-G010337	**Contract Period:** 10/1/98–9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King — Phone: 202-586-1693 — Fax: 202-586-8148
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<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Timothy Gessert
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<tr><td rowspan="2">Technical Monitor:
John Benner
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1997: $1,072,600
1998: $1,156,900
1999: $1,090,400</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:
Pursue a balanced research program that directly and indirectly supports our industrial partners and the CdTe PV device community. The Task directly supported industry by providing responsive characterization support and innovative solutions to difficult characterization problems, improving the fundamental understanding of material and device issues critical to industry, transferring technology and intellectual properties developed at NREL to industry, and through participation in the National CdTe Thin-Film Partnership Teams. The Task provided indirect industrial support by demonstrating leadership in the technology, developing fundamental understanding of both material and device issues, and by expansion of intellectual property base related to novel processes, device structures, and materials.

Approach/Background & Status/Accomplishments: Research tasks are divided into four study areas related to the device structure including: Transparent Conducting Oxide (TCO) and Window/Buffer-Layer Studies; Interface Studies; and Back-Contact Studies.

Within the TCO/Buffer-layer study area, we have continued to develop sputter-deposited Cadmium Stannate (CTO) and Zinc Stannate (ZTO) materials for use as conducting and barrier layers, respectively. These layers have been used to produce several record devices including a device where both CTO and ZTO were used with chemical-bath deposited (CBD) CdS to produce a CdS/CdTe demonstrating an NREL-confirmed 15.8% efficiency, thereby matching the world-record efficiency for a CdS/CdTe device. Another device was produced where, in addition to the use of CTO and ZTO layers, the CBD CdS was replaced with sputter-deposited CdS. This all-dry cell fabrication process produced a device with 14.0%**.** In another aspect of this study area, we have expanded an existing capability to produce state-of-the-art single and bi-layer SnO_2 films to include a study of Cd-doped SnO_2, CdO, Sn-doped CdO and CTO films. Significant results of this work include the production of CdO films with electron mobilities exceeding 200 cm^2/V-sec, and use of a NREL-developed dimethylcadmium-adduct precursor for higher temperature growth of CdO (required for simultaneous reaction of dimentylcadmium with tetramethyltin to form CTO).

Within the interface development study area, we have begun a new study that builds on previous results identifying that phase separation of CdS and CdTe occurs when S content exceeds ~10 at.%. This study has involved a close collaboration with an external chemical manufacturer (Cerac Inc., Milwaukee, WI) who has utilized their expertise in non-equilibrium processes to produce single-phase CdSTe-alloy powders. The focus next year is to use these powders at NREL in the fabrication of layers by close-space sublimation and/or sputter processing. In another part of this study area, efforts have continued to develop an "all-dry" vapor Cl process (to replace wet $CdCl_2$ process) and improve our understanding of how Cl influence material and device properties. Understanding the use of vapor $CdCl_2$ treatments is viewed as a critical step toward demonstration of an all-dry process for making CdS/CdTe PV devices. Further, the potential combination of all-dry $CdCl_2$ with all-dry back contact processes (see below) is viewed as an advantageous alternative to processes presently used by our industrial partners. A final part of this area is the development of a cross-Center working group that will foster utilization of device modeling software (e.g., SIM Windows, AMPS, etc.) to develop conceptual models of the effect of various device structures and processes on device performance. This effort is now supporting several of the projects within the Task including those related to device stability, window/buffer layers, and CdSTe-alloy interfaces.

Within the area of back contact studies, we have continued investigation of the NREL-developed, all-dry ZnTe-based contact with a focus to compare its stability with other typically used contacts. The study is a collaborative effort with First Solar LLC who maintain an ongoing interest in assessing the stability of novel contacts and contacting-related processes that may have advantages for in-line manufacturing. Initial reports from First Solar LLC indicate that the ZnTe contact is more stable than some typically used contacts, thereby deserving further study and development. Related contact studies have also produced devices demonstrating confirmed, world-record fill factors of 76.6%. In another part of this study area, we have developed a novel paste contact to replace the previously used contact paste that suffered from fabrication and reproducibility problems. The new paste consists of pre-weighed mixtures of readily available $Cu_{1.4}Te$ and HgTe powders, rather than custom-made powders of Cu-doped HgTe. We have also applied this "mixed-powder" approach to several non-Cu containing back contacts including mixtures of Sb_2Te_3 and HgTe. Using these Cu-free back contacts we were able to achieve device performance >13% for the first time at NREL without the use of Cu. A final part of this area included developing CdTe contacts using spray deposition of colloidal inks. This project was also performed in collaboration with First Solar LLC because it represents a contact option that may be consistent with atmospheric-pressure processes.

Planned FY2000 Milestones

- Transfer one Advanced Process to an industrial partner for further testing in their process (Key Milestone).
- Provide an industrial partner with expanded set of production devices incorporating NREL ZnTe-contacts for stability testing.
- Initiate studies related to doping of the CdTe, CdSTe, and/or CdS to increases V_{oc} above present maximum of ~860 mV.
- Develop, produce, and test novel precursor for potential use in CVD Cd_2SnO_4 development studies.
- Perform screening examination of NREL $CdCl_2$ processes using materials supplied by an industrial partner

Major Articles Published in FY99

Papers:

- D.M. Waters, D. Niles, T. Gessert, D. Albin, D. Rose, and P. Sheldon. Surface Analysis of CdTe After Various Pre-Contact Treatments, Proc. Of the 2nd World Conference on Photovoltaic Solar Energy Conversion, July 6-10, 1998, To Be Published in Proceedings, Vienna, Austria (European Commission, Luxembourg, 1988) p. 1031.
- D.H. Levi, L.M. Woods, D.S. Albin, T.A. Gessert, R.C. Reedy, and R.K. Ahrenkiel. The Influence of Grain Boundary Diffusion on the Electro-Optical Properties of CdTe/CdS Solar Cells, Proc. Of the 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, Austria (European Commission, Luxembourg, 1988) p. 1047.
- X. Wu, P. Sheldon, Y. Mahathongdy, R. Ribelin, A. Mason, H.R. Moutinho, and T.J. Coutts, "CdS/CdTe Thin Film Solar Cell with a Zinc Stannate Buffer Layer," AIP Conference Proceedings 462 (1999) p 37.
- X. Li, R. Ribelin, Y. Mahathongdy, D. Albin, R. Dhere, D. Rose, S. Asher, H. Moutinho, and P. Sheldon, "The Effect of High-Resistance SnO_2 on CdS/CdTe Device Performance," AIP Conference Proceedings 462, p 230.
- Y. Mahathongdy, D.S. Albin, C.A. Wolden, R.M. Balwin, "Vapor $CdCl_2$ – Optimization and Screening Experiments for an All Dry Chloride Treatment of CdS/CdTe Solar Cells,," AIP Conference Proceedings 462 (1999) p. 236.
- R. Dhere, H.R. Moutinho, S. Asher, D. Young, X. Li, R. Ribelin, and T.A. Gessert, "Characterization of SnO_2 Films Prepared Using Tin Tetrachloride and Tetramethyl Tin," AIP Conference Proceedings 462 (1999) p. 242.
- C. Narayanswamy, T.A. Gessert, S.E. Asher, "Analysis of Cu Diffusion in ZnTe Based Contact for Thin-Film CdS/CdTe Solar Cells," AIP Conference Proceedings 462 (1999) p. 248.
- D.H. Levi, L.M. Woods,* D.S. Albin and T.A. Gessert, and Dave Albin, "Back Contact Effects on the Electro-Optical Properties of CdTe/CdS Solar Cells,". AIP Conference Proceedings 462, p. 461.
- X. Li, D. W. Niles, F. S. Hasoon, R. J. Matson, and P. Sheldon, "The Effect of Nitric-Phosphoric Acid Etches on Material Properties and Back Contact Formation of CdTe-Based Solar Cells," J. Vac. Sci. Technol. A 17(3) p. 805 (1999).
- H. Moutinho, R. Dhere, M. Al Jassim, D. Levi, L. Kazmerski, "Investigation of Induced Recrystallization and Stress in Close-Space Sublimated and Radio-Frequency Sputtered CdTe Thin Films," J. Vac. Sci. Technol. A 17(4) p.1793 (1999).
- D.H. Rose, F.S. Hasoon, R.G. Dhere, D.S. Albin, R.M. Ribelin, X.S. Li, Y. Mahathongdy, T.A. Gessert, and P.Sheldon "Fabrication Procedures and Process Sensitivities for CdS/CdTe Solar Cells," Progress In Photovoltaics: Research and Applications, Vol. 7, No. 5, p. 331 (1999).
- X. Li, S. Asher, R. Ribelin, P. Sheldon, T. A. Gessert, "Properties of Fluorine-Doped Tin-Oxide Films," 46th AVS Mtg. (1999).
- H.R. Moutinho, R.G. Dhere, M.M. Al-Jassim, C. Ballif, L.L. Kazmerski, "An Alternative Procedure for the Deposition of Close-Space Sublimation CdTe/CdS Solar Cells," 46th AVS Meeting (1999).
- R.G. Dhere, M.M. Al-Jassim, K.M. Jones, H.R. Moutinho, T.A. Gessert, L.L. Kazmerski, "CdS/CdTe Interface Analysis by Transmission Electron Microscopy," 46th AVS Meeting (1999).

Patents:

- X. Wu, P. Sheldon, T.J. Coutts, "PV Devices Comprising Cadmium Stannate Transparent Conduction Films and Method for Making," NREL IR#95-35 (Allowed, July 13, 1999).
- X. Wu and P. Sheldon, "Novel process for Fabrication CdS/CdTe Thin-Film Solar Cells, and Cells Produced Thereby," NREL IR#98-39 (Filed).
- X. Wu, "A Novel Method for Preparation of Modified Cd_2SnO_4 Films with Plasma Edge of 0.85 μm" IR#00-04 (Disclosed).

Academic Publications:

- D M. Waters, "CdTe/CdS Solar Cells: Surface Analysis of CdTe Prior to Contact Application," M.S. Thesis, University of California, Santa Cruz, December 1998.
- Y. Mahathongdy, "Statistical Optimization & Analysis of Vapor CdCl2 Processing for CdS/CdTe Solar Cells," M.S. Thesis, Colorado School of Mines, July 1999.
- C. Narayansmamy, "SIMS Analysis of Cu in ZnTe-Based Back Contacts for CdTe/CdS Solar Cells," M.S. Thesis, University of Toledo, Oct. 1999.

PV Electronic Materials and Devices

Crystalline Silicon Materials Research

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
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	Organization Type: FF	Congressional District: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Ted Ciszek **Phone:** 303-384-6569 **Fax:** 303-384-6531 **E:mail**: ted_ciszek@nrel.gov	
Technical Monitor: John Benner **Phone:** 970-663-6496 **Fax:** 970-663-6430 **E:mail**: john_benner@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: $593,900 1998: $790,200 1999: $820,000	**Cost Share Funding:**

Project Objective: The goal of the Crystalline-Silicon (c-Si) Materials Research R&D Project is to accelerate the development of c-Si PV and to enhance the United States position in c-Si technology. This goal is approached through the following objectives:

- Develop innovative methods for the growth of next-generation c-Si to improve throughput, reduce energy use, and reduce cost.
- Improve the fundamental understanding of impurities and defects in crystalline silicon and their effects on PV performance.
- Provide technical assistance to industry in selected material, crystal growth, characterization, and modeling problems.

Approach/Background: (1.) *Silicon growth from the vapor phase on low-cost substrates for thin-layer solar cell devices.*
Two approaches were targeted. The first is to directly deposit the entire device structure (N+/P/P+) by (a) the iodine vapor transport technique (on glass or non-metal materials), or (b) atmospheric-pressure CVD with silane (on glass, metal-coated ceramics or glass, or sheet metal), which may have lower reactivity and a lower epitaxial growth temperature. The second approach is to generate a seed layer on a low-cost substrate (fast physical deposition followed by eutectic grain growth) and to achieve rapid (>1 μm/min) epitaxial growth of device-quality, thin Si on that layer by (a) or (b).
(2.) *A quantitative study of the effects of selected transition metal impurities on PV performance.*
The approach is to create a set of controlled samples with selected amounts of transition metals that exhibit weak (e.g. Cu), moderate (e.g. Fe), and strong (e.g. Ti) effects on solar cell performance, through growth by ultra-clean float zoning. This sample set will be valuable in understanding fundamental differences in Shockley-Read-Hall recombination and lifetime degradation caused by these prominent impurities in metallurgical-grade Si, and thus are important to the large Si PV industry. Lifetime characterization, modeling, and diagnostic solar cell analysis will be used to quantify degradation effects. Samples will be shared with interested researchers in NREL, universities, and industry. This work is to be started after we complete repairs and upgrades to the float-zoner.
(3.) *Coordinated research with industry to address silicon materials research needs.*
The approach is to work with selected PV companies on a work-for-others WFO or CRADA basis to solve selected Si materials problems. We completed a multi year funds-in CRADA effort to advance the technology of dendritic web silicon ribbon growth and initiated a synergistic research effort that will both address the silicon feed stock issue and help to supply the reactor we need for thin-layer Si CVD growth from silane [see (1.) above].

Status/Accomplishments:

(1.) *Silicon growth from the vapor phase on low-cost substrates for thin-layer solar cell devices.*

- 30-μm-thick silicon layers were deposited by chemical vapor transport with iodine at about 900°C for 10 minutes on both glass and heavily doped P+ silicon substrates, demonstrating a deposition rate of 3 μm /min. The average grain size was ~10 μm.
- The first thin-layer Si P/N junction devices were demonstrated and used to study the properties of the polycrystalline silicon. A number of techniques were initiated to characterize the material, including carrier lifetime, SIMS, Hall mobility, device parameters, SEM, EBIC, Auger, and spreading resistance measurements.
- A patent was filed on the novel iodine CVT growth method which, unlike previous iodine transport approaches, has the potential for open-system operation. Also, the growth mechanism for the method was determined, and the research was presented at international, national, and NREL-hosted conferences.

- We successfully alloyed metal substrates with physically deposited thin silicon films at their eutectic point without melting the metal substrate. The resulting substrate surface showed islands of silicon crystallites, which we intend to use as seeds for large grain deposition of thin Si device layers by chemical vapor deposition.

(2.) *A quantitative study of the effects of selected transition metal impurities on PV performance.*

- We completed the Fe-Ga pair defect studies, including diagnostic device analysis of the samples.
- Before moving on to the planned studies of Ti and Cu impurities, it is necessary to complete repairs on the Si float-zoner used for the generation of controlled impurity samples. Failed motor drive systems were completely reconfigured because repair parts were obsolete. At the same time, the vacuum system and control system were upgraded. This work is still underway, but is nearing completion.

(3.) *Coordinated research with industry to address silicon materials research needs.*

- We concluded a multi-year funds-in CRADA with EBARA Solar, Inc. under which the success rate of Si ribbon starts was more than doubled, undesirable motion of the shallow silicon melt from which the ribbons are grown was eliminated, wide web starts without extraneous dendrites was demonstrated, a thermally stable melt replenishment technique was introduced, and ribbon deformation and defect characteristics were analyzed. Four invention disclosures resulted from the work.
- We worked with a large manufacturer of polycrystalline Si feedstock to demonstrate the use of our electromagnetic semi continuous casting technology for consolidating particulate silicon into larger pieces. Three ingots were cast.
- We worked with GT Equipment, Inc., on the preliminary phases of a project to demonstrate faster Si feedstock deposition. We also were awarded a two-year DDRD project to investigate alternative methods for low-cost Si feedstock generation, a universal need of the Si PV industry.

Planned FY 2000 Milestones:

- Identify the most suitable substrates for iodine CVT growth of silicon thin layers for solar cells.
- Demonstrate the material quality of thin-layer Si grown by our novel iodine CVT technique through fabrication and characterization of efficient solar cell devices
- Operate a new CVT reactor to obtain layered material deposition with integral substrate transfer.
- Complete the study of Ti, Fe, and Cu transition metal impurity effects on charge-carrier recombination in controlled silicon samples, to determine the basis for the large differences observed in degradation of electronic properties.
- Complete the installation of a CVD reactor for Si feedstock and thin-layer growth research.

Major Articles Published in FY 1999:

- T.F. Ciszek, T.H. Wang, W.A. Doolittle, and A. Rohatgi, “Iron-Gallium Pair Defects in Float-Zoned Silicon,” in: High Purity Silicon V, Eds. C.L. Claeys, P. Rai-Choudhury, M. Watanabe, P. Stallhofer, and H.J. Dawson (The Electrochemical Soc., Proceedings Volume 98-13, New Jersey) pp. 230-240 (1998).
- P. Menna, Y.S. Tsuo, M.M. Al-Jassim, S.E. Asher, R. Matson, and T.F. Ciszek, “Purification of Metallurgical-Grade Silicon by Porous-Silicon Etching,” 2nd *World Conference and Exhibition on Photovoltaic Solar Energy Conversion Proceedings; July 6-10, 1998, Vienna, Austria,* pp. 1232-1236 (1998).
- T.H. Wang and T.F. Ciszek, "Effects of Sample Inhomogeneity and Geometry on Photoconductivity Decay," in: Recombination Lifetime Measurements in Silicon, ASTM STP1340, D.C. Gupta, F.R. Bacher, and W.M. Hughes, Eds., American Society for Testing and Materials, pp. 88-98 (1998).
- T.F. Ciszek and T.H. Wang, “Float-zone Pedestal Growth of Thin Silicon Filaments,” in: High Purity Silicon V, Eds. C.L. Claeys, P. Rai-Choudhury, M. Watanabe, P. Stallhofer, and H.J. Dawson (The Electrochemical Soc., Proceedings Volume 98-13, New Jersey), pp. 85-89 (1998).
- Tsuo, Y.S., Gee, J.M., Menna, P., Strebkov, D.S., Pinov, A., and V. Zadde, *Proc. 2nd World Conf. on PV Solar Energy Conversion*, pp. 1199- (1998).
- T.H. Wang, T.F. Ciszek, M. Landry, A. Matthaus, and G. Mihalik, “A Silicon Ingot Lifetime Tester for Industrial Use,” *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 443-452 (1999).
- Y.S. Tsuo, P. Menna, T.H. Wang, and T.F. Ciszek, “New Opportunities in Crystalline Silicon R&D,” *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 453-458 (1999)

PV Electronic Materials and Devices

New Ideas and User Functions

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/98–9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King Jeffrey Mazer
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David Ginley, Timothy Coutts, Pete Sheldon, and Scott Ward
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<tr><td rowspan="2">Technical Monitor:
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<tr><td>DOE Funding Allocation:
1997: $ 149,100 1999: $ 570,400
1998: $ 327,500</td><td>Cost Share Funding:</td></tr>
</table>

Project Objectives:
This Technology Area rolls together four activities within NREL's Electronic Materials and Devices Project that provide shared laboratory and intellectual resources among the primary materials task areas. These activities include exploratory research in new ideas for photovoltaic materials, processes, process integration, and device fabrication. The task activities are:

- Atmospheric processing utilizing nanoparticle based inks
- Non-conventional and p-type transparent conducting oxides (TCO)
- Thin-film process integration to develop concepts for new tools to facilitate both current and future research
- Provide state-of-the-art device design and fabrication capabilities for PV semi-conductors

Approach/Background: The overall approach is to look for opportunistic areas where some basic research activities could lead to an eventual substantial practical impact on PV technology and deployment. For example, TCOs are used in a variety of thin-film solar cells. As module areas increase, there will be an increasing demand to have TCOs with lower sheet resistances, while maintaining excellent optical properties. In addition, some materials are scarce and expensive. The demands will increase further for second-generation thin-film tandem cells. For these to be monolithically stacked, they would need to be connected via a low-resistance tunnel junction. This would, of course, necessitate the development of high-carrier concentration p^+ material to enable a junction to be formed.

We maintain the cleanroom facility and make its capabilities available to all of the research groups in the laboratory. We provide a reservoir of device processing expertise that can be applied to engineering a specific device for experimental applications. Additionally, we are engaged in the design and fabrication of novel devices that have potential to be useful in the long-term commercialization of PV technologies. These include the development of polycrystalline thin-film devices for use under moderate concentration, monolithically integrated III-V modules for high-flux operation and thin-film silicon device structures, among others.

Status/Accomplishments: Atmospheric processing: We have demonstrated that nanoparticle precursors can be employed to produce high quality materials. Principal areas of focus have been CdTe, CIS and metallic particles for contacts. In all cases, understanding the nature of the particle surface and subsequent interfacial reactions is critical to producing the desired end materials. We have developed approaches to derivatize the surface to as to prevent corrosion, lead to the appropriate reaction and produce stable inks. An area of focus in FY99 has been the development of nanoparticle based contact metallurgies based on Cu, Ag and Al for Si photovoltaics. In all cases we have been able to obtain high quality metal layers and after anneal, ohmic contact. We have also demonstrated the facility of Te based nanoparticle contacts to CdTe. We are continuing to develop new ink formulations with the goal of tailoring the metallurgy to the material (thermodynamically stable contacts) and of developing suitable inks for inkjet deposition, thereby eliminating patterning.

Contract #: DE-AC36-99G010337

Transparent conductors: Produced very high mobility cadmium oxide, made the first estimate of the electron effective mass in zinc stannate; commissioned and used the equipment for the *method of four coefficients;* initiated a study of alternative (higher cracking-temperature) pre-cursors for cadmium; made Mössbauer measurements on both cadmium and zinc stannates; performed modeling calculations that indicate specific charge carrier scattering mechanisms for zinc oxide; and, focused on the Cu-Al-O system for p-type TCO successfully developing a versatile synthesis approach for bulk materials and thin films using ex-situ oxygen anneals achieving doping levels to 10^{18}.

Process Integration: Completed a case study to help identify what research problems a Process Integration User Facility would help answer if applied to today's thin-film technologies; developed a framework for a flexible process tool to address process integration issues associated with today's thin-film photovoltaic semiconductors; and, developed a conceptual design that would allow integration of multiple thin-film deposition technologies and in-situ characterization tools into a single process stream in a flexible manner

Clean Room Facility: maintained operational equipment available to all the research teams in the laboratory; fabricated record breaking 32.3% efficient GaInP/GaAs/Ge concentrator cells using structures grown at Spectrolab; fabricated 50X CuIn(Ga)Se_2 cells from structures grown on stainless steel substrates at NREL; process multi-terminal devices used for characterizing the individual components of multi-junction devices; and, developed a new interconnect scheme for thin-film modules.

Planned FY 2000 Milestones:

- Demonstration of high quality large area Al contacts to Si and metal line production by direct ink jet writing
- Develop inks for industrial technology partners
- Show increased doping levels in CuAlO2 by oxygen annealing and substitutional doping
- Investigate the ternary phase field defined by the three binary oxides of tin, cadmium and zinc, seeking a quaternary compound or alloy with superior properties.
- Investigate both novel TCOs or alternate p-type materials materials, that may have intrinsically superior electro-optical properties
- Improved processes for making the *conventional* materials (i.e. by attacking extrinsic issues).
- Continuation of Process Integration research pending High-Performance PV Initiative Proposal Funding
- Fabricate and demonstrate a 25% efficient 1000X 1 cm^2 mini-module from GaInP/GaAs tandem structures grown by the High Efficiency Team.
- Fabricate 50 X thin-film CI(G)S devices that break the 20% efficiency barrier.

Major Reports/Articles Published in FY 1999:

Schulz, D. L.; Ribelin, R.; Curtis, C. J.; King, D. E.; Ginley, D. S.. **Nanoparticle-based contacts to CdTe.** Mater. Res. Soc. Symp. Proc. (1999), 536(Microcrystalline and Nanocrystalline Semiconductors--1998), 407-411. CODEN: MRSPDH ISSN:0272-9172. CAN 131:76094 AN 1999:364625 CAPLUS

Ginley, D. S.; Curtis, C. J.; Ribelin, R.; Alleman, J. L.; Mason, A.; Jones, K. M.; Matson, R. J.; Khaselev, O.; Schulz, D. L. **Nanoparticle precursors for electronic materials.** Mater. Res. Soc. Symp. Proc. (1999), 536(Microcrystalline and Nanocrystalline Semiconductors--1998), 237-244. CODEN: MRSPDH ISSN:0272-9172. CAN 131:95416 AN 1999:364597 CAPLUS

Ginley, D. S. **Atmospheric processing approaches for PV contacts,** Electrochemical Society Proceedings, (1999), Seattle WA.

R.E. Stauber, J.D. Perkins, P.A. Parilla and D.S. Ginley, **"Thin Film Growth of Transparent p-Type CuAlO2,"** Electrochemical and Solid-State Letters, vol. 2, iss. 12, pgs. 654-656 (1999).

John Thornton Memorial Award Lecture, "The Search for Novel Transparent Conducting Oxides: Cd_2SnO_4, Zn_2SnO_4 and CdO." Timothy J. Coutts, David L. Young, Xiaonan Li and W.P. Mulligan, 1999 AVS

"Process Integration Issues in Thin-Film Photovoltaics and Their Impact on Future Research Directions" Accepted for publication in Progress in Photovoltaics, January, 2000 Millennium Issue

"Thermophotovoltaic and Photovoltaic Conversion at High-Flux Densities," T. J. Coutts and J.S. Ward, IEEE Transactions on Electron Devices, Special PV edition, 10/99.

PV Electronic Materials and Devices

Polycrystalline Thin Film Solar Cells Based on $Cu(In,Ga)Se_2$

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
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Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Rommel Noufi **Phone:** 303-384-6510 **Fax:** 303-384-6430 **E:mail**: rommel_noufi@nrel.gov	
Technical Monitor: John Benner **Phone**: 303-384-6496 **Fax**: 303-384-6430 **E:mail**: john_benner@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1997: $1,365,700 1998: $1,418,500 1999: $1,356,900	**Cost Share Funding:**

Project Objective:

- Advance the development of CIS-based PV toward commercialization.
- Enhance the CIS R&D laboratory capabilities and technical skills to achieve a facility that supports the development of thin films from the fundamental stage to pre-communications.

Approach/Background:.

Activity 1: Processes Development

The primary objective here is to explore routes to commercialization of the CIS PV technology. The focus is on potentially low-cost and manufacturable processes. We examined the underlying materials science, the processing steps from substrate handling to finished product and device performance. We have adopted a vision for a processing scenario where the sequence is: Source material delivery to the substrate, compound formation and recrystallization followed by an in-situ surface termination step that also defines the junction; and the device or module is then completed with the deposition of the TCO.

Activity 2: Alternative Junction Formation

In the past year, we have shown with good confidence, the role of the CBD CdS and, based on this, we have fabricated devices based on CIS that do not use a buffer layer (CdS or any other) and that are state of the art in performance. We had set our objective to 15% efficiency for devices based on CIGS. We have shown 13.5% efficiency toward this objective. The 15% goal seems to be more challenging than we have anticipated. This year, we continue our activity toward the objective to develop a processing blueprint for fabricating a direct ZnO/CIGS junction that is aimed at simplifying the CIGS solar cells manufacturing process.

Activity 3: Alternative Substrate

We explore the growth of CIGS on stainless steel substrate and polymers and develop state-of-the-art devices. We examine the optimum sputtering conditions for in-house Mo films.

Activity 4: FundamentalUnderstanding of Absorber Material Growth/Properties

This year, we spent some effort to examine relationships between crystallographic texturing of CIGS and device performance. We explore growth steps that allow tailoring of the structural properties of CIGS

Activity 5: Baseline activities

This task is aimed at maintaining current state-of-the-art baseline materials, deposition, and on-going improvements.

Activity 6: Partnership with Industry/Technology Transfer

This activity describes briefly our ongoing commitment to lead/participate in the CIS National R&D team and execute CRADA and WFO.

Contract #: DE-AC36-99G010337

Status/Accomplishments:

Activity 1: We have made progress in two potentially low-cost/low temperature processes. In the electrodeposition process, we have demonstrated 15.4% efficient devices and reduced the length of the second stage step in the process. We have also demonstrated a 13.5% efficient device using hybrid sputtering/evaporation deposition at ambient temperatures followed by annealing in Se at high temperatures. Finally, we also explored an electro-less deposition scheme that resulted in excess of 13% efficiency.

Activity 2: Further understanding of the role of CdS in the CIGS/CdS devices was developed, especially the effect of the solution used with Cd and Zn salt in defining a shallow junction in the CIGS absorber. Devices made without CdS buffer (direct ZnO) using CIGS absorbers treated in ammonia solution containing Cd or Zn salts followed by ZnO deposition as well as devices made by direct sputtering of ZnO under mild conditions, have shown efficiencies in the range of 13-15%. The latter was a milestone for FY99.

Activity 3: We have translated the knowledge gained from our work on soda lime glass and the role of Na to growing CIGS on stainless steel substrates and demonstrating a 17.4% efficient device. We have also developed an extensive matrix of Mo deposition parameters vs. Mo film properties and effects on CIGS growth

Activity 4: We have examined modification to the CIGS growth method that allows tailoring of preferred orientation of the CIGS film, mainly the (112) and (204) textures. We find that texture is highly dependent on growth temperature, substrate material and its structural properties. **A world record efficiency of 18.8% was obtained on films showing the (204) orientation**.

Activity 5: In this area, we developed improvements in the CdS deposition that allows more transmission of light through the CdS film. We also developed an alternative set of ZnO deposition conditions that offer mild sputtering.

Activity 6: The account of our interaction with industry is described in the minutes of the National CIS $&D Team meetings of the Thin Film PV Partnership program.

Planned FY 2000 Milestones:
- Increase efficiency of buffer-less ZnO/CIGS to 16.5%
- Complete development of improved Mo films from in-house system
- Assess the potential of high Eg (>1.2eV) CIGS to make state-of-the-art devices
- Boost efficiency of CIGS devices on stainless steel to 18%.

Major Articles Published in FY 1999: (Examples below)

M. Contreras, B. Egaas, K. Ramanathan, J. Hiltner, A. Swartzlander, F. Hasoon, and R. Noufi, "Progress Toward 20% Efficiency in Cu(In,Ga)Se_2 Polycrystalline Thin-Film Solar Cells," Progress in Photovoltaics, **7**, 311 (1999)

K. Ramanthan, H. Wiesner, M. Contreras, S. Asher, J. Webb, R.Matson, and R. Noufi, "The Science and Technology of Junction Formation in $CuInSe_2$ based Thin Film PV Devices," Proc. Records of the 12th Sunshine Workshop, Tokyo, Japan, Jan. 1999

M. Contreras, B. Egaas, D. King, A, Swartzlander and T. Dullweber, "Texture Manipulation of Cu(In,Ga)Se_2 Thin-Films," Proceedings of the E-MRS, June 1999, Strasbourg, France.

R. N. Bhattacharya, W. Batchelor, J.F. Hiltner, and J.R. Sites, "Thin-Film Cu(In,Ga)SE_2 PV Cells from Solution-Based Precursor Layers," APL, **75**, 1431 (1999)

R. N. Bhattacharya, W. Batchelor and R. Noufi, "Electroless Deposition of Cu-In-Ga-Se," Electrochem and Solid State Letters, **2**, 222 (1999.

PV Electronic Materials and Devices

III-V High Efficiency and Concentrators

Contract #: DE-AC36-99G010337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Sarah Kurtz **Phone:** 303-384-6496 **Fax:** 303-384-6531 **E:mail**: sarah_kurtz@nrel.gov	
Technical Monitor: John Benner **Phone:** 970-663-6496 **Fax:** 970-663-6430 **E:mail**: john_benner@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1997: 918,200 1999: 962,900 1998: 942,300	**Cost Share Funding:**

Project Objective:
Project Objective: To establish III-Vs as a competitive terrestrial PV technology by developing III-V photovoltaic technologies, advancing related science and engineering, coordinating the allied efforts with our partners, and facilitating commercialization. This year's specific objective was a 32% monolithic solar cell.

Approach/Background: The successful deployment of PV concentrator systems would begin to address the DOE goal of generating a significant portion of our electricity from renewable sources. The tandem GaInP/GaAs cell grown on germanium has been successful in capturing market share for space applications. The current production capacity of these cells, if used for 1000X terrestrial concentrator systems, would be 1 GW/year. Furthermore, such cells are estimated to contribute only 21 cents/peak watt to the cost of a concentrator system. Thus, the GaInP/GaAs cells are well on their way to help make PV energy significant.

The current focus of this project is to achieve a higher efficiency concentrator cell. A four-junction concentrator cell based on the GaInP/GaAs technology (patent granted) has a theoretical efficiency of ~52%. Practically, such a cell could surpass 40% if appropriate materials could be identified. Toward this goal, we began this year with the investigation of candidate 1-eV materials, but when results indicated that these materials would not be useful in reaching the 32% milestone on time, we diverted our effort to include lower risk approaches, including a GaInP/GaAs/Ge cell. Many aspects of the growth of this three-junction device are poorly understood and were studied this year, e.g., nucleation of the III-V layers on germanium, cross diffusion of the III-V materials with germanium, and control of the germanium junction that is formed indirectly by the growth.

Status/Accomplishments: At the beginning of this year, we had determined that the material quality of GaInAsN is inferior and that optimization of the growth conditions does not result in material with diffusion lengths comparable to the thickness needed to absorb adequate light. However, the use of a p-i-n structure was demonstrated to increase the collection of photocarriers. We reduced the typical $1 \times 10_{17}/cm_3$ background hole concentration by counter doping with known n-type dopants. This reduced the carrier concentration and improved the photocurrent, but was difficult to control, and we were unable to achieve adequate photocurrents. One explanation for the high background hole concentration is the carbon contamination. The largest source of carbon in the growth of GaInAsN is the dimethylhydrazine (the trimethylgallium and trimethylindium are present in much smaller quantities). We tried hydrazine as a carbon-free nitrogen source, with the hope of reducing the background hole concentration. Unfortunately, although nitrogen incorporated very efficiently from hydrazine, the hole concentration was unchanged and the material quality was still poor.

Although there are other approaches that may improve the GaInAsN, it was clear to us that these would not be forthcoming in time to meet the 32% milestone. Thus, work on GaInAsN was postponed even though this meant missing an internal milestone related to the optimization of GaInAsN. We also explored a GaAs-Ge alloy, but found evidence of phase separation (as observed by transmission electron microscopy), and also of poor optoelectronic quality, including high background carrier concentration.

Studies of germanium surfaces exposed to arsine showed that, although the arsine is effective at cleaning the germanium surface, it also etches the surface, leading to step bunching and a relatively rough surface. Experience shows that growth of GaAs is facilitated by a smooth, rather than a rough, surface. In contrast, phosphine was found to clean the germanium surface without etching it significantly. Optimized nucleation of GaInP directly on germanium resulted in single-junction germanium cells with open-circuit voltages > 200 mV. Growth of GaAs and GaInP on (411) germanium surfaces was observed to produce superior morphology compared with most other germanium surfaces. Although these studies have furthered our understanding of III-V growth on germanium, these results have not yet been fully applied to three-junction GaInP/GaAs/Ge cells.

The 32% milestone was achieved with a three-junction, monolithic, concentrator cell made from GaInP and GaAs grown on a germanium substrate. The cell was grown at Spectrolab on production equipment using a design very similar to that of their space cells. The contacts and anti-reflection coating were added at NREL. Measurement of this type of cell is a research project in and of itself. The 32.3%±2% measurement completed at NREL will be compared with measurements at Sandia National Laboratories and at the Fraunhofer Institute. The 32.3% efficiency was achieved with an open-circuit voltage of 2.83 V, short-circuit current of 64 mA, and fill factor of 87% for a 0.10 cm_2 cell. This result is especially significant because it came from an effort that Spectrolab had initiated to assess the performance of their cells in terrestrial concentrator systems in preparation for making business plans for such a product. The 32% cell has triggered interest from companies manufacturing concentrator systems and from their customers, and captured media attention including an article in the Rocky Mount News, CNN website, and others.

The record-setting cell peaked in efficiency at only about 50 suns while other Spectrolab cells peaked in efficiency at concentrations as high as 150 suns. However, NREL in-house results demonstrated a GaInP/GaAs/Ge three-junction cell that maintained a respectable efficiency at 1000 suns. The tunnel junction under the contacting layer of this cell had a peak tunneling current capable of handling close to 10,000 suns worth of current. Spectrolab has not attempted to optimize their cells for performance at high concentration. These two results taken together, demonstrate the feasibility of a 32% cell operating at concentrations approaching 1000X.

Planned FY 2000 Milestones:
- Develop high-flux devices for operation at 500X and initiate testing at concentration
- Develop Ge cells that survive GaAs/GaInP cell growth while retaining at least 200 mV Voc
- Understand the parameters that impact nucleation of GaAs on Ge and apply to fabrication of state-of-the-art GaInP/GaAs cell
- Evaluate GaInAsN for 1.0 eV device in tandem cell

Major Articles Published in FY 1999:

- McMahon, W., et al., "Atomic-Resolution Study of Steps and Ridges on Arsine-Exposed Vicinal Ge(100)," Phys. Rev. B, 60, 2480-2487 (1999).
- Friedman, D., et al., “Hydrazine N Source for Growth of GaInNAs for Solar Cells,” J. Electrochem. Soc. Proc. 99-11, 185 (1999).
- Friedman, D., et al., “Comparison of Hydrazine, Dimethylhydrazine, and t-butylamine Nitrogen Sources for MOVPE Growth of GaInNAs for Solar Cells, accepted for publication in J. Cryst. Growth.
- Rannels, J., “The Case for a 40% Efficiency Goal for Photovoltaic Cells in 2005,” Proceedings of PVSEC, in press.
- Zhang, Y, et al., “Electronic and Optical Properties of Periodically Stacked Orientational Domains in CuPt-ordered GaInP2” Solid State Comm., 109, 99-103 (1999).
- Norman, A.G., et al., "Ge-related Faceting and Segregation During the Growth of Metastable (GaAs)(1-x)(Ge2)(X) Alloy Layers by Metal-organic vapor-phase epitaxy," Appl. Phys. Lett., 74, 1382-1384 (1999).
- Shan, W., et al., "Band Anticrossing in GaInNAs Alloys," Phys. Rev. Lett., 82, 1221-1224 (1999).
- Perkins, J.D., et al., "Nitrogen-activated transitions, level repulsion, and band gap reduction in GaAs1-xNx with x<0.03, " Phys.Rev.Lett., 82, 3312-3315 (1999).
- McMahon, W., et al., “Atomic-Resolution STM Study of a Structural Phase Transition of Steps on Vicinal As/Ge(100),” Phys. Rev. B, in press (1999).
- Olson, J.M., et al., “Structure of Ge(100) Surfaces for high-efficiency photovoltaic applications,” 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion Proceedings; July 6-10, 1998, Vienna, Austria, pp. 3540-3545 (1998).
- Friedman, D.J., et al., “1-eV GaInNAs solar cells for ultrahigh-efficiency multijunction devices,” 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion Proceedings; July 6-10, 1998, Vienna, Austria, pp. 3-7 (1998).
- Geisz, J., et al., “New Materials for Future Generations of III-V Solar Cells,” NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998; AIP Conference Proceedings, Vol. 462, pp. 372-377 (1999).
- Kurtz, S., et al., “Concentrator and Space Applications of High-Efficiency Solar Cells – Recent Developments,” NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998; AIP Conference Proc., Vol. 462, pp. 378-384 (1999).
- Ward, J., et al., “New Concepts for High-Intensity PV Modules for Use with Dish Concentrator Systems,” NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998; AIP Conference Proc., Vol. 462, pp. 385-392 (1999).
- McMahon, W., et al., “Surface Science in an MOCVD Environment: Arsenic on Vicinal Ge(100),” NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998; AIP Conference Proceedings, Vol. 462, pp. 395-400 (1999).
- Friedman, D., et al., “Exploration of GaInTlP and Related Tl-containing III-V Alloys for Photovoltaics,” NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998; AIP Conference Proc., Vol. 462, pp. 401-405 (1999).
- Abulfotuh, F., et al., “Investigation of Deep Levels in GaInNAs,” NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998; AIP Conference Proceedings, Vol. 462, pp. 492-498 (1999).
- Keyes, B., et al., “Optical Investigation of GaNAs,” NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998; AIP Conference Proceedings, Vol. 462, pp. 511-516 (1999).

Thin Film PV Partnership

Monolithically Interconnected Silicon-Film Module Technology

Contract#: ZAK-8-17619-1	**Contract Period:** 11/25/97–11/24/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	AstroPower, Inc. Solar Park Newark, DE 19716-2000	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** James A. Rand, Paul E. Sims **Phone:** 302-366-0400 **Fax:** 302-368-6474	
Technical Monitor: Ken Zweibel **Phone:** 303-384-6441 **Fax:** 303-384-6430 **E:mail**: ken_zweibel@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** AstroPower, Inc.
	DOE Funding Allocation: 1998: $625,000 1999: $790,000	**Cost Share Funding:** 1998: $384,000 1999: $526,000

Project Objective: AstroPower is employing Silicon-Film™ technology toward the development of an advanced thin-silicon-based, photovoltaic module product. This module combines the design and process features of advanced thin-silicon solar cells, is light trapped, and integrated in a low-cost monolithic interconnected array. This advanced product includes the following features:

- silicon layer grown on a low-cost ceramic substrate.
- a nominally 50 micron thick silicon layer with minority carrier diffusion lengths exceeding 100 microns.
- light trapping due to back- surface reflection and random texturing.
- back surface passivation.

These performance design features, combined with low-cost manufacturing using relatively low-cost capital equipment, continuous processing and a low-cost substrate, will lead to high performance, low-cost photovoltaic panels.

Approach/Background: Thin film polycrystalline silicon grown on a low cost substrate is one of the most sought after paths to low cost photovoltaic power. Cost reductions can be realized in module fabrication through the use of large-area, series-interconnected submodules. This design incorporates a method of partitioning the thin-film photovoltaic layer into sub-elements and reconnecting them as a series array. The sub-element device design consists of a thin (35-50 µm) polycrystalline silicon layer grown on a low-cost substrate. The thin silicon device structure allows the use of imperfect materials and increased doping levels, and lowers cost by minimizing the use of relatively expensive feedstock material. Diffusion lengths equivalent to twice the device thickness are required to assure high carrier collection through the bulk of the base layer.

The solar cell device structure incorporates light trapping and back surface passivation to improve energy conversion efficiency. Light trapping is achieved by using diffuse reflection from a randomly textured back surface resulting in enhanced optical absorption of weakly absorbed light and improved current generation. Electrical passivation of the back surface is achieved by minimizing surface recombination velocity at the barrier/silicon interface. Back surface passivation results in improved voltage, fill factor, and current.

Status/Accomplishments: Accomplishments for FY99 include the following:

Ceramic: A ceramic substrate has been developed that meets the chemical, mechanical, electrical, thermal, and economic criteria required for the growth and device processing of thin films of silicon. The size of this ceramic is presently 15 x 15 cm and the materials cost is on the order of $10 per square meter. The reflectance for a ceramic-air interface is near 100%. There is no evidence of contaminants in silicon films due to the ceramic after high-temperature processing. The ceramic-silicon structure is compatible with standard laboratory wet processes.

Silicon Deposition: Three new deposition systems were constructed during FY99. A small prototype CVD system was constructed based on a tube geometry. This system was capable of depositing silicon on 2 x 4 cm substrates. A larger CVD system was then constructed using a modification of the Silicon-Film™ technology. This system is capable of depositing on 15 x 15 cm substrates. A semi-continuous proprietary deposition system was constructed which is capable of high-speed deposition of silicon on multiple 15 x 15 cm ceramic substrates. AstroPower is also collaborating with the Institute of Energy Conversion at the University of Delaware to evaluate the potential of using hot-wire CVD to deposit silicon on ceramic substrates.

Silicon Solar Cell Fabrication: Standard laboratory procedures have been employed to evaluate silicon-on-ceramic layer quality. These processes have been found to be adequate and do not require modification due to the presence of the ceramic. AstroPower is collaborating with Professor Roy Gordon of Harvard University to evaluate the potential of using buried titanium nitride-based thin films as reflectors and to enhance conduction in the silicon-on-ceramic structure. Work has commenced on the identification and evaluation of high-temperature conductive inks that can be screen printed on the ceramic prior to the silicon deposition process.

Solar Cell Device Results:
- Achieved a short-circuit current density of 25.8 mA/cm^2 on a 0.6 cm^2, 20 micron thick silicon-on-ceramic device (NREL measurement). The quantum efficiency characteristic for this device suggests that a high level of light trapping and back surface passivation has been achieved (AstroPower measurement).
- Demonstrated a 9.1% efficient, 0.9883 cm^2 silicon-on-ceramic device. The solar cell parameters for this device were: Voc = 0.5669 V, Isc = 0.02064 A, Jsc = 20.88 mA/cm^2, FF = 76.91%, Imax = 19.06 mA, Vmax = 0.4721 V, Pmax = 8.997 mW (NREL measurement).
- Demonstrated a four element interconnected silicon-on-ceramic array which did not display any degradation due to the interconnection process (AstroPower measurement).

Planned FY 2000 Milestones:
- Complete/build low-cost screen printer for high throughput large modules.
- Complete design and build low cost encapsulation equipment
- Deliver a 10%, large-area monolithically interconnected module.
- Deliver sample demonstrating screen printing on sample up to 2000 cm^2.
- Deliver large-area encapsulated module.
- Deliver 13%, 30-cm^2 monolithically interconnected all back contact device.
- Deliver annual technical report.

Major Articles Published in FY 1999:
E.J. DelleDonne, D.H. Ford, R.B. Hall, A.E. Ingram, J.A. Rand, and A.M. Barnett, “Monolithically Interconnected Silicon-Film™ Module Technology,” *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 320-324 (1999).

E.J. DelleDonne, D.H. Ford, P.E. Sims, J.A. Rand, A.E. Ingram, J.C. Bisaillon, B.W. Feyock, M.G. Mauk, R.B. Hall, and A.M. Barnett, “High Current, Thin Silicon-on-Ceramic Solar Cell,” *Ninth Workshop on Crystalline Silicon Solar Cell Materials and Processes; August 9-11, 1999, Breckenridge, CO,* pp. 210-212 (August 1999).

A.M. Barnett, J.A. Rand, R.B. Hall, D.H. Ford, E.J. DelleDonne, A.E. Ingram, J.C. Bisaillon, B.W. Feyock, M.G. Mauk, and P.E. Sims, “High Current, Thin Silicon-on-Ceramic Solar Cell,” *11th International Photovoltaic Science and Engineering Conference, September 20-24 Hokkaido, Japan*, pp. 982 (September 1999).

D.H. Ford, J.A. Rand, E.J. DelleDonne, A.E. Ingram, J.C. Bisaillon, B.W. Feyock, M.G. Mauk, R.B. Hall, and A.M. Barnett, “High Current, Thin Silicon-on-Ceramic Solar Cell,” *IEEE Transactions on Electron Devices,* Vol. 46, Number 10, pp. 2162-2164 (October 1999).

Thin Film PV Partnership

Apollo Thin Film Process Development

Contract #: ZAK-7-17619-27	**Contract Period:** 5/1/98–4/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	BP Solar Inc. 2300 North Watney Way Fairfield, CA 94533	
	Organization Type: IN	**Congressional District**: 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D.W. Cunningham **Phone:** 707-438-3818 **Fax:** 707-428-7878	
Technical Monitor: H S. Ullal **Phone**: 303-384-6486 **Fax**: 303-384-6430 **E:mail**: harin_ullal@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: BP Solar Inc.
	DOE Funding Allocation: 1998: $187,500 1999: $470,833	**Cost Share Funding:** 1998: $322,052 1999: $717,470

Project Objective:
The objectives of this subcontract are to optimize CdTe electroplating and CdS chemical bath deposition operations, conduct process development, determine device performance and reliability, optimize laser process techniques, and enhance waste treatment and abatement systems to achieve zero-discharge.

Approach/Background:
BP Solar is currently introducing the Apollo® CdTe technology at its new Fairfield, CA production plant. The plant in California is designed and built to produce its thin-film module in high volume. This commitment is the result of BP Solar's extensive R&D program over the past ten years which has been successful in developing and characterizing a stable 8% CdTe 929 cm^2 module at the limited pilot line level. At Fairfield, BP Solar Inc. will scale up the Apollo® CdTe process to produce a 5,518 cm^2 and ultimately a 9,449cm^2, monolithic CdS/CdTe module.

Status/Accomplishments:
Installed a ground mounted, grid connected system using Apollo® modules in the grounds of the BP Solar facility at Fairfield, CA. The system contains 48, 5,518 cm^2 modules with a STC DC power of 1.68kW.
BP Solar delivered its 1999 milestone of two glass-to-glass encapsulated CdTe modules (5,518 cm^2) with aperture-area efficiencies between 8.0% and 8.5% (38.2W to 40.4W).
Work was initiated on large area (9,449 cm^2) Apollo® modules. NREL confirmed efficiencies between 7.8% and 8.3% for two of these glass-to-glass modules. The maximum power was 72.2W, which is currently the world record any thin film module.

Planned FY 2000 Milestones: Produce glass-to-glass encapsulated CdTe modules.(5,518 cm^2) with aperture-area efficiency of 8.5%.

Major Reports Published in FY 1999:
Thin-Film Photovoltaic Partnership – Apollo® Thin Film Process Development: Phase 1 Technical Report, May 1998–April 1999 ZAK-7-17619-27. (October 1999).

Major Articles Published in FY 1999:
None.

Thin Film PV Partnership

Research on Amorphous Silicon Cells and Modules

Contract #: ZAK-8-17619-02	**Contract Period:** 3/9/98–5/8/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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<tr><td>Organization Type: IN</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
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Phone: 303- 384-6441
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Solarex</td></tr>
<tr><td>DOE Funding Allocation:
1998: $655,019
1999: $715,000</td><td>Cost Share Funding:
1998: $760,700
1999: $774,000</td></tr>
</table>

Project Objective: The overall objective of this project is to develop high performance, large-area, amorphous silicon tandem modules on glass substrates. In Phase I, Solarex had the objective of demonstrating a stabilized conversion efficiency of 10% in 1 ft^2 tandem modules and increasing this stabilized efficiency to 11% in Phase II and 12% in Phase III. Another major objective is to demonstrate a stabilized aperture area efficiency of 9.5% in 8 ft^2 tandem modules in Phase III.

Approach/Background: Solarex plans to investigate several new amorphous silicon deposition modes with the goal of increasing deposition rate, feedstock utilization and PV module performance. The new approaches include hot-wire, Ar-dilution, He-dilution and modified PECVD reactors. Solarex will also be developing new diagnostic characterization tools to assist in the development of high quality amorphous silicon alloys and PV modules. The diagnostic tools under development include laser-defined diodes, in-line PV characterization of partially processed plates, real time spectroscopic ellipsometry (Penn State), optical interference spectroscopy (Univ. of VA), polarization differential reflectance (Univ. of VA) and optical emission spectroscopy.

Status/Accomplishments: Recent efforts have been focused on increasing the utilization of feedstock gases and on increasing the deposition rates while maintaining initial conversion efficiencies in the range of 9 – 10% for tandem devices on commercial tin oxide coated glass.

- Gemane consumption has been reduced by 50% and silane consumption by 40% without any adverse effect on device performance.
- The deposition rate for intrinsic a-Si has been increased from 0.1 nm/s to 0.3 nm/s without any adverse effect on the stabilized efficiency of single-junction a-Si cells.
- Other studies involving helium and argon dilution have shown that the deposition rate of a-Si can be increased by as much as 60% by using inert gas dilution (as compared to hydrogen dilution) without adversely affecting device performance.
- In addition, the total deposition time for the tunnel junction in the tandem solar cells has been reduced by a factor of three without any loss in device performance.

We have also investigated the effect of oil contaminants and dopant impurities on the stabilized performance of a-Si solar cells.

- Pump oil contamination on the discharge electrodes caused the efficiency to decrease by as much as 11% , but there was no significant effect on device performance when the oil was localized on walls not in the immediate vicinity of the plasma.
- Small amounts of boron contamination ($\sim 2.5 \times 10^{17}$ cm^{-3}) in the i-layer of p-i-n cells caused the initial conversion efficiency to fall by about 20%. Moreover, while the control cells degraded by ~ 23% after 625 hours of light soaking, the boron-contaminated cells degraded by ~ 29% and most of this degradation was irreversible.

We have also studied the effect of varying the cathode to anode spacing in DC PECVD reactors and found that both the tunnel junction and the a-SiGe i-layer in tandem devices are very sensitive to the spacing. The conversion efficiency of tandem cells decreased by about 9% when the cathode to anode spacing increased by 10% from the standard spacing.

Contract #: ZAK-8-17619-02

Planned FY 2000 Milestones: (1) Demonstrate a stabilized conversion efficiency of 11% in a 1 ft^2 amorphous silicon tandem module. (2) Demonstrate a stabilized conversion efficiency of 12% in a small-area (~ 0.25 cm^2) amorphous silicon tandem cell. (3) Demonstrate an average stabilized efficiency of 10% for 7 out of 10 modules (1 ft^2) fabricated on commercial tin oxide coated glass.

Major Articles Published in FY 1999:

R. R. Arya et al.,"R&D Issues in Scale-Up and Manufacturing of Amorphous Silicon Tandem Modules," *NCPV Photovoltaics Program Review; Proceedings of the 15th Conference, Denver, CO, 1998;* AIP Conference Proceedings, Vol. 462, pp. 94-99 (1999).

D. E. Carlson et al., "A Comparison of the Degradation and Annealing Kinetics in Amorphous Silicon and Amorphous Silicon-Germanium Solar Cells," MRS Meeting, San Francisco, CA, April 5-10, 1999.

A. R. Middya et al.,"He-Dilution to Increase Deposition Rate and Feedstock Utilization during the Growth of a-Si:H and a-SiGe:H Alloys," MRS Meeting, San Francisco, CA, April 5-10, 1999.

G. Ganguly et al., "Performance of a-Si:H Solar Cells at Higher Growth Rates," MRS Meeting, San Francisco, CA, April 5-10, 1999.

D. E. Carlson, "A Forecast – Photovoltaics in the Year 2030," Electrochemical Society Meeting, Seattle, Washington, May 2-6, 1999. Proceedings of the International Symposium, "Photovoltaics for the 21st Century," Proceedings Vol. 99-11, The Electrochemical Society, pp. 16-23 (1999).

D. E. Carlson, "Amorphous Silicon Photovoltaics: The Past, Present and Future," 11th International Photovoltaic Science and Engineering Conference to be held in Sapporo, Japan, September 20-24, 1999.

Thin Film PV Partnership

Nanostructure of a-Si:H and Related Alloys by Small-Angle Scattering of Neutrons and X-rays

Contract #: XAK-8-17619-31	**Contract Period:** 5/22/98–7/21/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King   Jeffrey Mazer
Phone: 202-586-1693   Phone: 202-586-2455
Fax: 202-586-8148   Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Colorado School of Mines (CSM)
1500 Illinois St.
Golden, CO 80401</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
D. Williamson and D.W.M. Marr
Phone: 303-273-3837 Fax: 303-273-3919</td></tr>
<tr><td rowspan="2">Technical Monitor:
Bolko von Roedern
Phone: 303-384-6480
Fax: 303-384-6531
E:mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $37,000
1999: $83,664</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: To improve the understanding of which nanostructural features are related to electronic materials properties that determine the performance of a-Si:H based solar cells. The project will determine whether small-angle neutron scattering can be used to determine hydrogen-related nanostructures and any changes that might occur in them during light soaking. The ASAXS technique shall be established as to determine non-uniform Ge incorporation into a-SiGe:H material. Determine the role of medium range order in light stability and other device behavior.

Approach/Background: Use both small-angle neutron (SANS) and x-ray scattering (SAXS) and conventional wide-angle x-ray diffraction techniques to investigate the nanostructures of amorphous and microcrystalline silicon-related solar cell materials and correlate them with optoelectronic and device properties. Extensive prior work with SAXS has established its value in correlating certain nanostructural features with degraded solar cell performance.

Status/Accomplishments: CSM completed the first SANS experiments on a-Si:H at the NIST Center for Neutron Research. Data are being analyzed. CSM continued to provide structural characterization of all samples to the device making groups. Especially, samples in the “protocrystalline” deposition regime were characterized. It was found that SAXS is very sensitive to detect and characterize microcrystalline inclusions in the material. CSM also characterized samples before and after they had been exposed to very high pressures by the UCLA group.

Planned FY 2000 Milestones: Evaluate a first set of experiments with SANS to establish its viability for determining hydrogen nanostructure. Further examine medium range order in a-Si:H related materials to establish its importance for light-induced metastability and device behavior.

Major Reports Published in FY 1999: Phase 1 Annual Report, Final version received

Major Articles Published in FY 1999:
D.L. Williamson et al, MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999), 2 articles, one of them invited, to be published.

Thin Film PV Partnership

Process Development and Basic Studies of Electrochemically Deposited CdTe-Based Solar Cells

Contract #: #: XAK-8-17619-28	**Contract Period:** 5/22/98–5/21/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	Colorado School of Mines 1500 Illinois St. Golden, CO 80401-1887	
	Organization Type: CU	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** V. Kaydanov T.R. Ohno **Phone:** (303) 273-3156 (303) 273-3847 **Fax:** (303) 273-3919 (303) 273-3919	
Technical Monitor: Bolko von Roedern **Phone**: (303) 384-6480 **Fax**: (303) 384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $251,426 1999: $327,472	**Cost Share Funding:**

Project Objective: Advance the processing for high-performance stable CdTe photovoltaic devices, by: (1) advancing the understanding how the basic electronic properties of CdTe thin film solar cells are related to composition, structure and processing procedure of the constituting layers; (2) studying microscopic processes in different parts of the cell responsible for degradation of electronic properties as a function of stress conditions; (3) optimizing the composition of the constituting layers, deposition procedures and postdeposition treatments to enhance cell performance; and (4) contributing to the development of accelerated lifetime prediction tests for the CdTe solar cells.

Approach/Background: Study electronic properties of polycrystalline thin films, in particular of grain boundaries, and devices prepared and stressed under varying conditions using variety of experimental methods and models. Optimize processing procedure of CdS/CdTe structure, composition and processing procedure of the front and back contacts.

Status/Accomplishments: AC impedance measurements enabled CSM to clarify to role of grain boundaries on the transport properties of polycrystalline materials. CSM successfully applied Near Field Scanning Optical microscopy (NSOM) to analyze CdTe solar cells. Both cell cross sections and surface topologies (after removal of the glass superstrate) were investigated. CSM contributed more results how the back contact of CdTe solar cells affect cell performance and stability.

Planned FY 2000 Milestones: Continue to conduct stress stability tests on cells. Establish major mechanisms for cell degradation. Further characterize the effect of grain boundaries on the

Major Reports Published in FY 1999: Phase 1 Annual report not yet received

Major Articles Published in FY 1999:
The following articles were published in 15th NPCV Photovoltaics Program Review; American Institute of Physics Conference Proceedings 462 (1999):

1. W. Song, D. Mao, V. Kaydanov, T.R. Ohno, J.U. Trefny, R.K. Ahrenkiel, D.H. Levi, S. Johnston, and B.E. McCandless, "Effect and Optimization of CdS/CdTe Interdiffusion on the Electrical Properties and CdS/CdTe Cell Performance," p. 194.
2. D. Morgan, J. Tang, V. Kaydanov, T.R. Ohno, and J.U. Trefny, "Degradation Mechanisms Studies in CdS/CdTe Solar Cells with ZnTe:Cu/Au Back Contact," p. 200.
3. A. Al-Kaoud, T. Wen, A. Gilmore, V. Kaydanov, T.R. Ohno, C. Wolden, L. Feng, and J. Xi,, "Atmospheric Pressure Chemical Vapor Deposition of SnO2: Processing and Properties," p. 212.

L.M. Woods, D.H. Levi, V. Kaydanov, G.Y. Robinson, and R.K. Ahrenkiel, "Electrical Characterization of Etched Grain-Boundary Properties from As-Processed px-CdTe-Based Solar Cells," p. 499**.**

Thin Film PV Partnership

Device Physics of Thin-Film Polycrystalline Solar Cells

Contract #: XAK-8-17619-07	**Contract Period:** 1/20/98–1/19/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Colorado State University Department of Physics Fort Collins, CO 80523	
	Organization Type: CU	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** James R. Sites Phone: 970-491-5850 Fax: 970-491-7947	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**303-384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $140,318 1999: $135,629	**Cost Share Funding:**

Project Objective: To (1) characterize and quantitatively separate individual losses in CI(G)S and CdTe cells and small modules, (2) explore mechanisms that allow small changes in impurity materials to have a significant performance impact, (3) develop a micron-size light probe, (4) characterize stability and transient response of cells at elevated temperature, and (5) integrate CdTe grain-boundary modeling with experimental data.

Approach/Background: Partnership with industry, NREL, and other universities to form an effective division of labor and communication network to collectively increase the commercial viability of thin-film polycrystalline modules.

Status/Accomplishments: (1) Systematic studies of "transients" in CIS cells and minimodules. (2) Documentation of elevated-temperature induced changes in CdTe cells careful characterization of changes in cells supplied by different manufacturers. (3) Completed construction and initial evaluation of small-light-spot probe with micron stepping control. (4) Quantitative loss analysis of several CuInSe2 and CdTe cells.

Planned FY 2000 Milestones: (1) Use small-spot probe to characterize non-uniform solar cell responses. (2) Continued contributions to clarify the problems of copper in contacting CdTe. (3) Continued leadership for the NREL subteams addressing transient effects in CIS and stress induced degradation in CdTe devices.

Major Reports Published in FY 1999: Phase I Annual Report, final version received 11/99

Major Articles Published in FY 1999:

"Stability of CdTe Solar Cells at Elevated Temperatures" J.F. Hiltner and J.R. Sites, 15th NCPV Photovoltaics Program Review, American Inst. of Physics Conf. Proc. 462, 170 (1999).

Thin Film PV Partnership

Development of a Thin-Film Based "Micro-Concentrator" Photovoltaic Technology

Contract #: ZAK-8-17619-25	**Contract Period:** 5/1/98–4/30/2001

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	DayStar Technologies, Inc. 303 S. Broadway, PMB-415 Denver, CO 80209 **Organization Type**: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** John R. Tuttle, Ph.D. **Phone:** 303-279-9505 **Fax:** 303-742-1899	
Technical Monitor: K. Zweibel **Phone**: 303.384.6441 **Fax**: 303.384.6430 **E:mail:** ken_zweibel@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $38,383 1999: $115,000	**Cost Share Information**: DayStar Technologies, Inc. **Cost Share Funding:** 1998: $8,754 1999: $13,000

Project Objective: DayStar Technologies, Inc. is developing a "flat-plate" concentrator PV module packaging technology as a reduced cost alternative to conventional module designs. This product is ideally suited for multi-megawatt projects where the opportunity exists to design dedicated 10-50KW systems at a 50% cost savings and to require only 15-25% of the costly cell material used in non-concentrator modules.

The optical lens and cell interconnect scheme was originally designed for use with thin-film solar cell components fabricated on flexible metallic sheet such as stainless steel. The package is now capable of accepting wafer-Si cell components as well, increasing the products market viability. The overall 3-year goals of the project are: 1) identify and address module and system product development issues; 2) produce module and system detailed design package; 3) produce pilot and full-scale system manufacturing tooling design package; 4) launch and operate pilot, followed by full-scale production facility.

The objective of this contract is to address research and development issues at the module level. DayStar will work through development issues in: 1) solar cell design, performance, and reliability under 2-8 suns of illumination; 2) cell modification and interconection into multi-cell strings; 3) lamination of interconnected cell package to lens and lens to coverglass; and 4) optical lens performance. The solar cell materials presently under consideration are single junction ZnO / $Cu(In,Ga)Se_2$ on a sheet stainless-steel substrate, and wafer-Si (poly or single x-tal) cells from various vendors.

Approach/Background: Replacing costly solar cell material with inexpensive ($20/m^2) optical lens material is, by design, an effective means for reducing the manufacturing cost of PV modules. DayStar has created a module design that more closely emulates the mechanical nature of conventional flat-plate PV products and realizes significant cost savings through optical concentration of 2-8 suns. In order to achieve these benefits, technical and cost issues pertaining to cell modification (grid design / dicing), interconnect, component lamination, and optics performance require investigation.

The salient technical issues include thermal matching of plastic lens with coverglass, cell interconnection methodology for automated assembly, optical efficiency of lens / coverglass couple, taking into account optical reflectivity of cell material, and thermal heating of cell materials under concentration. Many of these issues have corollaries in conventional module fabrication and hence are an advantage of this approach to concentration packaging. Those issues which are unique to this technology will be investigated thoroughly by DayStar.

Status/Accomplishments: The initial cell of interest for this module product is thin-film CIGS deposited on stainless steel substrates. For commercialization, the cell components would either be manufactured in-house or purchased from suppliers. Due to a lack of available off-the-shelf product of this type, a preponderance of the packaging development work has been accomplished using off-the-shelf wafer-Si cell components. Polycrystalline Si cells (typically square) are cut into 2-3mm wide strips in much the same manner as is done with the thin-film CIGS. The cells are interconnected into 10- and 23-cell strings for integration into lens/coverglass packages. Through repetitive sub-module (100-cm^2) fabrications, critical optical and electrical performance issues have been elucidated. Ag and Al reflector materials have been tested. Though Ag is a superior reflector, it presents some reliability issues when coupled with acrylic lens material.

The modeled optical efficiency for the reflective component of the lens is equal to the maximum attainable reflectivity for Ag and Al, i.e. 92 & 85%, respectively. This value is then coupled with the area-percentage coverage of reflector material vs. cell material, and then further coupled with the percentage of incident light that is direct in nature vs. diffuse in nature. Optical efficiencies of 80-85% have been measured, lower than desired. The problem has been traced to reflectivity off the Si surface, and therefore the measurements will be repeated using thin-film CIGS cells as the detector.

In addition to optical development, there has been progress in understanding how cell modification (wafer or sheet cutting) and interconnection processes affect the electrical performance of the module cell components. Losses/gains associated with each step, including operation under concentration, have been quantified. In DayStar's R&D facilities, there are limitations as to the how each process is realized in contrast to what could be done in an automated and mechanized production environment. It has been concluded that minimal losses can be incurred during production, and that thin-film on SS cells perform better than wafer-Si cells under actual operating conditions of 2-8 suns of concentration. It is anticipated, however, that improvements in the latter can be realized when wafer-Si cell components are designed and manufactured to our product specifications.

Several 50-100 cm^2 mini-modules have fabricated using wafer-Si and thin-film CIGS cell components. The "active-area" performance was measured outdoors at 8.0 & 7.2%, respectively. These performance values are considerably lower than desired and are traced to 1) reflectivity off the wafer-Si; 2) temperature rise and degradation of wafer-Si cells under concentration, and 3) inefficient current collection for CIGS cell strings.

Planned FY 2000 Milestones: Substantial emphasis in FY'00 will be placed on improving the Company's ability to fabricate greater quantities of thin-film CIGS for this technology development effort. The desired milestones for FY'00 under this subcontract include: 1) reproducible 13% total-area cell performance for CIGS-based cells; 2) reliable 12% 10-20 cell strings; 3) >10% (active-area) 50-cm^2 CIGS-based mini-modules; and 4) > 9% 500-cm^2 wafer-Si based mini-modules. Additionally, substantial effort will be expended towards outdoor measurements, outdoor testing, and module qualification testing. In so doing, DayStar will learn where laboratory and field development issues diverge.

Major Reports Published in FY 1999:

J.R. Tuttle, A. Szalaj, and T. Berens, "Development of a Thin-Film Based "Micro-Concentrator" Photovoltaic Technology," Annual Report to the National Renewable Energy Laboratory under Subcontract ZAK-8-17619-25, May 15, 1998 – May 14, 1999.

Major Articles Published in FY 1999:

Use of Very High Frequency Plasmas to Prepare a-Si:H Based Triple-Junction Solar Cells at High Deposition Rates

Contract#: ZAK-8-17619-18	**Contract Period:** 3/11/98–5/10/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Jeffrey.Mazer@ee.doe.gov	Energy Conversion Devices, Inc. 1675 West Maple Rd. Troy, MI 48084	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** S.J. Jones **Phone:** 248-362-4780 **Fax:** 248-362-0012	
Technical Monitor: K. Zweibel **Phone:** 303-384-6441 **Fax:** 303-384-6430 **E:mail:** ken_zweibel@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** ECD
	DOE Funding Allocation: 1998: $235,000 1999: $311,000	**Cost Share Funding:** 1998: $235,000 1999: $311,000

Project Objective: To develop a very high frequency (70 MHz), plasma-enhanced, chemical vapor deposition process for the fabrication of intrinsic layers for high efficiency amorphous silicon-based triple-junction solar cells at high deposition rates. These intrinsic layers are either amorphous silicon or amorphous silicon germanium alloy materials. The eventual goal is to prepare these materials at rates of 10 Å/s or higher while maintaining the cell efficiencies at the high values presently obtained for devices made using the standard 13.56 MHz frequency and low deposition rates (near 1 Å/s). Upon completion of a successful program, application of this high rate process to ECD's roll-to-roll solar cell production design will lead to higher machine throughput and reduced solar module cost.

Approach/Background: The deposition conditions used to prepare single-junction amorphous silicon (a-Si:H) and silicon germanium alloy (a-SiGe:H) cells by the very high frequency (VHF) technique will be optimized to obtain the highest cell efficiencies. These component cells will then be combined to create high efficiency a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells. The deposition conditions for these multi-junction cells will also be optimized to further increase the device performance. For the future incorporation of the technique into an ECD built roll-to-roll solar cell production line, cathode hardware designs will be tested which will allow for the uniform deposition of i-layers over a large area using the VHF technique and high deposition rates.

Status/Accomplishments: The following has thus far been accomplished: 1) preparation of a single-junction a-Si:H cell with a stable 8.0% AM1.5 efficiency using the VHF technique and a 10 Å/s rate, 2) preparation of a single-junction a-SiGe:H cell with a stable 2.6% red light efficiency (AM1.5 light filtered with 630nm cutoff filter) using the VHF technique and a 10 Å/s rate, 3) preparation of a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells with an initial (pre-light soaked) AM1.5 efficiencies above 11% (11.2% highest) and light soaked AM1.5 efficiencies of 9.7% using the VHF technique and a 10 Å/s rate for all of the i-layers.

Planned FY 2000 Milestones: The following are goals for this fiscal year: 1) preparation of a single-junction a-SiGe:H cell with a stable 2.8% red-light (630 nm filtered) efficiency using the VHF technique and a 10 Å/s rate.
2) preparation of a-Si:H/a-SiGe:H/a-SiGe:H triple-junction cells with light soaked AM1.5 efficiencies of 10.5% using the VHF technique and a 10 Å/s rate for all of the i-layers and 3) development of large area cathode hardware that will allow for the uniform deposition of amorphous silicon-based films at rates near 10 Å/s using the VHF technique.

Major Reports Published in FY 1999:

NREL Photovoltaic Program FY 1998 Annual Report, NREL/SR-520-26795, (September 1999).

Major Articles Published in FY 1999:

"Preparation of triple-junction a-Si:H nip based solar cells at deposition rates of 10 Å/s using a very high frequency technique." S.J. Jones, X. Deng, T. Liu, and M. Izu, *Mat. Res. Soc. Proc 1999 Spring Meeting* (in press)

Thin Film PV Partnership

Thin-Film CIGS Photovoltaic Technology

Contract #: ZAK-8-17619-21	**Contract Period:** 4/16/98-4/15/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Jeffrey Mazer — **Phone:** 202-586-2455 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	Energy Photovoltaics, Inc. (EPV) 276 Bakers Basin Road Lawrenceville, NJ 08648	
	Organization Type: IN	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** A.E. Delahoy **Phone:** 609-587-3000 **Fax:** 609-587-5355	
Technical Monitor: H.S. Ullal **Phone**: 303-384-6486 **Fax**: 303-384-6430 **E:mail:** harin_ullal@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Energy Photovoltaics, Inc. (EPV)
	DOE Funding Allocation: 1998: $698,515 1999: $811,328	**Cost Share Funding:** 1998: $174,629 1999: $202,832

Project Objective: The overall objective of this R&D program is to develop processing for versatile, large-scale, all-vacuum coating equipment to produce high efficiency, thin film CIGS PV modules. Sub-objectives include: an optimized Mo back electrode, a CIGS process capable of better than 15% device efficiency, scale up of CIGS coating to 7900 cm^2, a Cd-free buffer layer, high rate ZnO deposition, low loss patterning operations, a qualified encapsulation process, and stability testing. Accomplishment of these goals will enable cost effective manufacturing of CIGS modules.

Approach/Background: Valuable experience has been gained through operation of a pilot line capable of producing 4300 cm^2 CIGS modules, with module efficiency reaching 7.6% at 3100 cm^2. To deliver materials to the moving glass, EPV continues to refine linear evaporative sources capable of downward evaporation, and source heads with up to four independent linear sources have been built and operated. This approach allows a wide range of vacuum-based CIGS recipes to be implemented.

For junction formation, EPV relies on chemical bath deposition of CdS on a day-to-day basis, while pursuing alternative methods in parallel. These methods may include linear source evaporation of CdS or a Cd-free buffer material, and direct deposition of ZnO onto the CIGS. Exploration of Cd-free junctions is being pursued by the EPV sub-team of the National CIS R&D Team. After junction formation, the quality of the CIGS is being investigated in a collaborative arrangement by sub-band-gap spectroscopy.

For high rate ZnO deposition, EPV is currently exploring planar magnetron sputtering using ceramic ZnO targets.

Status/Accomplishments: Using linear source evaporation, CIGS has been prepared on 4300 cm^2 Mo-coated glass substrates using both EPV's *FORNAX* process and a three-stage sequential process. Two methods of real-time flux monitoring are employed, including conventional quartz crystal monitoring. Diagnostic devices produced on portions of the substrate have been prepared with efficiencies of 12% (V_{oc} = 581 mV, J_{sc} = 30.1 mA/cm^2, FF = 68.7%).

Of special significance is EPV's ability to build linear sources capable of Cu evaporation. This is a considerable technological feat given the high Cu source temperature. An overall thickness uniformity of the CIGS across a 40 cm width of the substrate of +-2.5% has been achieved.

Three classes of compounds related to CIGS have been synthesized at EPV and are being investigated for their utility as source materials: precursor materials, CIS and CIGS, and buffer materials. The compounds are analyzed using XRD and ICP.

The performance of Cd-free ZnO/CIGS junctions formed by a novel "soft" method was explored. In this method the ZnO was deposited by the simultaneous supply of fluxes of zinc and atomic oxygen (*ROMEAO* process, Reaction Of MEtal and Atomic Oxygen). This method avoids sputter damage and ion bombardment. Most of the devices exhibited a strong increase in V_{oc} upon light or field soaking. The devices were studied using a drive and interrogate procedure in which the device was driven between two steady states corresponding to two different voltage biases, with brief interrogation of V_{oc} at various times. The soaking effect was found to be thermally activated with an activation energy of 0.51eV. After soaking, a solar cell efficiency of 12.3% was achieved.

A ternary compound was synthesized at EPV and explored as a possible source material, with a view to its use in Cd-free buffer formation. XRD analysis confirmed the existence of the desired compound. The material was found to sublime, and Auger analysis confirmed the presence of all three elements in the film. The first set of devices using the sublimed material as a buffer layer exhibited V_{oc}'s in the range 450 – 620 mV.

A sub-band-gap spectrum of a CdS/CIGS device was obtained at 150K at the University of Oregon by transient photocapacitance spectroscopy. This spectrum revealed the band edge near 1.1eV, an Urbach tail with a characteristic energy E_0 of less than 20meV, and a shoulder of deep defect transitions between 0.75 to 1.0eV. The ability to evaluate E_0 for CIGS in a standard device configuration could make this a useful characterization tool.

The deposition rate (averaged over target width) of ZnO:Al sputtered onto 4300 cm^2 substrates from a ceramic target has been increased from 13 A/s to 48 A/s through increase of target power. Standard films applied to modules possess the following combination of properties: sheet resistance 23 Ω/sq and transmission 87%.

Planned FY 2000 Milestones: a) improved Mo electrode b) a 42 W 4300 cm^2 CIGS module c) scale up of CIGS deposition and associated processing to 7900 cm^2 d) a feasible buffer material deposited in-situ following CIGS deposition.

Major Reports Published in FY 1999:

Delahoy, A.E., Chorobski, D., Ziobro, F., and Kiss, Z.J. (1999) "Thin-Film CIGS Photovoltaic Technology," Annual Technical Report, NREL/SR-520-25713, 29 pp. Available from NTIS, Springfield, VA 22161.

Major Articles Published in FY 1999:

Delahoy, A.E., Ruppert, A., and Contreras, M., "Charging and Discharging of Defect States in CIGS/ZnO Junctions," *E-MRS 1999 Spring Meeting, June 1-4, 1999, Strasbourg, France (to be published in Thin Solid Films).*

Delahoy, A.E., Chorobski, D., Ziobro, F., and Kiss, Z.J., "Baseline Process Development for Pilot Line Production of CIGS Modules," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 144-151 (1999).

Delahoy, A.E. and Ruppert, A.F., "Zinc Oxide Formation Using Atomic Oxygen and Metal Flux Sources," *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion Proceedings, July 6-10, 1998, Vienna, Austria,* pp. 668-671 (1998).

Thin Film PV Partnership

Technology Support for High-Throughput Processing of Thin-Film CdTe PV Modules

Contract#: ZAK-8-17619-17	**Contract Period:** 4/1/98–3/31/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King — Phone: 202-586-1693 — Fax: 202-586-8148
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<tr><td>Organization Type: IN</td><td>Congressional District: 9</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
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Phone: 419-872-7661 Fax: 419-872-7665</td></tr>
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E:mail: harin_ullal@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
First Solar, LLC.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $1,032,511
1999: $945,416</td><td>Cost Share Funding:
1998: $258,128
1999: $654,623</td></tr>
</table>

Project Objective:
The project objective is to develop equipment and processes for very large-scale production of high-efficiency CdS/CdTe thin-film photovoltaics. This subcontract focuses on the development of high-rate semiconductor deposition, improvement of module efficiency, development of all-dry device processes, and testing of long-term stability.

Approach/Background:
The subcontract covered by this summary was awarded to Solar Cells, Inc. (SCI) in 1998. SCI had been conducting research and process development on CdS/CdTe solar panels since 1991. In February 1999, SCI and True North Partners, LLC of Phoenix, AZ jointly formed First Solar, LLC. True North Partners is a private equity firm which participates with selected companies by providing capital and operating experience. First Solar assumed all activities of SCI, including the research described in this report. The goal of SCI, and now of First Solar, has been to produce photovoltaics at very large volumes at costs competitive with traditional energy sources. To achieve this goal, this subcontract leverages First Solar's extensive knowledge of high-speed II-VI thin-film deposition and hot-glass transport and focuses new research in four areas: 1) process and equipment development, 2) efficiency improvement, 3) characterization and analysis, and 4) environmental, health, and safety.

Status/Accomplishments:
During FY 1999, First Solar made significant progress in all areas of this subcontract as described below:

- Process development:
  - Increased the output of the pilot production facility. 8616 8ft^2 CdS/CdTe-coated plates were produced (with a maximum of 542 plates in one week). 4106 8ft^2 submodules were produced with an average total-area efficiency of 6%.
  - Developed new measurement techniques. Mapping capability with up to 7200 points per plate for CdS and CdTe thickness and pinhole density was established. A new on-line, high-temperature CdS thickness measurement technique was also developed.
  - Improved CdTe thickness uniformity and reproducibility. From a population of more than 1100 plates, the mean standard deviation of CdTe thickness within a plate was 7.3% and the standard deviation of individual-plate averages was 6.8%.
  - Improved CdTe utilization to 72% on the pilot-production deposition system.
  - Developed new interconnect processes. A new laser-scribing method was demonstrated at a linear speed of 2000 mm/s. This will enable all of the metal-isolation scribes for a module to be done in less than one minute with only one laser.
  - Developed a polyester-encapsulation approach that has the potential to significantly decrease cost while improving durability.
- Equipment development:
  - Designed and built a high-throughput semiconductor-deposition system. The system, called the 100MW coater, is capable of depositing CdS and CdTe on a 4ft-wide web at line speed of up to 8 ft/min and thus should be capable of producing 1,500,000 8ft^2 CdS/CdTe plates per year. The system is currently in the debug and test phase of construction.
  - Designed and built a pilot-production vapor-$CdCl_2$ system capable of handling one 8ft^2 plate every 3 minutes.

In concert with other programs and additional internal funding, designed and began construction of a production facility with a capacity of 20MW/yr. The building is complete and the 100MW/yr-capacity coater, a 25MW/yr-capacity $CdCl_2$ line, and a 20MW/yr-capacity metal-deposition system have been sited and are in test.

- Efficiency improvement:
  - Set a new in-house efficiency record for standard sodalime glass substrates. A cell with a 3mm-thick sodalime-glass substrate, production TCO, an in-house-deposited buffer layer, and no anti-reflection coating was 13.9% efficient after 1 day of light soak.
  - As part of a program to develop APCVD (atmospheric-pressure chemical vapor deposition) TCOs and buffer layers, designed and built an APCVD system for $100cm^2$ substrates. A grating-monochromater quantum-efficiency (QE) system was also designed and built to enable characterization of devices with thin CdS and buffer layers.
  - Various post-deposition treatments, including vapor-$CdCl_2$ and alternative contacts were investigated and show promise for cost reductions and efficiency improvements.
  - A large, multicathode sputter-deposition system was developed and built to enable buffer-layer and back-contact research on the module scale. Leak problems were solved and the base pressure for the system is now excellent (3×10^{-6} torr).
- Characterization and analysis:
  - Several characterization techniques were used to increase understanding. Contactless-V_{oc} measurement was used to determine that vapor-$CdCl_2$ treatment is more uniform than wet-$CdCl_2$ treatment. Photoluminescence was used to determine that Cu introduces a shallow acceptor state in CdTe that can be unstable. Simulator IV(T) and field measurements were used to determine that the power output of modules was relatively insensitive (<5%) to temperature in the 25 to 50°C range.
  - Considerable effort was given to reliability verification and improvement. Array performance was found to be acceptable with the array at NREL unchanged within the margin of error of measurement (5%) after 5 years in the field. The output of one array was found to be decreasing at approximately 2%/year, but simulator measurements of modules showed the average of individual modules to be essentially unchanged. An extensive accelerated life test program, which included over 43,000 cell IV measurements, was used to test the stability of process parameters and develop a correlation between back-contact processing conditions and cell stability.
- Environmental, health, and safety:
  - Performed an emissions survey for the pilot-production facility that predicted for a production rate of 360 modules/day the cadmium emissions would be only 0.015% of the level that would require any permitting.
  - Made process improvements in edge delete, CdS material preparation, waste compaction, $CdCl_2$-vapor collection and wastewater treatment, resulting in reduced costs, reduced emissions, and improved operator safety.

Planned FY 2000 Milestones:
- Document CdTe utilization ≥ 90% over an 8-hour production run of 200 plates or best effort.
- Demonstrate thickness control of ± 5% within a plate and ± 10% plate-to-plate over a production run of 1000 plates or best effort.
- Demonstrate a full-scale semiconductor re-crystallization with a process time ≤ 5 min. or best effort.
- Demonstrate module aperture (6,729 cm2) efficiencies ≥ 10.5% or best effort.
- Complete second round of ALT (Accelerated Life Test) testing or best effort.

Major Reports Published in FY 1999:

NCPV FY 1998 Annual Report, NREL/BK-210-25626 (June 1999).

Rose, D.H., Powell, R.C, Grecu, D., Jayamaha, U., Hanak, J.J., Bohland, J., Smigielski, K., Dorer, G.L., "Technology Support for High-Throughput Processing of Thin-Film CdTe PV Modules," Phase I Annual Technical Report, NREL/SR-520-27149, 58 pp., Available from NTIS, Springfield, VA 22161 (1999).

Major Articles Published in FY 1999:

Powell, R.C., Jayamaha, U., Dorer, G.L., McMaster, H., "Scaling and Qualifying CdTe/CdS Module Production," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 31-36 (1999).

McMaster, A., Johnson, S., "High-Throughput Manufacturing of Thin-Film CdTe Photovoltaic Modules," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 669-673 (1999).

Powell, R., Dorer, G., Reiter, N., McMaster, H., Cox, S., Kahle, T., "Apparatus and Method for Depositing a Material on a Substrate," U.S. Patent 5,945,163 (Aug. 1999)

Thin Film PV Partnership

CdTe Module Testing and Study of Transients and Irreversible Effects in CdTe Thin-Film Solar Cells

Contract #: XCR-6-16773-01	**Contract Period:** : 05/23/96–11/30/98

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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<tr><td>Directing Organization:
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1996: $30,000 1998: $5,000
1997: $5,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Study the mechanisms of degradation if any in the CdTe PV modules.

Approach/Background: PV Materials Laboratory of FSEC has been studying the durability of PV modules. A small percentage of PV modules tend to degrade slowly in the harsh coastal climate. CdTe thin Film PV modules may be susceptible to degradation in the hot and humid climate. A detailed analysis may be able to point to degradation mechanisms if any of the CdTe thin film PV modules.

Status/Accomplishments: CdTe modules obtained from Solar Cells, Inc., (SCI, recently d.b.a. as First Solar) were connected to a resistor as a fixed load because a replacement could not be found for the problematic maximum-power-point tracker. The following data were collected: voltage, current, irradiance, three back-of-module temperatures, ambient temperature beneath the solar array, atmospheric pressure, wind speed, and relative humidity. The analysis included only data with irradiance values larger than 900 W/m^2. Readings of PV power were normalized to 1000 W/m^2. During the summer months, apparently the normalized power was reduced because of the increasing load mismatch occurring at higher temperatures. Hence the present cycle was continued until September 1998 to verify full power recuperation at lower temperatures. More recent data showed a small reduction in the normalized power. FSEC will continue to monitor this array from time to time to assess the long-term performance of CdTe modules in Florida's climate.

Planned FY 2000 Milestones: project completed

Major Reports Published in FY 1999: Final Report (unpublished)

Major Articles Published in FY 1999: none

Thin Film PV Partnership

$CuIn_{1-x}Ga_xSe_2$ Thin Film Solar Cells

Contract #: XAK-8-17619-12	**Contract Period:** 01/05/98–01/04/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King / Jeffrey Mazer
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1679 Clearlake Road
Cocoa, FL 32952-5703</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 15</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Neelkanth G. Dhere
Phone: 407-638-1442 Fax: 407-638-1010</td></tr>
<tr><td rowspan="2">Technical Monitor:
Bolko von Roedern
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E:mail: bolko_von_roedern</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $31,700
1999: $42,800</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: To develop selenization, sulfurization, and gallium incorporation techniques for the preparation of $CuIn_{1-x}Ga_x Se_{2-y}S_y$ thin films and solar cells. Apply the techniques developed during the study of the durability of crystalline silicon PV modules for the study of thin-film PV modules. Monitor the performance of thin-film PV modules in the hot and humid climate of Florida.

Approach/Background: Attempts made to optimize the bandgap of $CuIn_{1-x}Ga_xSe_2$ (CIGS) thin films by enhancing gallium incorporation resulted in the formation $CuIn_{0.5}Ga_{0.5}Se_2$ and $CuIn_{0.7}Ga_{0.3}Se_2$ phases, however, with poor morphology. Higher efficiencies are expected from $CuIn_{1-x}Ga_xSe_{2-y}S_y$ films having improved morphology and x of ~0.2 by replacing the second selenization by sulfurization and by Na addition in the form of Na_2S. A number of interesting techniques have been developed during study of durability of crystalline silicon PV modules. Some of these will be useful for the improving the durability of thin-film PV modules. Monitoring of thin-film modules in the hot and humid Florida climate will help in identifying any degradation mechanisms.

Status/Accomplishments: A quartz glass set up and a scrubber of H_2S gas have been designed and the components have been installed. A fume hood equipped with H_2S detector is being shared with other projects. $CuIn_{1-x}Ga_xSe_{2-y}S_y$ thin film solar cells have been prepared by replacing the second selenization by sulfurization so as to optimize the bandgap and thus to achieve higher efficiencies. Thin-film PV modules are being monitored at FSEC.

Planned FY 2000 Milestones: Continue testing of the SCI CdTe PV array on the low-bay lab roof of FSEC and other CIGS and a-Si:H thin film PV modules at the FSEC test facility. Continue sulfurization of ISET and other non-vacuum metallic precursors, gallium addition, selenization and Ga activation by heat treatment in nitrogen. Improve the baseline in-house diagnostic cell fabrication process including the sputtering of ZnO bi-layers.

Major Reports Published in FY 1999: Phase 1 Report received (unpublished)

Major Articles Published in FY 1999:

None

Thin Film PV Partnership

Process Development of Large-Area, Thin-Film CIGS Based PV Modules

Contract #: ZAK-8-17619-04	**Contract Period:** 02/05/98–02/04/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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<tr><td>Organization Type: IN</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
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1617 Cole Blvd.
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<tr><td rowspan="2">Technical Monitor:
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E:mail: harin_ullal@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Global Solar Energy, LLC</td></tr>
<tr><td>DOE Funding Allocation:
1998: $503,263
1999: $584,765</td><td>Cost Share Funding:
1998: $115,815
1999: $238,781</td></tr>
</table>

Project Objective: As a technology partner with NREL, Global Solar Energy (GSE) has initiated an extensive and systematic plan to accelerate the commercialization of thin film photovoltaics (PV) based on Copper Indium Gallium Diselenide (CIGS). GSE is developing the technology to deposit and monolithically integrate CIGS photovoltaics on a flexible substrate. CIGS deposited on flexible substrates can be fabricated into either flexible or rigid modules. Attaching the flexible CIGS to an inexpensive rigid panel by lamination or adhesive will produce low cost rigid PV panels for remote power, bulk/utility, telecommunication, and rooftop applications.

The specific objectives of this research and development include optimization of continuous roll-to-roll CIGS deposition processes; development and optimization of novel scribe and interconnect processes for module formation, and viable encapsulation and finishing methods to produce flexible and rigid mounted PV products.

Approach/Background: In the GSE approach, long (up to 700 m) continuous rolls of substrate are processed as opposed to individual small glass plates. Not until final module buss and power lead attachment is the continuous roll sectioned into individual panels. Roll-to-roll vacuum deposition has several advantages that translate directly to reduced capital costs, greater productivity, improved yield, greater reliability, lower maintenance, and a larger volume of PV.

In combination with roll-to-roll processing, GSE is developing evaporation deposition operations that enable low-cost and high-efficiency CIGS modules. In-line multi-source evaporation has been demonstrated at GSE to deposit high-quality CIGS films in a continuous roll-to-roll operation. Multi-source evaporation has other advantages including direct absorber formation (no selenization heat treatment) and high materials utilization of low-cost feedstock.

Status/Accomplishments: A two-pronged effort is underway to transition the CIGS deposition process into manufacturing at GSE. Effusion source development is conducted to improve the deposition uniformity and source robustness through design changes using a 16.5-cm web coater as a test platform. Successful modifications are incorporated into the design of effusion sources for use in a 33-cm manufacturing-scale web coater. As a result of this effort, a set of effusion sources is now installed in the 33-cm web coater that can provide excellent compositional uniformity across the web.

CIGS process development is focused on synchronizing the operation of the effusion sources, the Se delivery profile, substrate temperature, and a host of other parameters. A new GSE record cell efficiency near 10% on polyimide substrate has been achieved in the course of this process development. A program to substitute a stainless steel foil substrate for polyimide was initiated. A stainless steel product was selected and CIGS deposition optimization is proceeding. In the course of this effort, a roll-to-roll CIGS film on stainless steel was fabricated into a device with efficiency 11.5%, verified by NREL. Device yield on single lots processed entirely roll-to-roll have also been characterized. Lots with mean efficiency greater than 8% and standard deviation less than 0.5% are frequently observed.

Contract #: ZAK-8-17619-04

Cell interconnection for thin film CIGS modules on a polyimide substrate presents a considerable challenge. An interconnect scheme has been selected and the equipment necessary to implement this scheme has been procured, installed, and tested. The scheme requires both an ink-jet deposition step and the removal of material by selective laser scribing. Process development is advancing rapidly and significant progress has been made. Continuous, ink-jet lines less than 200µm in width have been demonstrated. The integrity of laser scribes has been verified optically and electrically. Flexible and rigid modules are fabricated from CIGS on stainless steel web from large area cells (60-100 cm^2) wired together using traditional techniques employed in crystalline Si modules. A flexible module with a power output of 20.4W and efficiency 7.6% was demonstrated with this approach.

A primary objective of the GSE lamination program is to begin development of viable encapsulation and finishing methods to produce flexible and rigid mounted PV products. Initial GSE product lines have been defined and several of these initial designs have been demonstrated. Methods for high-throughput lamination have been incorporated into the GSE process. In particular, a four-minute EVA cure is under evaluation. The resulting costs of lamination for a given throughput are projected to be significantly lower than traditional methods utilized in the PV industry. Lead termination techniques have been incorporated, and are expected to provide high-performance, automate-able choices as next-generation development occurs. The primary focus in the next phase of this subcontract will be a multitude of product stressing and certifications. These product certifications are expected to include flexible, semi-flexible, and rigid module products.

Planned FY 1999 Milestones:
Demonstrate process uniformity through fabrication of a matrix of small area cells having an average efficiency of greater than 10% over an area of 900cm^2.
Demonstration of CIGS modules having at least 9% conversion efficiency
Preliminary evaluation of commercially viable concepts for buss and power lead attachment to rigid and flexible PV product.

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).
Britt, J., Wiedeman, S., Wendt, R., Albright, S. (1999) "Process Development for CIGS based Thin Film Photovoltaic Modules," Phase I Technical Report, NREL/SR-520-26840, 32 pp. Available from NTIS, Springfield, VA 22161.

Major Articles Published in FY 1999: None

Optimization of Transparent and Reflecting Electrodes for Solar Cells

Contract #: XAK-8-17619-26	**Contract Period:** : 4/15/98–11/15/98

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	President and Fellows of Harvard College Office of Sponsored Research Holyoke Center 440 Cambridge, MA 02138	
	Organization Type: CU	**Congressional District:** 10
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** R. Gordon **Phone:** 617-495-4017 **Fax:** 617-495-4723	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $ 86,000 1999: $179,000	**Cost Share Funding:**

Project Objective: The objectives of the program are to develop new higher performance, lower cost transparent conductor layers and diffusion barriers for thin-film solar cells, and to work with manufacturers to scale up their deposition processes for commercial production.

Approach/Background: Atmospheric pressure chemical vapor deposition (APCVD) is a cost-effective process already being used in the production of transparent conductive oxide (TCO) layers in thin-film solar cells. Higher optical transparency and lower electrical resistance of these layers will lead to higher efficiency cells. Diffusion barriers between soda-lime glass and the TCO may also lower its electrical resistance. Efficiency may also be increased by placing buffer layers with high electrical resistance between the TCO and the absorbing layers of a cell.

Status/Accomplishments: Harvard developed an APCVD process for zinc stannate. These layers do not have high enough conductivities to be used by themselves as solar cell window layers. They could be useful as buffer layers in a-Si and CdTe solar cells.
The development of improved precursors and processes for the deposition of fluorine-doped zinc oxide (ZnO:F) is continuing.
The use of an amorphous aluminum oxide layer between the ZnO:F and its soda-lime glass substrate to date has not resulted in improved solar cell performance.

Planned FY 2000 Milestones:
Assess the potential for using APCVD zinc stannate films in solar cells.
Optimize the efficiency of amorphous silicon solar cells based on an APCVD process for transparent conducting fluorine-doped zinc oxide.
Develop an APCVD process for “doped” high-resistance tin oxide.

Major Reports Published in FY 1999: Phase 1 Annual Report (unpublished)

Major Article Published in FY 1999: none

Thin Film PV Partnership

Optimization of Processing and Modeling Issues for Thin Film Solar Cells

Contract #: ZAK-8-17619-33	**Contract Period:** 8/24/98–10/23/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Jeffrey Mazer — **Phone:** 202-586-2455 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	Institute of Energy Conversion (IEC) University of Delaware Newark, DE 19716	
	Organization Type: CU	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** R.W. Birkmire **Phone:** 302-831-6220 **Fax:** 302-831-6226	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Institute of Energy Conversion
	DOE Funding Allocation: 1998: $150,000 1999: $1,316,010	**Cost Share Funding:** 1998: $31,579 1999: $328,421

Project Objective: The overall goals are to develop the science and engineering basis needed to: 1) effectively transfer laboratory results to first time manufacturing, and 2) advance performance and manufacturability of thin film solar cells made from $Cu(InGa)(SeS)_2$, CdTe and thin Si materials. The objectives are to develop improved techniques for growth and analysis of semiconductor thin films and devices over large areas at high rates, and to assist industry in transferring laboratory results to economical manufacturing processes while maintaining high efficiencies.

Approach/Background: IEC will develop improved materials with bandgaps from 1.3 t o1.9 eV by alloying with S, and incorporate these CIGSS alloys in dual bandgap tandem cells. IEC will improve TCO/CdS/CdTe devices with thin CdS layers by altering the TCO or device processing; to perform stability tests on a variety of differently deposited CdTe devices and interpret results in terms of back contact and doping; and to optimize alternate Cl treatments. IEC will optimized p-layers, including microcrystalline layers, deposited by plasma CVD; and to explore the growth of large grain polycrystalline Si thin films by hot wire.

Status/Accomplishments: IEC has taken delivery on a new, large-area in-line co-evaporation system for CIS deposition. This purchase was cost-shared between NREL and the Institute. Effusion sources (15 cm wide) were designed and installed. IEC has established the kinetic rates for the replacement of Se with S under various sulfurization/selenization conditions. A CIGS cell with 16.3% (new in-house record) was fabricated. IEC has set up and used a station to stress test CdTe devices under light and elevated temperature exposure, and developed a higher substrate temperature evaporation process for CdTe resulting in larger grain materials. IEC continued to coordinate the evaluation of new transparent conducting layers for a-Si cells and optimized microcrystalline (µc) p-layers. The deposition chemistry for hot-wire deposited µc-Si films has been characterized.

Planned FY 2000 Milestones: Establish state-of-the-art device making capabilities in the large area in-line CIGS system. New back-contacting schemes for CdTe solar cells fabricated both in-house or by other groups will be stress tested and analyzed. An initial pathway to fabricate µc-Si solar cells on glass substrates will be developed. IEC will continue to support national Thin Film Partnership Teams in all programs, and continue to complete devices incorporating materials from other groups.

Major Reports Published in FY 1999: Phase 1 Annual report not yet received.

Contract #: ZAK-8-17619-33

Major Articles Published in FY 1999:

15th NCPV Program Review, American Institute of Physics Conf. Proc. **462** (1999):

1. R. Birkmire and M. Engelmann, "Chemical Kinetics and Equilibrium Analysis of I-III-VI Films," p.23.
2. E. Eser, S.S. Hegedus and W.A. Buchanan, "Preparation and Characterization of Micro-Crystalline Hydrogenated Silicon Carbide p-Layers," p. 254.
3. B.E. McCandless and R.W. Birkmire, "Influence of Processing Conditions on Performance and Stability in Polycrystalline Thin-Film CdTe-Based Solar Cells," p. 182.
4. J.E. Phillips and W.N. Shafarman, "Analysis of $Cu(In,Ga)Se_2$ Solar Cells: Why Performance Decreases with Increasing Ga Content," p. 120.

R. Aparico, A. Pant, and R. Birkmire, "Thin Polycrystalline Silicon Films by HWCVD," NREL/BK-520-26941 (8/1999), p. 152.

Thin Film PV Partnership

CIS-Type PV Device Fabrication by Novel Techniques

Contract#: ZAK-8-17619-10	**Contract Period:** 6/30/98–6/29/01

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Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** B.M. Basol, V.K. Kapur **Phone:** 310-216-4427 **Fax:** 310-216-2908	
Technical Monitor: H. S. Ullal **Phone:** 303-384-6486 **Fax:** 303-384-6430 **E:mail**: harin_ullal@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1998: $275,869 1999: $480,658	**Cost Share Information:** International Solar Electric Technology Inc. (ISET) **Cost Share Funding:** 1998: $10,000 1999: $11,483

Project Objective: The overall objective of this R&D effort is the development of a low-cost non-vacuum deposition technique for the fabrication of high efficiency CIS type devices. The major tasks include improvement of the efficiencies of solar cells fabricated on absorbers grown by the non-vacuum technique, deposition of large bandgap absorbers and fabrication of sub-modules and modules.

Approach/Background: The non-vacuum technique developed at ISET is a “particle deposition” method. In this approach sub-micron size particles with a fixed Cu/III metallic ratio are employed in the formulation of an ink or a paste. The ink is then deposited on the Mo/glass substrate in the form of a thin precursor layer. The precursor is annealed at elevated temperatures (>400 □C) to form a well fused and continuos $Cu\text{-}III\text{-}VI_2$ absorber. The technique offers excellent Cu/III uniformity ratio throughout the absorber layer since this ratio is fixed in the ink which is the source material.

Status/Accomplishments: During this period, most of the efforts were concentrated on the development of sulfur-containing larger-bandgap absorbers. An in-depth analysis of the sulfurization process for CIS absorbers was carried out to understand the mechanism(s) of sulfur distribution in these layers. It was discovered that sulfur distribution is a strong function of the stoichiometry, micro-structure and Ga content in the films. Sulfur diffusion constants in CIS with different Cu/III ratios were experimentally determined. Correlation of solar cell parameters with bulk sulfur and gallium contents was established. Vacuum deposited precursors yielded CIGSS absorbers that were used for the fabrication of 13.7% cells. Precursors deposited by the “particle deposition” method gave cells with 10-11% efficiency with open circuit voltages in the 0.5-0.6 V range. Minimodules were fabricated using CIS and CISS absorbers grown by the non-vacuum technique. A 134 cm^2 device with CIS absorber yielded an efficiency of about 6.3%, whereas a 64 cm^2 minimodule employing a CISS absorber gave about 7% efficiency. Smaller size minimodules yielded efficiencies as high as about 8%.

Planned FY 2000 Milestones: Work will continue to be concentrated on the large-bandgap CIS-type absorber deposition by the non-vacuum technique. Demonstration of submodules with better than 9% efficiency will be targeted during FY 2000. Device stability studies and the study of possible transient effects will be initiated. Various submodule integration approaches will be evaluated with the goal of identifying one that is most suited for the non-vacuum deposition technique. Work will be initiated on a Cd-free buffer layer to replace CdS.

Major Reports Published in FY 1999:

NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Basol, B., Kapur, V., Leidholm, C., Halani, A., Norsworthy, G., and Roe, R. (1999) “CIS-Type PV Device Fabrication by Novel Techniques, ” Final Technical Report, NREL/SR-520-26930, 19 pp. Available from NTIS, Springfield, VA 22161

Contract#: ZAK-8-17619-10

Major Articles Published in FY 1999:

Leidholm, C., et al., "Advances in CIS Devices Fabricated by a Non-Vacuum Technique," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462, pp. 103-108 (1999).

Basol, B., et al., "Efficient CIS Solar Cells Fabricated by a Novel Ink Coating Approach," *Electrochemical and Solid-State Letters* **1**, 252 (1998).

Basol, B., "Low-Cost Techniques for the Preparation of CIGSS Absorber Layers," *The European Materials Conf., E-MRS Spring Meeting, June 1-4, Strasbourg, France,* Proceedings, Paper Ref. O-VII.1 (1999).

Norsworthy, G., et al., "CIS Film Growth by Metallic Ink Coating and Selenization," *Solar Energy Materials and Solar Cells,* in press (1999).

Basol, B., et al, "Studies on Sulfur Diffusion into CIGS Thin Films," *Progress in PV,* in press (1999).

Thin Film PV Partnership

Research on Improved Amorphous Silicon and Alloy Materials and Devices Prepared using ECR Plasma Techniques

Contract #: XAF-8-17619-30	**Contract Period:** 07/01/98–6/30/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King Jeffrey Mazer
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Fax: 202-586-8148 Fax: 202-586-8148
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Ames, Iowa 50011</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 3</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Vikram Dalal
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<tr><td rowspan="2">Technical Monitor:
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E:mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $ 70,000
1999: $222,346</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objectives of this subcontract are to: develop a cost-effective amorphous silicon PV technology to foster a viable amorphous silicon PV industry in the United States. This will be carried out within the context of the research and development sub-Teams established by the NREL/EPRI Thin Film Partnership. The work is focussed on developing higher, performance, more stable a-Si and a-(Si,Ge)solar cells using innovative plasma deposition technology. Ultimately the goal of the Amorphous Silicon Team is to achieve 15% stable thin-film modules by 2005.

Approach/Background: The approach is to use controlled ECR plasma technology to deposit a-Si and a-(Si,Ge) solar cells. In particular, plasma conditions such as radical chemistry and ion bombardment will be varied to study their influence on material and device properties and stability. Both substrate and superstrate type cells will be made.

Status/Accomplishments: Diagnostic solar cells have been prepared using controlled ion bombardment for the preparation of a-(Si,Ge) alloys. ISU prepared device in which the amount of Ge alloying was altered for a portion of the intrinsic layer. From this, it was concluded the Ge alloying changes the conduction band offsets, rather than the valence band offsets. ISU has begun to prepare microcrystalline Si films using Mo-induced crystallization.

Planned FY 2000 Milestones: ISU will assess the benefits of chemical annealing. It will assess whether the ECR deposition technique can indeed grow films that lead to solar cells with greater stabilized efficiency.

Major Reports Published in FY 1999 Phase 1 Annual Report not yet received

Major Articles Published in FY 1999:

1. V. Dalal, "New Directions in amorphous and thin Film Silicon Materials and Devices," 15th NCPV Photovoltaics Program Review; American Institute of Physics Conference Proceedings, **462**, (1999), p. 82.
2. V.L. Dalal et al, MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999), 4 articles, to be published.

Thin Film PV Partnership

Atmospheric Pressure Chemical Vapor Deposition of CdTe for High Efficiency Thin Film PV Devices

Contract#: ZAK-8-17619-03	**Contract Period:** 1/26/98–1/25/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	ITN Energy Systems, Inc. 12401 West 49th Ave. Wheat Ridge, CO 80033	
	Organization Type: IN	**Congressional District:** 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator** P. Meyers **Phone:** 303-285-5135 **Fax:** 303-285-5179	
Technical Monitor: Ullal, H.S. **Phone:** 303 384-6486 **Fax:** 303 384-6430 E:mail: harin_ullal@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** ITN Energy Systems, Inc.
	DOE Funding Allocation: 1998: $198,310 1999: $241,721	**Cost Share Funding:** 1998: $28,033 1999: $17,500

Project Objective: Overall objective is improved thin film CdTe PV manufacturing technology with increased power conversion efficiency. Tasks required to accomplish the overall goal are grouped into 1) development of deposition apparatus and procedures which enable control of film growth over large area and 2) development of advanced measurement and analytical procedures which provide useful and effective device characterization.

Approach/Background: CdTe deposition by Atmospheric Pressure Chemical Vapor Deposition (APCVD) employs the same reaction chemistry as has been used to deposit 16% efficient CdTe PV films (Close Spaced Sublimation) but employs forced convection rather than diffusion as a mechanism of mass transport. APCVD enables discovery of fundamental mass transport parameters which, through application of established engineering principles, can be used to design high throughput, high yield manufacturing equipment. Device analysis will go beyond conventional one-dimensional device characterization and analysis toward two dimension measurements and modeling.

Status/Accomplishments: During Phase II initial CdTe films have been deposited by APCVD providing strong support for the premise that reaction chemistry is the same in both CSS and APCVD films. Based on analysis of the first generation APCVD reactor performance, several modifications and simplifications have been made which are expected to provide improved performance and to result in device quality CdTe films. Framework for a device characterization procedure for two-dimensional device analysis has been established and will be developed during the next year.

Planned FY 2000 Milestones:
- Demonstration of device quality CdTe films.
- Demonstration of 12% power conversion efficiency.
- Presentation of two-dimensional methods for characterization and analysis of device operation on a microscopic scale.

Major Reports Published in FY 1999:
"Atmospheric Pressure Chemical Vapor Deposition of CdTe for High Efficiency Thin Film PV Devices," Annual Report 26 January 1988 – 25 January 1999, NREL/SR-520-26566, P.V. Meyers, R. Kee, C. Wolden, L. Raja, V. Kaydanov, T. Ohno, R. Collins, M. Aire, J. Kestner and A. Fahrenbruch, Sept. 1999.

Major Articles Published in FY 1999:
P. Meyers, "Development of Thin Film CdTe PV Devices," *Twelfth "Sunshine" Workshop on Thin Film Solar Cells Technical Digest*, Aogakukaikan, (M. Konagai organizer) Shibuya, Tokyo, January, 1999.

Thin-Film PV Partnership

In-Situ Sensors for Process Control of $CuInGaSe_2$

Contract#: ZAK-8-17619-08	**Contract Period:** 2/10/98–2/09/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Materials Research Group, Inc.
12441 W. 49th Ave., Suite #2
Wheat Ridge, CO 80033-1927</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 2</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
I.L. Eisgruber
Phone: 303-425-6688 x 15 Fax: 303-425-6562</td></tr>
<tr><td rowspan="2">Technical Monitor:
H.S. Ullal
Phone: 303-384-6486
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E:mail: harin_ullal@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Materials Research Group, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $90,000
1999: $120,000</td><td>Cost Share Funding:
1998: $10,000
1999: $13,333</td></tr>
</table>

Project Objective:
Yield and reproducibility issues must be resolved for thin-film $CuIn(Ga)Se_2$ modules to be manufactured at a price that fulfills the technology's low-cost potential. The purpose of this subcontract is to develop in-situ sensors to improve yield, reproducibility, and efficiency of thin-film $CuInGaSe_2$ modules.

Approach/Background:
In-situ x-ray fluorescence is being used to monitor composition and thickness of deposited layers, and in-situ optical emission spectroscopy is being used to provide real-time feedback describing the deposition plasma. Characterization techniques were examined ex-situ for the initial part of the subcontract, including the investigation of interpretation and equipment issues. Characterization techniques are now being adapted for use in existing deposition systems. The impact of the in-situ characterization on yield and reproducibility will be reported.

Status/Accomplishments:
The composition of the $CuInGaSe_2$ absorber layer is the most critical and sensitive for device performance. Thus, x-ray fluorescence signals from $CuInGaSe_2$ films and their precursor layers have been analyzed first. A low-cost prototype composition sensor based on x-ray fluorescence has been assembled. Critical composition ratios measured by the sensor have been shown to agree with independent composition measurements and with theory. Designs to shield the sensor from the harsh deposition environment without degrading its signal are currently underway.

Planned FY 2000 Milestones:
Implementation of in-situ real-time process control for $CuInGaSe_2$ films, based on the composition sensor developed.

Major Reports Published in FY 1999:
I.L. Eisgruber, T.L. Wangensteen, C. Marshall, B. Carpenter, R. Treece, R. Hollingsworth, G. Patel, J. Ogard, P.K. Bhat, "In-Situ Sensors for Process Control of $CuIn(Ga)Se_2$ Module Deposition," *Phase II FY 1998 Annual Report*, NREL/SR-520-26382, (September 1999).

Major Articles Published in FY 1999:
None.

Thin Film PV Partnership

High Efficiency, Stable Hot Wire CVD Prepared Amorphous and Polycrystalline Silicon Film Solar Cells

Contract #: ZAK-8-17619-16	**Contract Period:** 4/10/98–4/9/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King   Jeffrey Mazer
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E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">MV Systems, Inc.
17301 West Colfax Avenue, Unit 305
Golden, CO 80401</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Arun Madan
Phone: 303-271-9907 Fax: 303-271-9771</td></tr>
<tr><td rowspan="2">Technical Monitor:
K. Zweibel
Phone: 303-384-6441
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E:mail: ken_zweibel@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
MVSystems Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $175,000
1999: $403,000</td><td>Cost Share Funding:
1998: $20,000
1999: $45,000</td></tr>
</table>

Project Objective:
The objective of this R&D contract is to develop a high quality amorphous and micro-crystalline (μc-) Si-based thin film alloy materials by Hot Wire Chemical Vapor Deposition and use these materials to fabricate high efficiency PV devices. The goal at the end of the three-year program is to demonstrate and deliver 12% stable a-Si-based devices and 10% μc-Si based devices.

Approach/Background:
Hot Wire Chemical Vapor Deposition (HWCVD) is important because silicon films can be produced as either amorphous or polycrystalline depending on process conditions; and the amorphous films have exhibited superior stability compared to PECVD films. A-Si:H solar cells with improved stability have been demonstrated by HWCVD, albeit at lower performance value in comparison with the PECVD approach. Micro-crystalline silicon (μc-Si) thin films in a solar cells configuration of moderate efficiency have been reported recently. MVS intends to explore the potential of the HWCVD deposition approach for both a-Si and μc-Si materials and their use in thin film silicon PV devices.

Status/Accomplishments:
The project was started on April 10, 1998. The following has been accomplished: completed the upgrade of a single chamber with the capability of PECVD and HWCVD deposition techniques and completed the following processing and characterization equipment for supporting the material and device research: solar simulator with light and dark J-V measurements, temperature-dependent conductivity measurement, thermal evaporator, and a RF magnetron sputtering system We have developed a new HWCVD approach which allows the fabrication of a-Si materials and μc-Si materials. We have demonstrated PV devices in the Schottky Barrier and p-i-n configurations with (i-layer produced using the HWCVD deposition technique) an efficiency of about 7.5. Post deposition anneal of thick a-Si materials lead to micro-crystalline material with grain size on the order of 170A.

Planned FY 2000 Milestones:
1. Finalize device structure and deposition techniques for fabricating the devices.
2. Finalize the HWCVD-PECVD system configuration.
3. Demonstrate an 8% stabilized efficiency device using a combination of deposition techniques (HWCVD-PECVD) and a combination of μc-Si and a-Si materials.

Major Reports Published in FY 1999:
First Annual Technical report sent to NREL on 10th April 1999.

Contract #: ZAK-8-17619-16

Major Articles Published in FY 1999:
Progress in high deposition rate amorphous and ploycrystalline silicon materials using the pulsed plasma and hot-wire CVD deposition techniques, Arun Madan, Scott Kuwahara, Solar Energy Materials and Solar Cells, 59,51,1999.

Deposition of high quality amorphous silicon by a new "Hot Wire" CVD technique, S. Morrison, Ken Coates, J.Xu, A.Madan. Presented at the MRS Spring Meeting, San Francisco, April 1999.

Thin Film PV Partnership

Characterization of Small Particle Formation in the Preparation of Amorphous Silicon Solar Cells and Determination of the Electric Field Profile in Solar Cells using Scanning Tunneling Microscopy

Contract #: DAD-8-18653-01	**Contract Period:** 07/01/98–09/30/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	National Institute of Standards and Technology Boulder, CO, 80309-0440	
	Organization Type: CU	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Alan C. Gallagher **Phone**: 303-497-3936 **Fax**: 303-492-5235	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $60,000 1999: $93,583	**Cost Share Funding:**

Project Objective: The objectives of this subcontract are to develop a cost-effective amorphous silicon PV technology to foster a viable amorphous silicon PV industry in the United States. This will carried out within the context of two of the research and developments sub-Teams established by the NREL/EPRI Thin Film Partnership. Project Objective: This work will (1) support the National Amorphous Silicon Team with expertise relating to film growth phenomena and nano-size particle formation during deposition of a-Si:H films, and (2) employ a new scanning tunneling microscope (STM) spectroscopic technique to measure the electric field profile in thin-film solar cells. Ultimately the goal of the Amorphous Silicon Team is to achieve 15% stable thin-film modules by 2005.

Approach/Background: Silicon particles inadvertently form within discharges, and deposit into growing a-Si:H films. Measure particle size and density within the discharge and on the substrate, and use this data to model particle growth and escape to the film. The losses in cells occur within many layers and interfaces, and are hard to measure individually. We will measure the apparent potential (AP) versus depth within a cleaved single, tandem and triple cell made from a-Si:H and its alloys.

Status/Accomplishments: NIST has measured particle densities and growth rates within 300 K silane discharges and developed a complete plasma-chemistry model for this growth process. NIST has measured the AP of a single and tandem cell, for one region of a cleaved surface.

Planned FY 2000 Milestones: Continue measurements of particle growth in silane/hydrogen mixtures and at elevated temperatures. Refine a quantitative model for the relationship of the AP and the STM current-voltage relation to the local carrier densities and quasi Fermi levels within the operating cell.

Major Reports Published in FY 1999: Phase 1 Annual Report, draft version received

Major Articles Published in FY 1999:

1. A. Gallagher et al, MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999), 2 articles, on of them by invitation, to be published.

Thin Film PV Partnership

Project Management

Contract#: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Ken Zweibel **Phone:** 303-384-6441 **Fax:** 303-384-6430 **E:mail:** ken_zweibel@nrel.gov	
Technical Monitor: Larry Kazmerski **Phone:** 303-384-6600 **Fax:** 303-384-6601 **E:mail:** larry_kazmerski@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1999: $1,400,000	**Cost Share Funding:**

Project Objectives:

- To support the near-term transition to first-time manufacturing and scale-up of thin film a-Si, CIS, CdTe, and film Si;
- To build a technology base upon which these advanced PV technologies can (1) successfully improve manufacturing and (2) continue to progress in terms of performance, reliability, and reduced cost for products meant to compete in the PV marketplace; and
- To sustain innovation to support progress toward ambitious long-term PV cost and performance goals (i.e., 15% modules @ under $50/m^2$ and capable of lasting 30 years).

Approach/Background:

FY1999 Research Tasks within the Partnership's National R&D Teams

National Team	FY1999 Major Tasks
CIS	Improved Manufacturability, Lower-Temperature CIGS Deposition on Polyimide, Addition of Sulfur to CIS Made by Selenization, Module Transients and Stability, Two-Junction, CIS-Based Cells
a-Si	Improved Multijunction Efficiencies, Improved Stability, Low-Band Gap Alternatives, Increased Deposition Rates without Loss of Performance
CdTe	Contacts, Thin CdS (improved efficiency), and Cell and Module Stability Testing and Protocols
ES&H	Module Recycling, In-Plant Waste Handling, Toxicity Guidelines, Greenhouse gas reduction

Status/Accomplishments:

One of our Technology Partner subcontractors, Siemens Solar Industries (SSI), Camarillo, CA, made a major impact on PV by (1) introducing the CIS technology to the marketplace for the first time; (2) achieving a DOE Five Year Plan Key Milestone for 10% commercial thin film modules; (3) delivering to NREL a 1-kW array of these modules, averaging a staggering 11.4% module efficiency under standard conditions; (4) breaking the world record for the highest efficiency thin film module of *any* kind (12.1%), and (5) topping off this string of achievements by winning (jointly with NREL and the California Energy Commission) a prestigious R&D100 Award for their new CIS module products. The SSI CIS modules are much more efficient than any competing thin film technology, the closest of which are at about 8% efficiency. The achievement of these milestones depended on overcoming technical barriers to cell and module performance; and manufacturability issues such as area uniformity and process reproducibility/yield. These were resolved in partnership with DOE/NREL through SSI's funding support in the Thin Film PV Partnership and its collaborations in the National CIS R&D Team. Several news releases concerning these achievements are available from SSI on request.

Contract#: DE-AC36-98-GO10337

United Solar continued to make substantial technical progress in improving the efficiency of their triple-junction amorphous silicon cells and modules. They reached 10.4% for an amorphous silicon module, the highest such efficiency in the world. United Solar is using the triple-junction technology in their exciting roof-shingle product, which won the R&D100 Award and the Popular Science "Best of" Award last year. Demonstrating the wide usefulness of the roof shingle approach, United Solar also made the most powerful PV module - a 300 W module made on a flexible substrate for use on flat roofs. Progress in the triple junction technology was partially funded by the DOE/NREL Thin Film Partnership, and the efficiency improvement was a special collaborative milestone shared by the Partnership's Amorphous Silicon National R&D Team. United Solar has also previously received DOE/NREL support from PV MaT and PV Bonus.

Two companies, First Solar (Toledo, OH) and BP Solarex (Fairfield, CA) made progress toward the first-time introduction of commercial CdTe modules at the multimegawatt level. First Solar is a joint venture of Solar Cells Inc. As such, First Solar received a significant infusion of capital to build a CdTe plate and module production facility in Toledo. Using their ultra-high rate vapor transport deposition system, the plant is designed for 100 MW annual production of CdTe-coated plates. If completed successfully, it would be the largest PV plant in the world. Shakedown tests are scheduled for early next year. Meanwhile, BP Solarex is in shakedown tests of their 7 MW CdTe production facility in Fairfield. All equipment has been installed, and modules are being fabricated. Both First Solar and BP Solarex are active participants in the Thin Film Partnership and its National CdTe R&D Team. First Solar also receives funding from PV MaT. In contrast with CIS, commercial CdTe modules are expected to be in the 8% range. However, their cost of manufacturing is expected to be less, making them quite competitive in the marketplace on a cost per watt basis.

Planned FY 2000 Milestones:

- Provide timely funding for ongoing contracts (funding actions)
- Achieve an a-Si cell whose i-layers are prepared at rates at or near 10 A/s with a stable total area cell efficiency of 9% (sample)
- Fabricate an approximately 1000 cm^2 flexible CIGS module with aperture area efficiency greater than 6%. All thin films will be deposited using a continuous roll-to-roll process (sample).
- 13% amorphous silicon cell (sample)
- Hold at least one team meeting of each national R&D team (meeting notes)
- Increase a world record module efficiency (any size) of at least one thin film technology (sample)

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626 (June 1999).

Major Articles Published in FY 1999:
K. Zweibel, "Issues in Thin Film PV manufacturing cost reduction," *Solar Energy Materials & Solar Cells 59*, 1999, 1-18.

K. Zweibel, "Thin Film PV Manufacturing: Materials Costs and Their Optimization," *Solar Energy Materials & Solar Cells*, August 1999 (in press).

K. Zweibel, "A Baseline Evaluation of Thin Film a-Si, CIS, and CdTe for the 21st Century," Electrochemical Society Meeting, Seattle, May 1999

K. Zweibel, "Thin Film Photovoltaics," for *Technology's Critical Role in Energy & Environmental Markets*, USAEE/IAEE Conference, Albuquerque, Oct. 1998

Joe Del Cueto and B. Von Roedern, "Temperature-Induced Changes in the Performance of Amorphous Silicon Multijunction Modules in Controlled Light-Soaking," *Progress in PV 7*, 101-112 (1999)

B. Von Roedern, "Materials Requirements for Buffer Layers Used to Obtain Solar Cells with High Open-Circuit Voltages," *Materials Research Society* 557 (1999).

Thin Film PV Partnership

Stable a-Si:H Based Multijunction Solar Cells with Guidance from Real Time Optics

Contract #: XAF-8-17619-22	**Contract Period:** 07/17/98–9/16/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 — **E:mail:** Richard.King@ee.doe.gov Jeffrey Mazer — **Phone:** 202-586-2455 — **Fax:** 202-586-8148 — **E:mail:** Jeffrey.Mazer@ee.doe.gov	The Pennsylvania State University University Park, PA 16802 **Organization Type**: CU	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Christopher R. Wronski — **Phone:** 814-865-0930 — **Fax:** 814-863-5341 Robert W. Collins — **Phone:** 814-865-3059 — **Fax**: 814-865-2326	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax**: 303-384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $175,000 1999: $159,000	**Cost Share Funding:**

Project Objective: The objectives of this subcontract are to: develop a cost-effective amorphous silicon PV technology to foster a viable amorphous silicon PV industry in the United States and help the U.S. amorphous silicon PV industry to be competitive by enhancing performance and cost-efficiency, e.g., by using higher deposition rates. An important aspect is to improve the understanding of the details of all mechanisms limiting device performance. The advantages of using new materials preparation schemes, material and device characterization schemes, and device modeling schemes will be documented.

Approach/Background: Develop processing schemes for fabrication of high performance, stable a-Si:H based multijunction solar cells with guidance from real time optics and detailed characterization of materials and device structures.

Status/Accomplishments: Using real time optics characterized the growth, microstructure and amorphous/microcrystalline phase boundaries in protocrystalline thin film materials. Established a "protocrystalline" growth regime using spectroscopic ellipsometry. Cells with a protocrystalline thin intrinsic layer at the p/I interface exhibit larger open-circuit voltages and less light-induced degradation. PennState obtained stable a-Si:H solar cells including 1900 Å intrinsic layers with fill factors of 0.70 in the degraded state. PennState collected detailed data on the degradation kinetics of solar cells and materials. PennState is the only US amorphous silicon group invited by NEDO/PVTEC to participate in their 1999 international collaborative program.

Planned FY 2000 Milestones: Develop novel higher stability, efficient solar cell structures based materials at the amorphous side of the boundary between the amorphous and microcrystalline structure. Contribute to better understand the light induced degradation (publish paper)

Major Reports Published in FY 1999: Phase 1 draft Annual Report received

Major Articles Published in FY 1999:

C.R. Wronski and/or R.W. Collins et.al., MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999), 7 articles, to be published..

Thin Film PV Partnership

CIS and CdTe Based Tandem Solar Cell Studies using AMPS

Contract #: XAF-8-17619-35	**Contract Period:** 10/15/98–10/14/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King — Phone: 202-586-1693 — Fax: 202-586-8148
Jeffrey Mazer — Phone: 202-586-2455 — Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Pennsylvania State University
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University Park, PA 16802</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
S.J. Fonash
Phone: (814) 865-4931 Fax: (814) 865-3018</td></tr>
<tr><td rowspan="2">Technical Monitor:
Bolko von Roedern
Phone: (303) 384-6480
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E:mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
EPRI (“Special Topic”)</td></tr>
<tr><td>DOE Funding Allocation:
1999: $50,000</td><td>Cost Share Funding:
1999: $50,000</td></tr>
</table>

Project Objective: To provide modeling support for the Thin-Film Partnership’s CIS and CdTe PV cell and module development effort using the “AMPS” code previously developed at PennState University

Approach/Background: The model will be used to understand the performance limiting mechanisms of polycrystalline solar cells. PennState will assist with the development of realistic parameter sets used for modeling. Specific emphasis is on assessing the performance of tandem polycrystalline solar cells, where the model is use to predict the performance of multijunction devices based on data obtained on component cells.

Status/Accomplishments: During Phase 1, PennState worked largely on understanding the transient phenomena (reversible changes) observed in the performance of CIS solar cells. The model suggested that experimentally observed changes in the device capacitance cannot account for the changes in device performance. Self consistency check were carried out to see how realistic the presently used set of input parameters for CIS solar cells is.

Planned FY 2000 Milestones: Provide modeling support as needed. Better identify the mechanism responsible for transient effects in CIS solar cells. Model the performance decrease that is experimentally observed in wider bandgap CI(G)S(S) alloys. Need to evaluate possible reductions of scope due to possible lack of EPRI cost-sharing.

Major Reports Published in FY 1999: Phase 1 Annual Report not yet due.

Major Articles Published in FY 1999:

H.Zhu, A. K. Kalkan, J. Hou, and S.J. Fonash, “Application of AMPS-1D for Solar Cell Simulations,,” 15th NCPV Program Review Meeting, American Institute of Physics Conference Proceedings 462, (1999) p.309.

Thin Film PV Partnership

Numerical Modeling as a Tool for Analyzing Thin-Film Solar Cells

Contract #: XAK-8-17619-36	**Contract Period:** 12/07/98–12/06/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King — Jeffrey Mazer **Phone:** 202-586-1693 — **Phone:** 202-586-2455 **Fax:** 202-586-8148 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Purdue University 1285 Electrical Engineering Building West Lafayette, IN 47907-1285 **Organization Type**: CU	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J.L. Gray **Phone:** (765) 494-3390 **Fax:** (765) 494-3393	
Technical Monitor: Bolko von Roedern **Phone**: (303) 384-6480 **Fax**: (303) 384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $ 37,000	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: To provide modeling support for the Thin-Film Partnership's CIS and CdTe PV cell and module development effort using the "ADEPT" code previously developed at Purdue University.

Approach/Background: The model will be used to simulate junction properties of CIS and CdTe cells, with a focus on understanding transients and stress induced degradation. The model will be maintained to enhance user friendliness, capabilities, and to update it to run in improved hardware and software environments.

Status/Accomplishments: Parameter sets for the modeling of CdTe cells have been established. A MatLab (commercial software) ADEPT toolbox has been created. The 2-dimensional version of the ADEPT code has been reworked. Modeling schemes include simulations of the capacitance response of a CdTe cell. This requires proper consideration of the recombination and generation statistics for electrons and holes at each trapping level.

Planned FY 2000 Milestones: Test the consistency of the model by comparing experimental and simulation results. This work will focus on cases where distinct changes were made in device processing, for example, when modeling CdTe or CIS devices prepared without the usual CdS heterojunction layer.

Major Reports Published in FY 1999: none (not due until 12/99)

Major Articles Published in FY 1999: -

Thin Film PV Partnership

Commercialization of CIS-Based Thin-Film PV

Contract #: ZAK-8-17619-19	**Contract Period:** 9/25/98–11/24/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	Siemens Solar Industries 4650 Adohr Lane Camarillo, CA 93010	
	Organization Type: IN	**Congressional District:** 23
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Dale E. Tarrant **Phone:** 805-388-6328 **Fax:** 805-388-6580	
Technical Monitor: H.S. Ullal **Phone:** 303-384-6486 **Fax:** 303-384-6430 **E:mail:** harin_ullal@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Siemens Solar Industries
	DOE Funding Allocation: 1999: $795,354	**Cost Share Funding:** 1999: $795,353

Project Objective: The primary objectives of this subcontract are to scale-up substrate size and to increase production capacity of the baseline SSI CIS-based module process while introducing SSI's first CIS-based products. An additional mid- to longer-term objective is to advance CIS based thin-film technology thereby assuring future product competitiveness by improving module performance, cost per watt produced, and reliability. These combined objectives are pursued to fabricate efficient and stable thin-film modules made by scaleable, manufacturable, low-cost techniques.

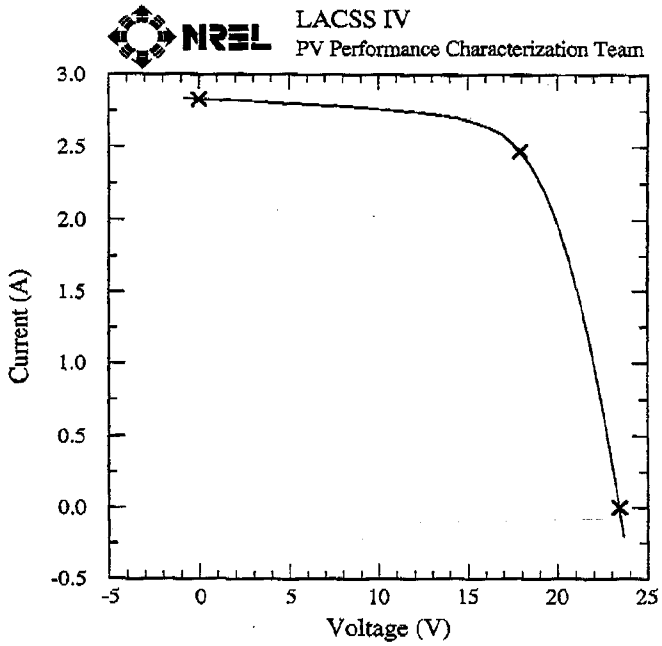
Approach/Background: SSI is applying systematic research, development, production and business methodologies to a carefully planned substrate size and capacity scale-up of CIS-based thin-film technology. These methodologies include Statistical Process Control (SPC), Analysis of Variation (ANOVA), and Design of Experiments (DOE) --- approaches widely recognized as appropriate for manufacturing businesses. SSI is also conducting research and development on longer-term issues in support of SSI's ongoing commitment to improve this technology. SSI is independently and in conjunction with TFPPP team activities pursuing improved understanding of processes, devices, and materials. SSI's role in advancing mid- to longer-term CIS technology emphasizes issues related to commercialization of CIS technology and assured future product competitiveness.

Status/Accomplishments: Siemens Solar is the first company in the world to start production of PV modules based on CIS thin-film technology. This is a major milestone in the development of PV. First available as 5-Watt and 10-Watt modules in 1998, this year R&D Magazine recognized the significance of this event by awarding the prestigious R&D 100 Award to the Siemens Solar family of CIS solar modules. This award is shared by NREL, the California Energy Commission and SSI.

Deliverables for this subcontract phase were defined as 900-cm^2 (~1-ft^2) CIS-based commercial modules with AM 1.5 aperture-area efficiency of 10%. The specification for these commercial modules is most closely matched by the 10-Watt "ST10" module. However, activities during this subcontract period led to the availability of larger commercial products with higher efficiencies than anticipated at the time the deliverables were defined. SSI expanded the CIS product line in 1999 to include 20-Watt "ST20" modules and 40-Watt "ST40" modules that were delivered to NREL during this subcontract phase.

Record breaking efficiencies of more than 12 percent (figure below) were verified by NREL for an ST-40 module. Achieved in advance of DOE milestone for the year 2000, SSI accomplishments demonstrate that CIS meets and should continue to meet the DOE goals. Remaining R&D challenges are to scale processes to even larger areas, to reach higher production capacity, to demonstrate in-service durability over even longer times, and to advance the fundamental understanding of CIS-based materials and devices with the goal of further efficiency improvements for future products.

Contract #: ZAK-8-17619-19



	Module	per Cell	
Pmax	44.3		W
Eff	12.1		%
Voc	23.4	0.558	V
Isc	2.8		A
Jsc		32.5	mA/cm^2
FF	66.9		%
Area	3651	86.9	cm^2

Planned FY 2000 Milestones: The primary goals of this subcontract are to scale the substrate size from approximately 900 cm^2 (~1 ft^2) to approximately 4000 cm^2 by the middle of the Phase II, and to achieve pilot production rates of 500 kW per year by the end of Phase III. Deliverables for the subcontract include CIS-based products and representative modules delivered to the NREL Module Testing Team for outdoor testing and evaluation. SSI will continue mid-term and longer-term thin-film R&D with the goals of:

- Assuring future product competitiveness
- Improving module performance
- Reducing cost per watt
- Assuring product reliability

Major Reports Published in FY 1999:

D. Tarrant, R. Gay, "Thin-Film Photovoltaic Partnership Program - CIS-based thin film PV Technology. Final Technical Report, September 1995 through December 1998," (October 1999) NREL report NREL/SR-520-27148.

D. Tarrant, R. Gay, "Thin-Film Photovoltaic Partnership Program - CIS-based thin film PV Technology. Phase 2 Technical Report, October 1996-October 1997," (May 1998) NREL report NREL/SR-520-24751.

Major Articles Published in FY 1999:

Dennis Willett, "Siemens CIS Module Reliability Testing," 1998 Photovoltaic Performance and Reliability Workshop, Cocoa Beach, Florida, November 3-5, 1998.

R. D. Wieting, "CIS Product Introduction: Progress and Challenges," National Center for Photovoltaics Program Review Meeting, Denver, Colorado, September 9, 1998, to be published in *AIP Conference Proceedings*.

R. D. Wieting, "Experience and Developments in Manufacturing of CIS Products," 12th Sunshine Workshop, Tokyo, Japan, January 28, 1999.

Thin Film PV Partnership

Electroabsorption and Transport Measurements and Modeling Research in Amorphous Silicon Based Solar Cells

Contract #: XAK-8-17619-23	**Contract Period:** 3/24/98–3/23/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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Richard King Jeffrey Mazer
Phone: 202-586-1693 Phone: 202-586-2455
Fax: 202-586-8148 Fax: 202-586-8148
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E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Syracuse University
Department of Physics
Syracuse, NY 13244-1130</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 25</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Eric A. Schiff
Phone: 315-443-3901 Fax: 315-443-9103</td></tr>
<tr><td rowspan="2">Technical Monitor:
Bolko von Roedern
Phone: 303-384-6480
Fax: 303-384-6531
E:mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: : $75,000
1999: $130,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The primary objective of this project is to improve the understanding of the factors which limit the open-circuit voltage of amorphous silicon based solar cells; it should be noted that the open-circuit voltages achieved to date are only about 60% of the electrical bandgap in this class of cells. The second objective is to improve the understanding of photocarrier transport in amorphous silicon and related materials.

Approach/Background: The experimental approach to understanding open-circuit voltages (V_{OC}) will emphasize built-in potential (V_{bi}) estimates using electroabsorption techniques. In conjunction with this experimental work a program of computer modeling emphasizing the open-circuit voltage will be carried through, with a particular emphasis on marrying the modeling with the best available parameters from experiments at Syracuse University and elsewhere. Transport measurements will emphasize determination of hole and electron drift-mobilities in advanced materials and devices using the photocarrier time-of-flight technique. Improvements in the technique will be carried through to improve measurement capabilities in solar cells, thus avoiding the ambiguities and inconvenience associated with specially-prepared mobility test structures.

Status/Accomplishments: The Syracuse group continued to characterize samples of interest to the amorphous silicon device community using time-of-flight, electroabsorption and modeling techniques. Material prepared at Pennsylvania State University with high hydrogen dilution was found to have slightly lower electron and slightly higher hole drift mobilities than "standard" a-Si:H material. Syracuse University continues to evaluate the role of hydrogen with respect to light-induced degradation. The website set up for modeling has been updated.

Planned FY 1999 Milestones:
Continued characterization of new a-Si:H and a-SiGe:H materials as required by other members of the NREL national team.
Continued AMPS modeling work geared at understanding the mechanisms limiting V_{OC}.
Continued contribution towards understanding light-induced degradation of a-Si:H-based materials

Major Reports Published in FY 1999: Phase 1 Annual Report, Final version received

Major Articles Published in FY 1999:

E.A.Schiff et al, MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999), 3 articles, to be published.
To be Published, Proceeding of 18th Int. Conf. On Amorphous and Microcrystalline Semiconductors (ICAMS-18), Snowbird, UT (August 1999), published as special issue of Journal of Non-Crystalline Solids: (a) J. Lyou, N. Kopidakis, and E.A. Schiff, "Charge Modulation Spectra in Phosphorus Doped a-Si:H;" (b) N. Kopidakis and E.A. Schiff, "Hydrogen -mediated Models for Metastability in a-Si:H: Role of Dihydride bonding.

Thin Film PV Partnership

High-Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology

Contract#: ZAK-8-17619-09	**Contract Period:** 03/06/98–3/05/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	United Solar Systems Corp. 1100 West Maple Road Troy, MI 48084	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** S. Guha **Phone:** 248-362-4170 **Fax:** 248-362-4442	
Technical Monitor: K. Zweibel **Phone:** 303-384-6441 **Fax:** 303-384-6430 **E:mail**: ken_zweibel@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** United Solar Systems Corp.
	DOE Funding Allocation: 1998: $892,000 1999: $879,000	**Cost Share Funding:** 1998: $892,000 1999: $879,000

Project Objective:

To obtain high efficiency amorphous silicon (a-Si) alloy multijunction cells and modules with low manufacturing cost and high reliability. The program goal is to obtain 12% stable modules that will qualify IEEE-Std 1262-1995 reliability testing.

Approach/Background:

Using a spectral-splitting, triple-junction structure, we have achieved world-record stabilized total-area cell and aperture-area module efficiencies of 12.0% and 10.2%, respectively. We are also operating a production line with an annual capacity of 5 MW using the triple-junction approach. We shall further improve efficiency by optimizing the component cells of the triple-junction structure and lower manufacturing cost by depositing the cells at higher rates. We shall also carry out fundamental studies to improve our understanding of a-Si alloy materials and cells.

Status/Accomplishments:

- Modules with initial aperture-area efficiencies of ~12% have been light soaked at NREL. After 1000 hours of one-sun light soaking at 50 ^{o}C, the highest stabilized aperture-area module efficiency is 10.5%. This is the highest efficiency confirmed to date for amorphous silicon alloy modules, and met the Phase I program goal.
- Triple-junction cells with initial total area efficiency of 13.5% have been sent to NREL. After confirmation of the efficiency, light soaking will be carried out at United Solar.
- We have established that materials and solar cells made near the amorphous-to-microcrystalline transition exhibit better quality and stability. Optimum conditions for growing the material depends on the substrate on which the film is grown and also on the thickness of the film. This 'on the edge' material has stirred much interest in the scientific community and stimulated many activities in the field.
- Extensive experiments are in progress to obtain a better understanding of the degradation in the quality of material and cells as the deposition rate is increased. a-Si alloy top cells have been deposited at 3-10 Å/sec which show comparable quality to those deposited at lower rates. Optimization of a-SiGe alloy solar cells deposited at high rates is under way.
- We have been collaborating with several universities and with NREL as part of the a-Si team effort to obtain a better understanding of materials and cells.

Planned FY 2000 Milestones:

- Triple-junction modules with stabilized aperture-area efficiency of 11.0%.
- Triple-junction cells deposited at 3-5 Å/s showing total-area stabilized efficiency of 11.1%.

Contract#: ZAK-8-17619-09

Major Reports Published in FY 1999:

Guha, S. (1999). "High Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology," Annual Technical Progress Report, Subcontract No. ZAK-8-17619-09, 69 pp.

Major Articles Published in FY 1999:

Guha, S., Yang, J., Williamson, D.L., Lubianiker, Y., Cohen, J.D., and Mahan, A.H., "Structural, defect, and device behavior of hydrogenated amorphous Si near and above the onset of microcrystallinity," *Appl. Phys. Lett.* **74**, 1860 (1999).

Banerjee, A., Yang, J., and Guha, S., "Optimization of high efficiency amorphous silicon alloy based triple-junction modules," *MRS 1999 Spring Meeting Proceedings; April 5-9, 1999, San Francisco, CA* (to be published).

Yan, B., Yang, J., Guha, S., and Gallagher, A., "Analysis of plasma properties and deposition of amorphous silicon alloy solar cells using very high frequency glow discharge," *MRS 1999 Spring Meeting Proceedings; April 5-9, 1999, San Francisco, CA* (to be published).

Yang, J. and Guha, S., "Amorphous silicon alloy materials and solar cells near the threshold of microcrystallinity," *MRS 1999 Spring Meeting Proceedings; April 5-9, 1999, San Francisco, CA* (to be published).

Lyou, J.H., Kopidakis, N., Schiff, E.A., Guha, S., and Yang, J., "Electroabsorption spectra and built-in potentials in amorphous silicon-germanium alloy solar cells," *MRS 1999 Spring Meeting Proceedings; April 5-9, 1999, San Francisco, CA* (to be published).

Lyou, J.H., Kopidakis, N., Schiff, E.A., Guha, S., and Yang, J, "Infrared electroabsorption spectra in amorphous silicon solar cells," *MRS 1999 Spring Meeting Proceeding; April 5-9, 1999, San Francisco, CA* (to be published).

Mahan, A.H., Beyer, W., Williamson, D.L., Yang, J., and Guha, S., "An explanation for the low temperature H evolution peak in a-Si:H deposited 'on the edge of crystallinity'," *ICAMS 18 Proceedings; August 23-27, 1999, Snowbird, Utah* (to be published).

Palinginis, K.C., Cohen, J.D., Yang, J., and Guha, S., "Defect bands in a-Si-Ge:H alloys with low Ge content," *ICAMS 18 Proceedings; August 23-27, 1999, Snowbird, Utah* (to be published).

Lubianiker, Y., Cohen, J.D., Williamson, D.L., Lubarsky, G., Rosenwaks, Y., Yang, J., and Guha, S., "Structural and electronic properties of optimized a-Si:H films," *ICAMS 18 Proceedings, August 23-17, 1999, Snowbird, Utah* (to be published).

Guha, S. and Yang, J., "Science and technology of amorphous silicon alloy photovoltaics," *IEEE Trans. Electron Devices* **46**, 2080 (1999).

Thin Film PV Partnership

Photocharge Transport and Recombination Measurements in Amorphous Silicon Films and Solar Cells by Photoconductive Frequency Mixing

Contract #: XAK-8-17619-24	**Contract Period:** 4/20/98–7/05/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King   Jeffrey Mazer
Phone: 202-586-1693   Phone: 202-586-2455
Fax: 202-586-8148   Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Regents of the University of California
405 Hilgard Ave.
Los Angeles, CA 90024-1406</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 29</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
R. Braunstein
Phone: 310-825-1841 Fax: 310-206-5668</td></tr>
<tr><td rowspan="2">Technical Monitor:
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Phone: 303-384-6480
Fax: 303-384-6531
E:mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $43,500</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The first objectives of this project is to directly measure the transport properties of amorphous silicon layers used in solar cells and to improve the understanding how these properties change under light-soaking and as the deposition conditions are altered.

Approach/Background: By employing our well established photomixing technique, analysis of the transport properties of amorphous silicon layers and devices are performed. The deduction of the transport parameters directly from photomixing measurements will be attempted. UCLA will work on improving the theories of transport phenomena in disordered materials. Films of interest to the NREL/EPRI amorphous silicon team will be measured and light-soaked as needed.

Status/Accomplishments: Further systematic photomixing studies were carried out on a-Si:H materials promising greater stability upon light-soaking. Using a specialized sample, UCLA investigated the photomixing signals in both sandwich and coplanar configurations. UCLA also characterized microcrystalline Si films.

Planned FY 2000 Milestones: Films deposited by ECR remote plasma deposition, hot-wire deposition, and hydrogen diluted rf plasma deposition will be characterized in the annealed and light-soaked states using the photomixing technique and the results will be compared to standard a-Si. A better understanding of the similarities and differences of the transport properties in amorphous and microcrystalline materials will be developed.

Major Reports Published in FY 1999: Phase 1 Annual Report received

Major Articles Published in FY 1999:

1. Yi Tang, Shirung Dong, G.S. Sun, R. Braunstein, and B. von Roedern, "Determination of the built-in electric field near contacts to polycrystalline CuInSe2–Probing Local Charge Transport Properties by Photomixing," 15th NCPV Photovoltaics Program Review; American Institute of Physics Conference Proceedings **462**, (1999), p. 109.
2. A. Kattwinkel, R. Braunstein, and Q. Wang, "Transition from Hydrogenated Amorphous Silicon to Microcrystalline Silicon, MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999), to be published.

Thin Film PV Partnership

Future CIS Manufacturing Technology Development

Contract #: XAK-8-17619-32	**Contract Period:** : 7/8/98–7/7/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King Jeffrey Mazer **Phone:** 202-586-1693 **Phone:** 202-586-2455 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Chemical Engineering Department, University of Florida (UF) P.O. Box 116005 Gainesville, FL 32605	
	Organization Type: CU	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** T.J. Anderson **Phone:** 352-392-0882 **Fax:** 352-392-9513	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E:mail:** bolko_von_roedern@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $105,000 1999: $228,000	**Cost Share Funding:**

Project Objective: The objective of this project is to develop improved processing schemes for the fabrication of $CuInSe_2$-based solar cells. Equally important is the advancement of our understanding of the important thermochemical and structural properties of the absorber material, as well as the mechanisms of thin film growth and recrystallization. The objective will be accomplished through innovative material and device preparation methods, modeling of the chemical reaction pathways, comparison of deposition control schemes, and using characterization techniques to correlate film properties and device performance.

Approach/Background: A team of researchers from 3 disciplines is working to demonstrate a process for rapid fabrication of CIS absorber layers which is suitable for the manufacture of high efficiency thin film modules. This process first deposits a thin ‘seed’ layer of large grain size CIS at low rate by a migration enhanced process, followed by high rate deposition of a mixed phase precursor material using a plasma assisted process. An analysis of the phase equilibria in the Cu-In-Se system has suggested the use of stacked binary compounds of CuSe, Cu_3Se_2 or $CuSe_2$ and InSe, In_6Se_7 or In_4Se_3 will produce a low temperature liquid phase to assist in the formation of large grain size CIS films. This work will verify the approach in CIS, extend it to CIGS, explore the use of Rapid Thermal Processing (RTP) and implement advanced process control strategies. The project will also investigate the use of the alternative buffer layer materials In_x (OH,S) and Mg(S,Se).

Status/Accomplishments: UF continued to grow a variety of CIS compositions using the binary compound layered precursor structure. RTP of selected film structures has resulted in the formation of the $CuInSe_2$ phase. Progress was made to improve the control of the deposition process. UF delivered to NREL an epitaxial $CuInSe_2$ film grown on a (111) SrF_2 substrate. Depositions of ZnO films were carried out with an attempt to optimize the carrier mobilities.

Planned FY 2000 Milestones: Milestones include the fabrication of CIS PV devices from stacked binary compound precursor films using RTP, establishing a CBD process for depositing MgSe and Inx(OH,S) films on, implement improved signal filtering and autocalibration for the flux sensors, assess the Ga-Se phase diagram, and complete software for predicting flux distribution and a Kalman observer. UF will assist CIS PV companies in implementing CIS film deposition control strategies.

Major Reports Published in FY 1999: Phase 1 Annual Report not yet received

Major Articles Published in FY 1999:

1. C.-H. Chang, A.A. Morone, B.J. Stanbery, C. McCreary, M. Huang, C.-H. Huang, S.S. Li and T.J. Anderson, "Growth and Characterization of CdS Buffer Layers by CBD and MOCVD," 15th NCPV Photovoltaics Program Review Meeting, American Institute of Physics Conference Proceedings 462 (1999) p. 114.

Thin Film PV Partnership

Properties of Wide-Gap Chalcopyrite Semiconductors for Photovoltaic Applications

Contract #: XAK-8-176193-04	**Contract Period:** 7/16/98–7/15/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King Jeffrey Mazer
Phone: 202-586-1693 Phone: 202-586-2455
Fax: 202-586-8148 Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">University of Illinois
1-107 ESB, 1101 Springfield Ave.
Urbana, IL 61801</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 15</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
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Bolko von Roedern
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E:mail: bolko_von_roedern@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Electric Power Research Institute.
3412 Hillview Ave., P.O. Box 10412
Palo Alto, CA 94303</td></tr>
<tr><td>DOE Funding Allocation:
1998: $16,000
1999: $40,750</td><td>Cost Share Funding:
1998: $32,000
1999: $74,000</td></tr>
</table>

Project Objective: The objectives of this project are to obtain fundamental understanding of wide-gap chalcopyrite semiconductors and photovoltaic devices. Information to be obtained includes significant new fundamental materials data necessary for accurate modeling of single and tandem-junction devices, new information on the basic materials science of wider-gap chalcopyrite semiconductors to be used in next-generation devices, and practical information on the operation of devices incorporating these materials.

Approach/Background: Thin-film epitaxial and polycrystalline layers of $Cu(In,Ga)(S,Se)_2$ will be produced and characterized. Deposition will use a hybrid sputtering and evaporation method shown previously to produce high-quality epitaxial layers of $Cu(InGa)Se_2$. Initial depositions of sulfide alloys will produce polycrystalline materials for purposes of rough stoichometry and deposition temperature determination. Upon satisfactory results on glass, we will switch to GaAs substrates and increase the deposition temperature consistent with our experience on deposition of selenides. We will characterize the layers using a wide array of state-of-the-art optical, electrical, microchemical and microstructural analysis available at the University of Illinois. These techniques will also be provided to assist members of the National CIS Team of which, through this contract, we are a member. We plan to determine the fundamental properties of $Cu(In,Ga)(S,Se)_2$ semiconductors as a function of composition and deposition conditions. Further, we plan to produce solar cells from these materials and determine the factors limiting performance of the devices based on analysis of the materials and device results.

Status/Accomplishments: U. Illinois successfully grew epitaxial CIS materials on GaAs substrate. Diagnostic devices were fabricated in collaboration with IEC. It was possible to achieve a reasonably well performing back contact to the GaAs. Valuable analytical services were provided to other CIS team members.

Planned FY 2000 Milestones: Continue characterization of CIS based devices in term of defects. Compare device results of the epitaxial devices with standard polycrystalline devices to assess the role of polycrystallinity and grain boundaries on device performance. It may be necessary to negotiate a reduction in the scope of this work, because EPRI may not be able to provide the cost share funding originally negotiated.

Major Reports Published in FY 1999: not yet received

Contract #: XAK-8-176193-04

Major Articles Published in FY 1999:

1. A. Rockett, "The Electronic Effects of Point Defects in Cu(Inx,Ga1-x)Se2 Devices," 15th NCPV Photovoltaics Program Review; American Institute of Physics Conference Proceedings **462**, (1999), p. 132.

2. M. Bodegård, K. Granath, L. Stolt, and A. Rockett, "The Behavior of Na Implanted Into Mo Thin Films During Annealing," Solar Energy Mater. and Solar Cells **58(2)**, 199-208 (1999).

3. A. Rockett, K. Granath, S. Asher, M.M. Al Jassim, F. Hasoon, R. Matson, B. Basol, V. Kapur, J.S. Britt, T. Gillespie and C. Marshall, "Na Incorporation in Mo and CuInSe2 from Production Processes," Solar Energy Materials and Solar Cells **59(3)**, pp 255-264 (1999).

4. A. Rockett, R.N. Bhattacharya, C. Eberspacher, V. Kapur, and S.-H. Wei, "Basic Research Opportunities in Cu-Chalcopyrite Photovoltaics," J. Electrochem. Soc., in press.

5. A. Rockett, "Electronic Effects of Point Defects in $Cu(In_xGa_{1-x})Se_2$," Thin Solid Films, in press and, Proc. of the E-MRS, June, 1999, CD ROM format, in press.

Thin Film PV Partnership

Search for Factors Determining the Photodegradation in High-Efficiency a-Si:H-based Solar Cells

Contract #: XAK-8-17619-11	**Contract Period:** 1/16/98–1/15/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
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Chapel Hill, NC 27599-3255</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 4</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Daxing Han
Phone: (919)-962-5002 Fax: (919)-962-0480</td></tr>
<tr><td rowspan="2">Technical Monitor:
Bolko von Roedern
Phone: 303-384-6480
Fax: 303-384-6531
E:mail: bolko_von_roedern</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $101,250
1999: $136,750</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this work is to develop improved understanding of carrier collection and open-circuit voltage limitations of a-Si:H-based solar cells. These limitations will be described in terms of transport properties and recombination losses via midgap and tail-state defects. The work will verify or disprove the role of hydrogen diffusion as the cause of the metastability.

Approach/Background: Study a-Si:H-based materials and devices using the following spectroscopies: (1) Electroluminescence (EL) Spectroscopy; (2) Internal Electric Field Profile, Ei(x), using a null-current technique to measure the interface electric field profile in p-i-n solar cells; (3) Photothermal Bending Spectroscopy (PBS) as an innovative techniques to characterize the complex photodegradation mechanisms; (4) Nuclear Magnetic Resonance (NMR) and MQ NMR to study the hydrogen microstructure and its dynamics.

Status/Accomplishments: UNC has contributed detailed Raman and PL-evaluations of films grown near the transition from amorphous to microcrytalline film structure. Films made close to this transition exhibit reduced light-induced degradation. It is well known that the transition of amorphous to microcrystalline film structure is substrate and film thickness dependent. NMR results suggest that the hydrogen resonance of the narrow line originates from hydrogen originally associated with the broad line. The experimental evidence of photo-structural changes of a-Si has been further confirmed. There is no one-for-one correlation between such structural changes and Staebler-Wronski Degradation.

Planned FY 1999 Milestones: (1) Complete a detailed characterization of H-motion, -bonding, and light-induced changes in hot-wire material in comparison to glow discharge material; (2) Establish the feasibility to detect hydrogen motion in a-Si:H by measuring NMR spectra above room temperature; (3) Establish the null-current forward bias transient method to separate degradation of the bulk absorber region and of the junction regions.

Major Reports Published in FY 1999: Phase 1 Annual report, NREL/SR-520-26522 (5/1999)

Major Articles Published in FY 1999:

1. Daxing Han, T. Gotoh, M. Nishio, T. Sakamoto, S. Nonomura, S. Nitta, Q. Wang, E. Iwaniczko, and A.H. Mahan, "Photo-induced Structure Metastability and the Staebler-Wronski Effect in a-Si:H," 15th NCPV Photovoltaics Program Review; American Inst. of Physics Conf. Proc., 462, 260 (1998).
2. Daxing Han, et.al., MRS Symp. Proc. Vol 557 (Material Research Society Spring Meeting, 1999), 3 articles, to be published.

Thin Film PV Partnership

Identifying Electronic Properties Relevant to Improving Stability in a-Si:H Based Cells and Overall Performance in a SiGe:H Based Cells

Contract #: XAF-8-17619-05	**Contract Period:** 1/16/98–1/15/02

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King   Jeffrey Mazer
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Eugene, OR 97403</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 4</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
J.D. Cohen
Phone: 541-346-4775   Fax: 541-346-3422</td></tr>
<tr><td rowspan="2">Technical Monitor:
Bolko von Roedern
Phone: 303-384-6480
Fax: 303-384-6531
E:mail: bolko_von_roedern</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $ 97,600
1999: $134,432</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objectives of this subcontract are to: develop a cost-effective amorphous silicon PV technology to foster a viable amorphous silicon PV industry in the United States. This will carried out within the context of two of the research and developments sub-Teams established by the NREL/EPRI Thin Film Partnership. Our effort will focus on the characterization of the electronic properties of a Si:H and a-SiGe:H films obtained from a variety of outside sources, most of which will be compared with the performance of companion p-i-n cells. Ultimately the goal of the Amorphous Silicon Team is to achieve 15% stable thin-film modules by 2005.

Approach/Background: To characterize the properties of these a Si:H and a-SiGe:H alloys using junction capacitance spectroscopic techniques, including drive-level capacitance profiling, transient photocapacitance and transient junction photocurrent spectroscopies, modulated photocurrent methods. On some occasion, ESR spectroscopy will also be employed.

Status/Accomplishments: Light-soaking behavior of a-SiGe:H was studied in detail. It was found that the Ge dangling bond was dominant in the annealed state, even for 2% Ge alloys, while the light-soaked state is dominated by Si dangling bonds. The effect of microcystalline inclusions in a-Si:H films on the light-induced degradation kinetics was studied and modeled in great detail

Planned FY 2000 Milestones: Examine electronic properties of a Si:H films as a function of deposition rate. Continue to assess properties of a Si:H material grown with high hydrogen dilution. Examine electronic properties of a-SiGe:H alloys in the mid-gap regime (Ge concentrations below 20at.%). Correlate electronic properties with matched p-i-n cells wherever possible.

Major Reports Published in FY 1999: Phase 1 Annual Report, draft version received

Major Articles Published in FY 1999:

J.D. Cohen et.al. Proc. Of the Material Research Society Spring Meeting, (MRS Symposia Proceedings **557**, (2 papers) to be published.

K.C. Palinginis, J.D. Cohen, J.C. Young, and S. Guha, "Defect bands in a-SiGe:H alloys with low Ge content," to be published , Proc. 18th Int. Conf. On Amorphous and Microcrystalline Semiconductors, August 1999.

Y. Lubianker, J.D. Cohen, G. Lobarsky, Y. Rosebwaks, J. Young, and S. Guha, "Structural and electronic properties of optimized a-Si:H films, to be published , Proc. 18th Int. Conf. On Amorphous and Microcrystalline Semiconductors, August 1999.

Thin Film PV Partnership

Advanced Processing Technology for CdTe and High Band Gap CIGS Solar Cells

Contract #: ZAF-8-17619-29	**Contract Period:** 5/26/98–7/25/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	University of South Florida (USF) 4202 E. Fowler Ave. Tampa, FL 33620	
	Organization Type: CU	**Congressional District:** 11
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D.L. Morel and C.S. Ferekides **Phone:** 813-974-2508 and 813-974-4818 **Fax:** 813-974-5250	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E:mail:** bolko_von_roedern	**B&R Code**: EB22	**Cost Share Information**: EPRI (Special Topic)
	DOE Funding Allocation: 1998: $172,461 1999: $278,941	**Cost Share Funding:** 1998: $66,316 1999: $123,544

Project Objective: The objectives of this work are to develop improved solar cell processing schemes for CdTe and CIGS based solar cells which are capable of further enhancing the performance and long-term stability and to reduce the manufacturing costs of commercial thin-film photovoltaic modules. Important aspects of the research will be to develop improved understanding and insights to how process modifications affect device performance. CIGS cells with wide band gaps of the absorber layer will be produced and evaluated as suitable candidates for CIS-based tandem devices.

Approach/Background: For both CdTe and CIGS based technologies we will fabricate and evaluate complete device structures. Although some devices will be fabricated on substrates such as 7059 glass for evaluative purposes, most devices will use soda lime glass, the industry standard. The process approaches, which we will develop, will be consistent with the realities of manufacturability. Stability testing of select devices will also be conducted under appropriate simulation conditions to relate any observed instabilities to process parameters.

Status/Accomplishments: USF has mapped out the processing parameter space for their CIGS deposition process and correlated this with solar cell parameters. The initial processing of $CuGaSe_2$ cells resulted in devices with unexpected low values for V_{OC}. AMPS modeling is used to understand this voltage limitation. In the CdTe area USF continue the development of all-CSS devices. Components for a new CdTe deposition system were acquired with subcontract funds. Emphasis is placed on understanding what causes the interactive nature of cell processing, i.e., understand why, if one layer is changed, all other layers and the device processing have to be reoptimized.

Planned FY 2000 Milestones: Understand what causes the lower than expected voltage in $CuGaSe_2$ cell. Develop better window layers for CIGS and CGS cells. Determine the key processing requirements for CSS deposited CdS for high efficiency CdTe cells. Development of back contacts for CdTe solar cells. Improved understanding of the interactive nature of device optimization. Possibly, this subcontract has to be renegotiated and reduced in scope due to a lack of EPRI funding required for cost-sharing the wide-bandgap CGS work.

Major Reports Published in FY 1999: Final Report of Previous subcontract NREL/SR-520-25941 (10/1998)
Contract #: ZAF-8-17619-29

Major Articles Published in FY 1998:
The following articles were published in 15th NPCV Photovoltaics Program Review; American Institute of Physics Conference Proceedings **462** (1999):

A. Jayapayalan, H. Sankaranarayanan, M. Shankaradas, P. Panse, R. Narayanaswamy, C.S. Ferekides, and D.L. Morel, "Interface Mechanisms in CIGS Solar Cells," p. 152.

D. Marinskiy, S. Marinskaya, V. Viswanathan, D.L. Morel, and C.S. Ferekides, "Studies of Heat Treated CSS CdS Films, " p. 176.

Thin Film PV Partnership

High Efficiency Thin-Film Cadmium Telluride and Amorphous Silicon-Based Solar Cells

Contract #: ZAF-8-17619-14	**Contract Period:** 3/4/98–3/3/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Jeffrey Mazer — **Phone:** 202-586-2455 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Jeffrey.Mazer@ee.doe.gov	The University of Toledo 2801 W. Bancroft Toledo, OH, 43606	
	Organization Type: CU	**Congressional District:** 9
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** A.D. Compaan (P.I.) — **Phone:** 419-530-4787 — **Fax:** 419-530-2723 X. Deng (co-P.I.) — **Phone:** 419-530-4782 — **Fax:** 419-530-2723	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E:mail:** bolko_von_roedern	**B&R Code:** EB22	**Cost Share Information:** The University of Toledo
	DOE Funding Allocation: 1998: $253,500 1999: $278,118	**Cost Share Funding:** 1998: $174,435 1999: $177,086

Project Objectives: To develop improved solar cell processing schemes for CdTe-based and for a-Si:H-based solar cells which can further enhance the performance and long-term stability of these devices and/or reduce the manufacturing costs of commercial thin-film photovoltaic modules based on these devices.

Approach/Background: The CdTe-based cell effort is focused on the use of planar magnetron sputtering for deposition of the active semiconductor layers as well as the electrode/contact structures. The a-Si:H-based effort is focused on plasma-enhanced chemical vapor deposition (PECVD) of a-Si:H, a-Si:Ge:H as well as polycrystalline and nanocrystalline forms of these materials. Devices are tested by current-voltage, quantum efficiency, and photovoltage measurements. The cell fabrication efforts are supported by characterization studies which include photoluminescence, Raman scattering, optical absorption, SEM, EDS, x-ray diffraction, Hall effect, conductivity, and capacitance-voltage measurements.

Status/Accomplishments: The UT group has fabricated triple-junction a-Si/a-SiGe/a-SiGe devices with ~11% (initial) efficiency and reached 11.6% efficiency in an all-sputtered CdS/CdTe cell. UT has developed a new nitrogen doped ZnTe back contact for CdTe solar cells. UT has also completed a comprehensive CdTe solar cell study using multilayer SnO_2 front contact layers. UT has carefully characterized the optimum deposition parameters for a-Si:H and a-SiGe:H in its deposition system and has developed the capability to deposit the transparent top contact (ITO).

Planned FY 2000 Milestones: Continued active participation in teaming activity, work will include studies and analyses of back contacting schemes for CdTe solar cells. The a-Si work will focus on different cell contacting schemes and on an improved understanding of voltage limitations of a-Si solar cells.

Major Reports Published in FY 1999: Phase 1 Annual Report, final version received 11/99

Major Articles Published in FY 1999:

The following articles appeared in the Proceedings of the 15th NCPV Photovoltaics Program Review; American Institute of Physics Conference Proceedings **462** (1999):

1. X. Deng, “Study of Triple Junction Amorphous Silicon Alloy Solar Cells;” p.297
2. D. Grecu & A.D. Compaan, “Photoluminescence Study of Cu Diffusion in CdTe;” p. 224.
3. A.D. Compaan, I. Matulionis, and S. Nakade, “Lasers and Beam-Delivery Options for Polycrystalline Thin-Film Scribing,” p. 42.

X. Deng, et.al., MRS Symp. Proc. Vol **557** (Material Research Society Spring Meeting, 1999), 4 articles, to be published.

Thin Film PV Partnership

Characterization of Amorphous Silicon Thin Films and PV Devices

Contract #: XAK-8-17619-13	**Contract Period:** 1/14/98–1/13/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	University of Utah Salt Lake City, UT 84112 **Organization Type**: CU	 **Congressional District:** 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** P. Craig Taylor **Phone:** 801-581-8751 **Fax:** 801-581-4246 (or 801-581-4801)	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E:mail:** bolko_von_roedern	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $63,400 1999: $91,596	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: The objective of the research is to characterize the defects, impurities and metastabilities in hydrogenated amorphous silicon (a-Si:H), in hydrogenated amorphous silicon-germanium alloys (a-Si_xGe_{1-x}:H) and in other related alloys of importance to photovoltaic devices. Of special interest is to develop an understanding of the degradation of a-Si:H and related alloys and to pursue options to eliminate this degradation.

Approach/Background: Various optical and magnetic resonance techniques are employed to examine the role of defects , impurities and metastabilities in a-Si:H and related alloys. Optical techniques include photothermal deflection spectroscopy to measure low levels of optical absorption, photoluminescence and photoluminescence excitation spectroscopy, and various modulated optical spectroscopies. Magnetic resonance techniques include electron spin resonance and optically detected magnetic resonance. Measurements are made on individual films and on device structures.

Status/Accomplishments: We have demonstrated the feasibility of using second harmonic detection of electron spin resonance (ESR) to enhance signal-to-noise ratios and used this technique to measure samples supplied by other participants in the PV thin film partnership. This sensitive technique has now been used to study the light induced increase in spin density as a function of the temperature used during illumination (60 to 340 K). The time dependence of the LESR generation and decay dependence was also measured. Spin resonance measurements on hot-wire deposited a-Si:H showed that only a small fraction of the hydrogen atoms participate in spin-lattice relaxation.

Planned FY 2000 Milestones: We plan to continue the very sensitive ESR and LESR measurements. We will complete measurement of the temperature dependence of the kinetics, including the dispersion, for the production of silicon dangling bonds in a-Si:H and related alloys. Comparisons between PECVD and hot wire samples will be made. In making diagnostic devices in our 3-chamber, PECVD system, we will resolve the question whether S-alloying of a-Si:H can improve stabilized cell performance.

Major Reports Published in FY 1999: Phase 1 Annual Report NREL/SR-520-27298 (10/1999)

Major Articles Published in FY 1999:

P.C. Taylor et al, MRS Symp. Proc. Vol **557** (Material Research Society Spring Meeting, 1999), 3 articles, to be published.

Thin Film PV Partnership

Alternative Window Schemes for $CuInSe_2$-Based Solar Cells

Contract #: XAF-8-17619-06	**Contract Period:** 12/29/97–12/28/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">Washington State University (WSU)
Pullman, WA 99164-3140</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
L.C. Olsen
Phone: (509) 372-7221 Fax: (509) 372-7100</td></tr>
<tr><td rowspan="2">Technical Monitor:
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Fax: 303-384-6531
E:mail: bolko_von_roedern</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $138,700
1999: $120,875</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective is to develop window alternatives (replacing CdS) for $Cu(In,Ga)Se_2$ solar cells to meet the DOE goal set for the 2005 to achieve commercial, low-cost, 15% efficient thin-film photovoltaic modules.

Approach/Background: The approach is to optimize MOCVD-deposited alternative window layers and obtain state of the art $Cu(In,Ga)Se_2$ solar cells. Emphasis is placed on investigations of ZnO, ZnSe and ZnS compounds as replacements for CdS, and on optimization of the complete process of cell fabrication. In particular, approaches to growth of window layers compatible with subsequent processing steps including TCO and collector grid deposition that yield stable, efficient solar cells are being investigated.

Status/Accomplishments: Approaches to growth of thin crystalline layers of ZnO and ZnSe by MOCVD onto $Cu(In,Ga)Se_2$ were developed in previous programs. Capabilities for MOCVD deposition of ZnS and sputtering conductive ZnO for TCO films have been added. WSU coordinated a comprehensive experimental study on transient effects in CIS-based solar cells.

Planned FY 2000 Milestones: Demonstrate proof of concept results for ZnS window layers. Fabricate an efficient complete solar cell based on CIGS, an alternative window layer, a TCO, collector grids and MgF_2 AR coating with all processes beginning with the window layer being done by the subcontractor. Develop a much enhanced understanding of the role of buffer layers on device optimization.

Major Reports Published in FY 1999: Phase 1 Annual report (draft version) received

Major Articles Published in FY 1999:
L.C. Olsen, F.W. Addis, and K. Vaidynathan, "Alternative Buffer Layers for $CuIn(Ga)Se_2$ Solar Cells," 15th NCPV Program Review, American Institute of Physics Conference Proceedings **462**, 164 (1988)

Thin Film PV Partnership

Identifying and Overcoming Degradation Mechanisms in CdTe Solar Cells

Contract #: AAK-7-17619-15	**Contract Period:** 7/27/98–7/26/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King / Jeffrey Mazer **Phone:** 202-586-1693 / **Phone:** 202-586-2455 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	Weizmann Institute of Science Rehovot, Israel	
	Organization Type: CU	**Congressional District:**
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** David Cahen, G. Hodes, K. Gartsman **Phone:** + 972-8934-2246 **Fax:** + 972-8934-4139	
Technical Monitor: Bolko von Roedern **Phone**: 303-384-6480 **Fax:** 303-384-6531 **E:mail:** bolko_von_roedern	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $34,000 1999: $127,000	**Cost Share Funding:**

Project Objective: Develop improved understanding of the mechanisms leading to degradation of CdTe solar cells during their use and the testing of various ways to reduce such degradation.

Approach/Background: We will check the assumption that atomic migration of contact constituents is involved in the device degradation. For this we need to identify and measure such atom mobility. For this purpose several techniques that have been used by us in single crystals will need to be adapted for use with polycrystalline thin films. These include the p/n junction motion and transient ion drift (capacitance decay). Subsequently new ways to make contacts as well as ways to prevent atom motion will be explored and their efficacy tested, by dome of the above-mentioned techniques. Prominent among these will be CdTe surface modifications.

Status/Accomplishments: Cells supplied by NREL and First Solar were Stress-tested. Detailed LBIC studies were carried out and showed non-homogenous response of these cells. Weizmann established its own back-contacting procedure using electroless Ni-P deposition. These contacts result in good photovoltaic behavior, but were found to be NiTe.

Planned FY 2000 Milestones: Establish experimental capabilities to measure diffusion of species in CdTe solar cells. Complete experiments aimed at separating degradation effects in back contact region from those in the absorber and front junction regions, for devices with commonly used back contacts. Pursue schemes to minimize diffusion along grain boundaries, and report on the effectiveness of such schemes.

Major Reports Published in FY 1999: None directly relevant to this contract.

Major Articles Published in FY 1999: None directly relevant to this contract.

Thin Film PV Partnership

Assessment of Critical Thin Film Resources

Contract#: RAF-9-29609	**Contract Period:** 4/2/99–9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Managers:
Richard King Jeffrey Mazer
Phone: 202-586-1693 Phone: 202-586-2455
Fax: 202-586-8148 Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Jeffrey.Mazer@ee.doe.gov</td><td colspan="2">World Industrial Minerals
14142 Denver West Parkway # 170
Golden, CO 80401</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
James Guilinger
Phone: 303-216-1135 Fax: 303-271-9266</td></tr>
<tr><td rowspan="2">Technical Monitor:
Ken Zweibel
Phone: 303-384-6441
Fax: 303-384-6430
E:mail: ken_zweibel@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $24,650</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: To develop an up-to-date assessment of the potential availability and costs of several key thin film feedstock materials: tellurium, indium, gallium, cadmium sulfide, and cadmium telluride. These materials are essential components of important, new polycrystalline thin film PV technologies (copper indium-gallium diselenide and cadmium telluride devices) that have the potential to make energy-significant contributions to the global energy infrastructure. We wished to examine whether possible future availability or cost bottlenecks would cause serious problems.

Approach/Background: A leading authority on the availability of these resources, World Industrial Minerals, was contracted to prepare the studies. World Industrial Minerals had previously performed a limited study of tellurium availability for Golden Photon, Inc. The PI, Jim Guilinger, sought information from written sources and through interviews with suppliers.

Status/Accomplishments: The contract was successfully completed with the issuance of five reports, one each on each of the key materials. *The following summarizes our findings:*

Tellurium: Although a rare material in the Earth's crust, there is substantial tellurium produced as a by-product of copper, gold, lead, and platinum refining. There are no mines devoted to tellurium as a primary product. However, unlike other rare elements, sites with tellurium concentrations high enough to be mined have been identified. It is believed that tellurium availability or price will not represent a serious impediment to CdTe production for the foreseeable future.

Indium: Though indium is not as rare a material as tellurium, it is more dispersed and therefore much harder to find as a concentrated mineral deposit. There are no primary sources of indium, and at this point, such sources are not envisaged. Commercial indium is available almost exclusively as a by-product of zinc, with copper and lead as future, higher-priced sources. There are several competing uses of indium in the marketplace. It is possible that the increasing cost and tightening availability of indium could become issues for the large-scale manufacturing of CIGS modules (over 1 GW/year production). Alleviating strategies will include: making thinner cells (possibly including light-trapping to go below 1 micron thickness); increasing materials utilization in processes (including recycling at the process and module levels); substituting gallium for indium (but see next paragraph), or other substitution strategies that have not yet emerged.

Gallium. Gallium is not a rare material. It has the same concentration in the Earth's crust as lead. However, it is a rarely used and rarely mined material. It does not occur as a primary metal. Commercial gallium is almost always a by-product of bauxite. Although the amount of gallium in the Earth's crust is huge (over 2 million metric tons reserve), increasing the use of gallium sharply would cause bottlenecks, raising cost and limiting availability. Perhaps the best hope for increased gallium availability is the potential increase in the Ga recovery rate from bauxite, which today is only 40%. Substituting gallium for indium is not a certain solution to the indium availability issue for CIGS modules.

CdS powder. Despite the ubiquity of CdS in polycrystalline thin films, and its past use in paints worldwide, it is actually a potential availability concern. Asarco is the only source of high-purity CdS powder. Huge amounts of CdS for pigment is produced (over 3000 metric tons), but it is not pure enough for PV use. It appears that purified CdS would be available if the PV industry needs it, based on either increased production from Asarco or increased purification of the CdS for pigments. Only temporary supply/demand imbalances are expected to arise. In the future, PV companies may purchase elemental feedstocks and make their own powders in order to assure quality control and reduce cost.

CdTe powder. Viewed independently of the issue of tellurium availability (see above), the availability of purified CdTe powder is not a concern because the simple process used to produce it can easily be scaled up to larger volumes by existing suppliers.

It is clear that although there will be quite a bit of initial leeway in the availability issues (below 1 GW/year), once the polycrystalline thin film technologies reach large-scale production, some attention will have to be paid to these issues in terms of cell design, processing, and waste minimization/recycling. It appears that the CIGS device is somewhat more vulnerable to availability issues than the CdTe device.

Planned FY 2000 Milestones: None (project completed)

Major Reports Published in FY 1999:

Guilinger, Jim (1999) "Assessment of Critical Thin Film Resources," Technical Report (in press).

Major Articles Published in FY 1999:

None.

Photovoltaic Environmental, Health and Safety Assistance Center

Contract #: Project #: PV-1516	**Contract Period:** 10/1/98-9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Brookhaven National Laboratory Building 830 Upton, NY 11973-5000	
	Organization Type: FF	**Congressional District**: 1
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigators** V.M. Fthenakis **Phone:** 516-344-2830 **Fax:** 516-344-4486 **E:mail:** fthenakis@bnl.gov P.D. Moskowitz **Phone:** 516-344-2017 **Fax:** 516-344-4486	
Technical Monitor: A. Bulawka **Phone**: 202-586-5633 **Fax**: 202-586-5127 **E:mail:** Alec.Bulawka@ee.doe.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1994: $400,000 1997: $300,000 1995: $380,000 1998: $300,000 1996: $300,000 1999: $300,000	**Cost Share Funding:**

Project Objective: Assist the safe and environmentally friendly operation of photovoltaic facilities and products, extending from R&D to manufacturing and deployment. The specific objectives of the Center are to prevent accidents, reduce EH&S occupational and public risks, and reduce environmental and safety related costs. These objectives are paramount to the economic viability and public acceptance and support of PV systems.

Approach/Background: The BNL Center conducts the following types of activities: 1) It provides direct support to DOE Headquarters, the National Renewable Energy Laboratory (NREL) and Sandia National Laboratory (SNL) to ensure that the operations of their facilities and those of their contractors are operated in an environmentally responsible manner. 2) It conducts EH&S audits, safety reviews and incident investigations, as needed. 3) It assists the photovoltaic industry to identify and examine potential EH&S barriers and hazard control strategies for new photovoltaic material, process and application options before their large-scale commercialization. To facilitate the application of knowledge derived from the above activities, BNL hosts workshops, tutorials and symposia, uses electronic mail and a web page, and publishes articles in the peer-reviewed literature (150 publications up-to-date).

Status/Accomplishments: In FY 1999, we organized a workshop on lead-free soldering where we briefed the PV industry on pending regulatory and electronic industry trends and facilitated the transfer of ASE Americas solder technology to the rest of the PV industry. We handled 25 requests for assistance and information from industry, the public, media, universities, and private and government agencies; we conducted new studies on recycling infrastructure and regulatory trends, on recycling pretreatment, and on the impact of PV on CO_2 emissions' reduction. We assisted Astropower with HF handling and Pb-free soldering, Siemens Solar with CIS safe operation guidelines, and BP Solarex with selecting recycling options. To facilite the transfer of our research results, we published 4 journal papers, and gave 3 workshop/conference presentations.

Planned FY 2000 Milestones: In FY 2000, we plan to keep assisting the DOE, NREL and Sandia and answer public inquires, on PV EH&S issues, as needed. Regarding our industry outreach, we plan to follow up inquires from EPV, Astropower, BP Solarex, and ASE Americas. Regarding industry-wide EH&S, we will investigate: The toxicology and safe handling of CdS powder, cost effective ways for handling PV manufacturing waste, feasibility and cost-benefit analyses of new waste-management technologies. We will also follow-up on the Pb-free solder issue, on regional air pollution benefits from PV deployment, and will investigate EH&S issues regarding the deployment of Million Roof Initiative as needed.

Contract #: Project #: PV-1516

Major Reports Published in FY 1999:

Fthenakis V., Zweibel K., and Moskowitz P., (editors) Proceedings of the Photovoltaics and the Environment 1998, Workshop, July 23-24, 1998, Keystone, CO, Brookhaven National Laboratory, BNL-52557, Feb. 1999.

Fthenakis V.M. and Moskowitz P.D., The Value and Feasibility of Proactive Recycling, AIP Conference Proceedings 462, (ed. Al-Jassim et al.), pp. 332-337, American Institute of Physics, Woodbury, NY, 1999.

Ciccarelli G. Fthenakis V.M. and J. Boccio, A Method of Analysis for Gas Explosions: H_2Se case study, Journal of Loss Prevention, 12, 157-165, 1999.

Fthenakis V.M. and Themelis N., Assessing and Managing Risks in Engineering, *EARTHmatters*, Columbia Earth Institute, 3, 20-21, 1999.

Fthenakis V.M., HGSYSTEM: A Review, Critique, and Comparisons with Other Models, *Journal of Loss Prevention*, 12, 525-531, 1999.

Fthenakis V.M., Morris S.C., Moskowitz P.D. and Morgan D., Toxicity of CdTe, CIS and CGS, *Progress in Photovoltaics*, in press.

Fthenakis V.M. and Moskowitz P.D., Photovoltaics: Environmental, Safety and Health Issues and Perspectives, *Progress in Photovoltaics*, Millennium Issue, in press.

Technology Development

PVMaT

Cost Reduction and Manufacture of the SunSine™ AC Module

Contract#: ZAX-8-17647-03	**Contract Period:** 4/21/98–12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Applied Power Corp., Ascension Technology Division 1210 Homann Drive Lacey, WA 98503	
	Organization Type: IN	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** E. Kern **Phone:** 781-684-6101 **Fax:** 781-890-2050 Miles Russell **Phone:** 781-684-6102 **Fax:** 781-890-205 Gregory Kern **Phone:** 303-417-1418 **Fax:** 303-417-1423	
Technical Monitor: Holly Thomas **Phone:** 303-384-6400 **Fax:** 303-384-6604 **E:mail**: holly_thomas@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Applied Power Corp., Ascension Technology Division
	DOE Funding Allocation: 1998: $144,280 1999:$154,232	**Cost Share Funding:** 1998: $61,834 1999:$(17,657)

Project Objective: Ascension Technology's (APC/AT) objectives are to achieve the following:

- 40-50% reduction in inverter manufacturing costs,
- 40% or more reduction in inverter size from 169 to 100 square inches;
- 4% increase in peak inverter efficiency from 87 to 91% at full power; UL listing, FCC certification, export certifications;
- establish a production capability of 5,000 SunSine™ inverters/year through manufacturing improvements and production line design improvements;
- 0.10% failures at time of installation/turn-on;
- a 5 year warranty; and
- reach a rating of 250 W_{ac} at PTC for the SunSine™ AC Module Rating.

Approach/Background: The objective of this subcontract over its two phases is to continue to improve the manufacturability and reliability of the SunSine™ AC Module and address design improvements in order to reduce the cost to manufacture the SunSine™ inverter by 40-50% per unit. This work will also boost its performance and enhance its marketability by adding customer-valued features. AT will accomplish these advancements by reductions in the following areas:

- Die-cast aluminum enclosure and base plate;
- Soft switching for cost reduction and performance gains;
- Circuit board and component optimization for performance gains and size reduction;
- Streamlined inverter/PV panel assembly/test at ASE Americas, the PV laminate supplier; and
- Develop a conduit-ready version and versions for export markets.

Status/Accomplishments: A soft switching topology was selected and implemented. Soft switching in the dc/dc buck portion of the inverter was functionally tested up to a power level of 450 Watts. The number of main power circuit board components was reduced from 236 to 187 parts, a reduction of 21%. The proposed name of the product was changed from "SunSine325 AC Module" to "SunSine AC Module" to reduce confusion as to the power rating of the product. Two generations of inverter circuit boards have been fabricated and tested to verify various control and power circuit changes. The main circuit board size has been reduced from 89.9 square inches to 42.0 square inches, a reduction in size of 53%. Most of the circuit board components, 88%, have been changed from through-hole to surface-mount components. Use of surface-mount components will help to lower production costs. A prototype of the inverter was reviewed by manufacturing and select vendors to ensure ease and low cost of manufacturability. A prototype casting enclosure was designed and fabricated, however the size of the design was determined to be too large and will be redesigned in Phase II. As part of their cost share, APC/AT has acquired two important pieces of test equipment to aid in the product development process, a spectrum analyzer for in house EMC testing and a programable AC Power Source to do IEEE-P929 voltage and frequency testing. Export markets and technical requirements for selling into those markets were reviewed and it was decided that the added development time and added product costs would negatively impact the product version for U.S. markets. APC/AT decided to focus on U.S. markets and may consider versions for export at a later time. The improvements achieved during this period are anticipated to reduce inverter production costs by 42%, and anticipated AC Module production costs by 17%.

Contract#: ZAX-8-17647-03

Planned FY 2000 Milestones:
- Deliver a prototype of the new SunSine^{TM} AC Module to the NREL Outdoor Test Facility; instrumented and monitored for thermal performance of the power electronic components;
- Design final die-cast packaging of the inverter;
- Complete inverter testing to FCC, UL and TUV HALT requirements;
- UL Listing of this model of the AC Module;
- Pilot production run of 110 units; and
- Begin full production and commercial shipments of the new SunSine^{TM} AC Module.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PVMaT

Cost Reductions in High Volume EFG PV Module Manufacturing Line

Contract #: ZAX-8-17647-10	**Contract Period:** 8/5/98–10/4/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	ASE Americas 4 Suburban Park Drive Billerica, MA 01821-3980	
	Organization Type: IN	**Congressional District:** 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J. Kalejs **Phone:** 978-947-5993 **Fax:** 978-663-7555	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: ASE Americas
	DOE Funding Allocation: 1998: $168,000 1999: $972,801	**Cost Share Funding:** 1998: $182,000 1999: $1,046,557

Project Objective: The objective of this PVMaT subcontract over its three-year duration is to advance ASE Americas' PV manufacturing technologies in order to lower costs of ASE manufacturing systems through development of improved, larger and thinner, wafer production in process integration, Statistical Process Control implementation, data systems implementation, and ISO9000 and ISO14000 implementation.

Approach/Background: ASE Americas will meet these objectives by:
- Developing manufacturing processes which can be scaled-up to high volumes in manufacturing,
- Developing the growth of thin EFG tubes with improved productivity and production of solar cells from the resulting thin wafers,
- Improveing crystal growth, laser cutting and wafer etching technology to obtain higher cutting speeds and stronger EFG wafers, and cell processing for improved efficiencies, and
- Investigating Flexible Manufacturing through the development of large-area EFG wafers, continuous improvement, and advanced module manufacturing.

Status/Accomplishments:
- Completed key node analysis, carried out design-of-experiment matrices on the cell line to optimize efficiencies, performed a capacity and bottleneck study, prepared a baseline chemical waste analysis, and initiated statistical process control (SPC) charting for the production line.
- Increased cell efficiencies in manufacturing to an average in excess of 14.2%, with the help of design-of-experiment matrices carried out on the cell line and SPC methods.
- Designed, constructed, and tested a 50-cm-diameter, edge-defined, film-fed growth (EFG) cylinder crystal growth system to successfully produce thin cylinders up to 1.2 meters in length and down to 100 microns in wall thickness.
- Successfully deployed new high-speed lasers and nozzle designs on a laser wafer-cutting system with the potential to decrease cutting labor costs by 75% and capital costs by a factor of two.
- Achieved laser-cutting speeds of up to 8x the pre-contract level and initiated an evaluation of this system in production.
- Identified laser-cutting conditions that reduce damage for both Q-switched Nd:YAG and copper-vapor lasers with the help of a breakthrough in fundamental understanding of cutting with these short-pulse-length lasers
- Identified process for co-firing of silicon nitride and aluminum with rapid thermal processing methods at Georgia Tech that optimize the bulk EFG material lifetimes
- Improved large-volume manufacturing of 10-cm x 15-cm EFG wafers by developing laser-cutting fixtures, adapting carriers and fabricating adjustable racks for etching and rinsing facilities, and installing a high-speed data collection network
- Initiated etching and fracture studies to guide development of methods to reduce stress in wafers and raise wafer strength so as to improve wafer yield.
- Initiated a module field studies program to collect data on field failures to help identify potential manufacturing problems.

- Initiated testing on new encapsulants, which cure at room temperature, in order to improve flexibility and provide higher yields for thin wafers in lamination.

Planned FY 2000 Milestones:
- Demonstrate mechanical and electrical yield loss reduction of 10% each on manufacturing line relative to Phase I baseline.
- Demonstrate a 10% reduction in chemical waste relative to Phase I baseline.
- Demonstrate Georgia Tech processes for increasing EFG solar cell efficiency using selective emitters, oxide formation, back surface fields, silicon nitride and gettering.
- Complete design, construction, and installation of advanced laser wafer laser-cutting system for cutting 50-cm diameter cylinder.
- Complete modifications to crystal growth process, laser cutting system and etching processes, to produce lower stress and stronger EFG wafers.
- Complete initial analysis of field test samples and obtain preliminary reliability results for module using the new encapsulation technology.
- Complete evaluation of initial reliability and quality aspects of the AC module.

Major Reports Published in FY 1999:

B. Bathey, B. Brown, J, Cao, S. Ebers, R. Gonsiorawski, B. Heath, J. Kalejs, M. Kardauskas, E. Mackintosh, M. Ouellette, B. Piwczyk, M. Rosenblum, and B. Southimath, “PVMaT Cost Reductions in the EFG High Volume PV Manufacturing Line,” Annual Subcontract Technical Report, 5 August 1998- 4 August 1999, NREL/SR-520-27478, (November 1999).

Major Articles Published in FY 1999:

A. Roy, B. Mackintosh, J. P. Kalejs, Q.-S. Chen, H. Zhang and V. Prasad, “A numerical model for inductively heated cylindrical silicon tube growth system,” J. Crystal Growth, to be published.

Silicon-Film™ Solar Cells by a Flexible Manufacturing System

Contract #: ZAX-8-17647-01	**Contract Period:** 4/16/98–4/1/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	AstroPower, Inc. Solar Park Newark, DE 19716-2000	
	Organization Type: IN	**Congressional District:** 1:
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J. Rand and J. Culik **Phone:** 302-366-0400 **Fax:** 302-368-6474	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: AstroPower, Inc
	DOE Funding Allocation: 1998: $874,734 1999: $1,005,352	**Cost Share Funding:** 1998: $890,479 1999: $1,058,659

Project Objective: The objective of this subcontract over its three year duration is to advance AstroPower's manufacturing process for the production of large-area Silicon-Film™ solar cells in order to reduce solar-cell and module cost and expand production capacity and develop a manufacturing system for a 50-MW fully integrated manufacturing plant that will produce a variety of panel and module products.

Approach/Background: AstroPower will meet these objectives by developing several flexible solar cell manufacturing processes capable of handling large area Silicon Film™ sheets at high speeds and generating solar cells of various sizes in a manufacturing-friendly environment. These in-line Silicon Film™ processes will include metallurgical-grade silicon purification, chemical surface etching, junction diffusion, and contact metalization.

Status/Accomplishments:

- Completed optimization of AR coating thickness and index of refraction for Silicon-Film™ textured surface.
- Fabricated cells processed with in-line water-based cleaning.
- Completed design of, and purchased components for, an integrated in-line surface etching system for Silicon-Film™ plank processing.
- Designed prototype process for production of PV-grade silicon from metallurgical-grade. The process is designed to operate at a rate of 100 Kg/hr.
- Demonstrated production of Silicon-Film™ sheet using PV-grade silicon upgraded from MG-grade.
- Completed lower cost new module junction box.
- Designed large-area Silicon- Film™ roof-top module.
- Developed a size-based family of Silicon-Film™ products.

Planned FY 2000 Milestones:

- Transfer the HF diffusion oxide etch system and process to the Silicon-Film™ manufacturing line.
- Complete assembly of an integrated in-line surface etching system for Silicon-Film™ planks.
- Develop a new front contact metalization process for Silicon-Film™ solar cells.
- Demonstrate a diffusion length of 150µm in as-grown Silicon-Film™ sheet.
- Demonstrate the production of Silicon-Film™ sheet at 2.4 m/min.
- Complete the construction of a prototype large-area Silicon-Film™ roof-top module system.
- Implement in-line contactless wafer/plank characterization techniques into AstroPower's Silicon-Film™ production line.
- Complete the development and optimization of the 31-cm wide Silicon-Film™ sheet fabrication process.
- Fabricate large-area, 900 cm^2, solar cells with efficiency of 12%.
- Complete conceptual design of 50MW/yr Silicon-Film™ manufacturing line.

Contract #: ZAX-8-17647-01

Major Reports Published in FY 1999:
Culik, J.S., Rand, J.A.,, Bai, Y., Bower, J.R., Cummings, J.R., Goncharovsky, I., Jonczyk, R., Sims, P.E., Hall R.B., and Barnett, A..M., "Silicon-Film^{TM} Solar Cells by a Flexible Manufacturing System," Annual Subcontract Technical Status Report, 16 April 1998 - 31 January 1999, NREL/SR-520-26834, (September 1999)

Major Articles Published in FY 1999:
Jonczyk, R., "Characterization TiO_x Single Layer Antireflective Coating on Silicon-Film^{TM} Material," Ninth Workshop on Crystalline Silicon Solar Cell Materials and Processes.
Barnett, A.M., Culik, J.S., Ford, D.H., Hall, R.B., Mauk, M.G., and Rand, J.A., "Silicon-Film^{TM} Solar Cells," Eleventh International Conference on Microelectronics..

PVMaT

Production of Solar Grade (SoG) Silicon by Refining of Liquid Metallurgical Grade (MG) Silicon

Contract #: ZAX-8-17647-13	**Contract Period:** 5/21/98-12/19/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Crystal Systems, Inc.
27 Congress Street
Salem, MA 01970</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Chandra Khattak
Phone: 978-745-0088 Fax: 978-744-5059</td></tr>
<tr><td rowspan="2">Technical Monitor:
Marta Symko-Davies
Phone: 303-384-6528
Fax: 303-384-6490
E:mail: marta_symko_davies@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Crystal Systems, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $143,500
1999: $386,500</td><td>Cost Share Funding:
1998: $61,500
1999: $156,705</td></tr>
</table>

Project Objective: The objective of this PVMaT program is to produce solar grade (SoG) silicon feedstock by refining metallurgical grade (MG) silicon in the liquid state so that this material can be used as feedstock for ingot processes such as the Heat Exchanger Method (HEM) for photovoltaic applications. It is intended to continue this technology development in larger scale using thermo-chemical refining techniques and reduce the impurities in MG silicon to less than 1 ppma level at the 500 kg level.

Approach/Background: The approach is based on thermo-chemical refining of metallurgical grade (MG) silicon using the Heat Exchanger Method. The reduction of most impurities to less than one ppma level was demonstrated with approximately 3-kg charge of MG silicon with this approach. The present program will focus on the development of equipment and procedures for upgrading MG silicon to the SoG level consistent with theoretical analysis and experimental results. Prototype experiments will be carried out with up to 450-kg charge size. The projected production cost of SoG silicon is less than $20/kg.

Status/Accomplishments: CSI reported achieving the goal of reducing metallic impurities to less than 1 ppma and B & P to 10ppma for the 60-kg charge size using simple refining processes in the molten state to upgrade commercially available MG silicon. MG silicon, as received from the supplier, was melted in a modified Heat Exchanger Method (HEM) furnace and refining was carried out in the molten state. The refining processes involved purging gases through the melt, reactions with moisture, slagging and stirring of the bath. After refining processes were completed the charge was directionally solidified. This significant result of reducing B and P from the original values in MG silicon using very simple procedures is unique and has been achieved with large charge size and has the potential of easy scale up. These results are consistent with the theoretical analysis and modeling carried out in-house. The experimental parameters used have not been optimized and a similar approach will be pursued for further scale-up in charge sizes and for further reduction of impurities, especially B and P. Commercially available MG silicon was obtained for these experiments from several MG silicon producers worldwide. These samples were analyzed for impurities, and some were used for upgrading experiments. During the entire experimental stage, safety procedures were developed for carrying out the experiments safely using reactive gases.

The refining procedures developed are simple processes which are scaleable and are not expected to add significant costs of refining, therefore, conversion of MG silicon to SoG silicon should result in low-cost added value.

Planned FY 2000 Milestones: Continue R&D efforts initiated in 1999 towards executing prototype development for production of SoG silicon by refining of liquid metallurgical grade silicon. CSI shall design and fabricate prototype systems for refining of 100-150 kg charge MG silicon, demonstrating metallic impurities to be less than 1 ppma and Boron and Phosphorous to be less than 10 ppma. Upon adequate demonstration at the 100-150 kg charge MG silicon, design and fabrication of prototype systems for 300-450 kg MG silicon charge will be executed. This will then be followed by production experiments for refining of 300-450 kg charge MG silicon.

Contract #: ZAX-8-17647-13

CSI shall characterize the refined MG silicon from 300-450 kg production as well as demonstrate the economic feasibility of this project through characterization evaluations. Adequate demonstration will be shown of the reduction of impurities, including B and P, to less than 1 ppma at the 300-450 kg level.

Major Reports Published in FY 1999:

Khattak, C. P., Joyce, D. B., and Schmid, F. (1999), "Production of Solar Grade (SoG) Silicon by Refining Liquid Metallurgical Grade (MG) Silicon," Annual Report, NREL/PVMaT Phase 5A1, Subcontract No. ZAX-8-17647-13 (Phase I), 32 pp.

Major Articles Published in FY 1999:

C. P. Khattak, D. Joyce, F. Schmid, "Production of Solar Grade (SoG) Silicon by Refining Molten Metallurgical Grade (MG) Silicon," *NREL NCPV Meeting, Breckenridge, CO*, August 9-11, 1999.

PVMaT

Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy Manufacturing Technology

Contract #: ZAX-8-17647-09	**Contract Period** 6/22/98–8/21/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Energy Conversion Devices 1675 West Maple Road Troy, MI 48084	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** M. Izu **Phone:** 248-280-1900 **Fax:** 248-280-1456	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Energy Conversion Devices
	DOE Funding Allocation: 1998: $333,000 1999: $942,000	**Cost Share Funding:** 1998: $567,000 1999: $709,990

Project Objective: The objective of this subcontract over its three year duration is to advance Energy Conversion Devices' PV manufacturing technologies in order to support the PVMaT cost-reduction and capacity-increase goals with the development of manufacturing technologies which allow a 25-30% reduction in module cost ($/W) and a 60% increase in manufacturing capacity (MW/year) over the United Solar 4th Quarter 1997 annualized manufacturing capacity.

Approach/Background: Energy Conversion Devices, Inc. will meet these objectives by:

- Developing, fabricating and installing a new substrate heating system and temperature sensor system designed to achieve more accurate temperature controlling and monitoring for the production of high-efficiency solar cells,
- Developing, fabricating, and installing a set of in-line real-time material quality monitoring systems for the United Solar Systems production machines,
- Demonstrating the feasibility of using Zn metal targets in the DC sputtering process to prepare ZnO layers for high performance back-reflectors for incorporation of the process into United Solar's 5-MW amorphous silicon (a-Si) module production line, and
- Redesigning the internal hardware for the a-Si intrinsic layer deposition chambers used in the 5-MW United Solar's production line.

Status/Accomplishments:

- Designed, tested, and verified improved performance of the new substrate heater.
- Completed design, pilot machine installation, and performance evaluation of optical sensors for in-line vacuum operation.
- Completed design and installation of second generation sensors in a-Si pilot deposition machine.
- Fully tested a new cathode design for improved uniformity.
- Designed and bench-tested in-line non-contacting PV capacitive diagnostic system and installed the system in the 5-MW a-Si deposition machine for evaluation.
- Designed and bench-tested a reflectometer and demonstrated a new low-cost zinc metal process for the backreflector deposition machine.

Planned FY 2000 Milestones:

- Complete the installation and evaluation of performance of new substrate heating and temperature monitoring system in United Solar's production machine.
- Complete installation of 3rd generation sensor hardware system on United Solar's production equipment.
- Complete the deposition of the new high quality back-reflector material over a 100-m length using the new deposition process, as well as preparing high efficiency triple-junction cells using this process
- Complete a hardware design for the implementation of the new back reflector deposition process into United Solar's 5-MW production line.

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- Demonstrate a ±5% uniformity in static i-layer deposition over 80% of the cathode area at up to 2 times the previous deposition rate for production of the i-layer, as well as demonstrate a 3% increase in performance of i-layers for a-Si based on solar cells.
- Complete the design for a third generation internal hardware geometry.
- Complete design and testing of the first-generation prototype pinch valve.
- Complete installation of the third generation internal hardware.

Major Reports Published in FY 1999:
Izu, M., "Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy PV Manufacturing Technology," Annual Subcontract Technical Status Report, 22 June 1998 - 21 June 1999, NREL/SR-520-27535, (November 1999)

Major Articles Published in FY 1999: None

PVMaT

Continuous, Automated Manufacturing of String Ribbon Si PV Modules

Contract #: ZAX-8-17647-07	**Contract Period:** 5/21/98-7/20/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Evergreen Solar 211 Second Ave Waltham, MA 02154	
	Organization Type: IN	**Congressional District**: 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Jack Hanoka **Phone:** 781-890-7117 **Fax:** 781-890-7141	
Technical Monitor: Marta Symko-Davies **Phone**: 303-384-6528 **Fax**: 303-384-6490 **E:mail**: marta_symko_davies@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Evergreen Solar, Inc.
	DOE Funding Allocation: 1998: $363,500 1999: $977,929	**Cost Share Funding:** 1998: $155,786 1999: $419,112

Project Objective: Continue to advance Evergreen Solar's PV technology to achieve a multi-megawatt crystalline silicon manufacturing line, which is highly automated and virtually continuous.

Approach/Background: Exploit Evergreen's unique and innovative technology in the areas of silicon ribbon growth, cell making, and module manufacturing. Focus on crystal growth, cell manufacturing, module lay-up and factory layout and automation. Use developments in this project to further the objective of a high-throughput automated production line.

Status/Accomplishments: During FY 199 efforts were divided into: (1) crystal growth; (2) cell manufacturing; (3) module lay-up; and (4) factory layout and automation. Most of the work was in areas 1, 2, and 4.
The accomplishments in crystal growth include the development of a new string material, edge meniscus control (a patent was filed on this), reduced consumable costs, and the design and construction of a lower cost, automated crystal growth machine. Results of all these are an increase of run length of at least 2x, an increase in cell efficiency of 5% (relative), an improvement in total factory yield of 20%, a reduction in consumable costs of 60%, and a (projected) reduction in new furnace costs of 20%. In addition, the prognosis for an automated crystal growth machine is now very good. In the cell area, a wet chemical etch step-the pre-diffusion etch-has been eliminated entirely and design and construction of a high speed (600/hour) machine for contact and AR application nearly completed.

Planned FY 2000 Milestones: conduct parallel manufacturing R&D efforts initiated in 1999 to address: increased automation and throughput in diffusion, glass-etch, high-speed drying and printing of contacts, high speed contact application and increases in efficiency through implementation of hydrogen passivation; increased manufacturing automation and throughput; as well as decreased labor through the development of a patterned backskin, an in-line tester, and an automated stringing operation; and implementation of layout and automation of a multi-MW crystal growth, cell processing, and module fabrication line, particularly in areas of material handling and process flow.
In the module lay-up area, efforts have begun demonstrating the cost effectiveness of laying-up the backskin material developed under the previous PVMaT subcontract.
ESI expects to move to a new site for multi-MW production in early 2000, enabling a continuous, automated module manufacturing facility. To this end, they have worked closely with Fraunhofer Institute for Manufacturing at Boston University for aid in all aspects of manufacturing science and plant layout.

Major Reports Published in FY 1999:
Hanoka, J. I., 1st Annual Report on this contract. Submitted to NREL, June 1999.

Major Articles Published in FY 1999:
Hanoka, J. I. Invited paper presented at 11th International Conference on Photovoltaic Science and Engineering. Hokkaido, Japan, September 1999.
Paper submitted for Proceedings publication.

Specific PVMaT R&D in CdTe Product Manufacturing

Contract #: ZAX-8-17647-06	**Contract Period:** 5/8/98–7/7/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">First Solar, LLC.
1702 North Westwood Ave.
Toledo, Ohio 43607</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 9</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
J. Bohland
Phone: 419-534-3377 Fax: 419-534-2794</td></tr>
<tr><td rowspan="2">Technical Monitor:
Richard Mitchell
Phone: 303-384-6479
Fax: 303-384-6604
E:mail: richard_mitchell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Solar Cells, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $554,000
1999: $840,167</td><td>Cost Share Funding:
1998: $249,714
1999: $378,764</td></tr>
</table>

Project Objective: The objective of this subcontract over its three-year duration is to continue the advancement of the First Solar manufacturing technologies in order to: develop high-throughput, low-cost processes for the lamination, potting and laser scribing portions of the First Solar's CdTe module manufacturing line; improve acceptance of First Solar products into existing and new markets and improve the acceptance and variety of the First Solar product line to provide an opportunity to penetrate market segments other than those which are served by its standard frameless, 60cm x 120cm module; and establish a safety, health and environmental program which will place First Solar in a leadership position relative to comparable businesses both within and outside of the photovoltaic industry.

Approach/Background: First Solar will meet these objectives by:

- Developing low-cost lamination processes with throughputs raised from 18 modules/hour to at least 30-modules/hour while simultaneously reducing labor costs by 50% and lowering capital requirements by a factor of four,
- Developing high-throughput, low cost potting by increasing potting line throughput by a factor of at least four, reducing labor costs by at least a factor of ten, and increasing overall quality,
- Developing improved laser scribing techniques and equipment by engaging industry experts and vendors to implement state-of-the-art techniques and automation,
- Certifying First Solar modules according to IEEE 1262 and UL 1703 in three successive, evolutionary steps depending on product changes due to market demand and product changes, and
- Refining and improving environmental, health and safety programs including use of external industry experts leading to ISO 14,000 certification and implementation of best-demonstrated-practices of world class programs.

Status/Accomplishments:

- Completed design specification for high throughput laminator, initiated debugging, and prove-in at a rate of thirty modules per hour.
- Achieved a ten-fold reduction in unit related capital costs and a 90% reduction in unit related labor costs. These results exceed the program objectives of a four-fold reduction in capital costs and a 50% reduction in labor costs.
- Passed IEEE 1262 Sequence "A" testing (200 thermal cycles), Sequence "B" up to heat-humidity -freeze cycling, Sequence "C" up to damp heat testing and Sequence "F".
- Initiated preliminary qualification testing of the standard First Solar module for IEEE 1262, IEC 1215, and UL 1703.
- Completed implementation of critical ES&H improvements on the First Solar production line with the assistance of industry experts such as the Ohio Bureau of Workers' Compensation. Highlights include improvement of local ventilation controls for cadmium in the edge deletion, laser and cadmium chloride application processes, the implementation of a comprehensive lockout-tagout program in conjunction with electrical safety training, first aid, bloodborne pathogens and CPR training, material handling and fork truck training as wellas a revised respirator training program. A comprehensive facilities emissions survey was done to demonstrate compliance with environmental regulations.

- Completed a thorough review of First Solar’s potting preparation and potting processes including time studies, equipment utilization, materials yield, and flow.

Planned FY 2000 Milestones:
- Complete modifications to First Solar potting process including improvements in methodology and resource allocation
- Complete qualification testing on First Solar’s modified module for IEEE 1262, IEC 1215, and UL 1703.
- Complete comprehensive ES&H assessment First Solar’s production facility including prioritization of improvement areas; established measurement targets; and comparisons to industry historical levels.
- Complete review of First Solar’s laser scribing process including parameter flexibility, capital costs, and cycle time.
- Complete industry survey to determine additional needs for pursuing ISO 14000 certification
- Complete a thorough review of First Solar’s potting preparation and potting processes including time studies; equipment utilization; materials yield; and flow.

Major Reports Published in FY 1999:
J. Bohland, K. Kormanyos, G. Faykosh, V. Champion, S. Cox, M. McCarthur, T. Dapkus, K. Kamm, and M. Flis, “Specific PVMaT R&D in Cd Te Product Manufacturing,” Annual Subcontract Technical Report, 8 May 1998 - 4 May 1999, NREL/SR-520-27574, (submitted for publication).

Major Articles Published in FY 1999: None

PVMaT

Manufacturing Cost and Throughput Improvements for CIGS-based Thin Film PV Modules

Contract #: ZAX-8-17647-11	**Contract Period:** 7/7/98–9/6/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Global Solar Energy 12401 W. 49th Avenue Wheat Ridge, CO 80033	
	Organization Type: IN	**Congressional District**: 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** R. Wendt, S. Wiedeman **Phone:** 520-546-6313 x 18 **Fax:** 520-546-6318	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Global Solar Energy
	DOE Funding Allocation: 1998: $290,000 1999: $788,030	**Cost Share Funding:** 1998: $136,471 1999: $264,885

Project Objective: The objective of this PVMaT subcontract over its three-year duration is to improve speed and yield for manufacturing thin-film CIGS PV modules. Areas identified that had the greatest impact on manufacturing yield and speed were: (1) high rate all-laser layer-specific scribing for monolithic integration; (2) eliminating screen printing by development, of commercial ink-jet techniques for high-speed, large-area thin-film PV module fabrication on a flexible substrates; (3) development of uniform, high rate (27 cm/min) absorber deposition with high materials utilization; (4) in-situ measurement and control of CIGS properties ; and (5) the development of a more robust back contact as a replacement for molybdenum to decrease the cost by over 50% and substantially reduce scheduled and unscheduled downtime.

Approach/Background: Global Solar Energy will meet these objectives by:

- Refining the all-laser, multiple-beam, high-speed scribing method for all CIGS PV layers, resulting in 23cm/sec beam translation speeds while achieving high yields using advanced machine vision control.
- Designing and adapting commercial ink-jet printing for module manufacturing to replace screen-printing.
- Integrating ink-jet printing into laser scribing equipment in the manufacturing production line resulting in freedom to generate complex patterns to tailor module performance voltage and current specifications.
- Modifying existing multi-source co-evaporation sources for high-rate CIGS deposition process on a continuous moving flexible substrate in production-based equipment .
- Optimizing source-sequence and relative flux profiles to achieve high efficiency at fast deposition rates.
- Designing, building and integrating Parallel Detector Spectroscopic Ellipsometer (PDSE) into the thin-film CIGS production line.
- Developing algorithms for real-time, full closed-loop control of CIGS thickness and stoichiometry.
- Developing alternative back contacts that are more amenable to high rate production and result in less debris generation.

Status/Accomplishments: Several significant technology improvements were demonstrated in Phase I of this subcontract, some exceeded the third-year milestones. Key Phase I accomplishments include:

- Developed and demonstrated a selective all-laser monolithic integration process with rates of 23 cm/sec.
- Demonstrated back contract ‘through’ scribes at 30 and 46 cm/sec, exceeding Phase 3 speed goals.
- Adapted commercial ink jet printing technology to monolithic integration.
- Established parameters to print and cure fine insulator lines at rates up to 30-cm/sec (exceeding the Phase III PV-MAT program goal).
- Modified proprietary GSE effusion sources resulting in CIGS deposition rates of up to 24-in/min (400% of the base rate).
- Deposited CIGS at 300% of base rates resulting in device quality material with >8% efficiency.
- Demonstrated PDSE (Parallel Detector Spectroscopic Ellipsometry) in-situ analysis of CIGS.
- Developed algorithms for rapid real-time collection and interpretation of PDSE data to determine CIGS composition, band-gap and thickness.

- Developed new bi-layer back contact for flexible polymer substrates that is more compatible for fabricating modules.
- The new bi-layer reduced overall cost of back contact raw materials and substantially reduced scheduled downtime for debris removal.

Planned FY 2000 Milestones:
- Integrate high speed scribing processes into manufacturing equipment, demonstrate robust and repeatable scribing.
- Complete analysis and integration of industrial ink-jet hardware into production based equipment for high-speed module manufacturing.
- Complete evaluation of CIGS deposited at increased rates in production-based equipment. Determine the effect of CIGS deposition rate on composition profile, binary phase formation, and film adhesion.
- Complete testing of PDSE in the 15-cm web coater and install in the production based equipment.
- Complete characterization and analysis, and select alternate back contact material and process for alternate back contact deposition on flexible polymer and stainless steel substrates at 12 inches/min

Major Reports Published in FY 1999:

Wiedeman, S., Wendt, R.G., "Photovoltaic Manufacturing Cost and Throughput Improvements for Thin Film CIGS based Modules," Annual Subcontract Technical Report, 7 July 1998 - 6 July 1999, NREL/SR-520-27590, (submitted for publication).

Major Articles Published in FY 1999: None

PVMaT Monolithic a-Si Modules on Continuous Polymer Substrates

Contract #: ZAF-5-14271-4	**Contract Period:** 7/5/95–12/31/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Iowa Thin Film Technologies
2501 North Loop Drive
Ames, Iowa 50010</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 3</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
F. Jeffrey
Phone: 515-292-7606 Fax: 515-294-9584</td></tr>
<tr><td rowspan="2">Technical Monitor:
Richard Mitchell
Phone: 303-384-6479
Fax: 303-384-6604
E:mail: richard_mitchell@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Iowa Thin Film Technologies</td></tr>
<tr><td>DOE Funding Allocation:
1995: $937,375 1998: $605,553
1996: $265,000 1999: $162,000
1997: $697,781</td><td>Cost Share Funding:
1995: $890,000 1998: $202,104
1996: $0 1999: $64,007
1997: $0</td></tr>
</table>

Project Objective: The objective of this PVMaT subcontract over its three-year duration was to advance Iowa Thin Film Technologies' manufacturing technology through manufacturing process research and development in order to reduce module manufacturing costs on the ITFT production line by 68%, increase a-Si module performance, and provide the groundwork for expansion of their production capacity.

Approach/Background: Iowa Thin Film Technologies was to meet these objectives by increasing the throughput of their metalization, a-Si deposition, laser-scribing and welding processes and by automating the module assembly and test process.

Status/Accomplishments: During this subcontract, ITFT increased throughput and decreased costs in nearly all aspects of its thin-film a-Si photovoltaic manufacturing process. Overall manufacturing costs were reduced by 61% through the implementation of several manufacturing line improvements developed under this program. Specific accomplishments include:

- Incorporated a 1-mil substrate rather than the standard 2-mil substrate on their production line resulting in a and 50% cost-saving for this material,
- Completed process development of on a single-pass a-Si deposition system resulting in a 37% throughput improvement.
- Implemented process and machine improvements on TCO deposition system resulting in a throughput improvement of 275% including; detailed parameter optimization of deposition temperatures, process gas flows, carrier gas flows, and web speeds.
- Developed a new alignment technique for both the laser scriber and printer systems, improving registration accuracy from 100 microns to 10 microns, reducing alignment time significantly, and increasing throughput by 75% on the scriber and 600% on the printer.
- Designed and implemented new automated techniques for the module assembly processes including; automated busbar attachment, roll based lamination, and automated die cutting of finished modules, resulting in throughput improvements ranging from 200% to 1200% relative to hand labor rates.
- Designed and implemented an automatic test machine that improved throughput by 300% relative to hand testing procedure and reduces human handling errors.
- Identified a combination encapsulation material with a cost that is only 10% of standard EVA /Tefzel and is suitable for medium lifetime applications.

Planned FY 2000 Milestones: None - Contract Completed in October of 1999.

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None

PVMaT

Project Management

Contract #: DE-AC36-99G010337	Contract Period: 10/1/98–9/30/99

Sponsoring Office Code: EE-11	Performing Organization(s)	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District**: 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** C. E. Witt **Phone**: 303-384-6402 **Fax**: 303-384-6490 **E:mail**: ed_witt@nrel.gov Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail**: richard_mitchell@nrel.gov Holly Thomas **Phone**: 303-384-6400 **Fax**: 303-384-6604 **E:mail**: holly_thomas@nrel.gov Marta Symko-Davies **Phone**: 303-384-6528 **Fax**: 303-384-6490 **E:mail**: marta_symko_davies@nrel.gov	
Technical Monitor: Larry Kazmerski **Phone**: 303-384-6600 **Fax**: 303-384-6601 **E:Mail**: larry_kazmerski@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $1,261,726	**Cost Share Funding:**

Project Objective:
- Help the U.S. PV industry improve module manufacturing processes and equipment.
- Accelerate manufacturing cost reductions for PV modules, balance-of-systems components, and integrated systems.
- Increase commercial product performance and reliability.
- Enhance the investment opportunities for substantial scale-ups of U.S.-based PV manufacturing plant capacities.

Approach/Background:
- The Project is a government/industry research and development (R&D) partnership between the U.S. federal government (through the U.S. Department of Energy [DOE]) and members of the U.S. PV industry.
- Multi-year projects are being carried out through cost-shared awards made in response to competitive solicitations.
- Each proposal from the U.S. photovoltaic industry is evaluated by panels of experts in the technology, manufacturing, business planning, and applications, including utility executives.
- Funding identified here supports technical management, subcontract administration, fees, and other direct recharges in support of subcontracts awarded under this project and described under the PVMaT Technology Area in this Project Summary.

Status/Accomplishments:
- Completed definitization and renewal of on-going PVMaT subcontracts.
- Collected, analyzed, and reported on capacity/cost/recharge data from PVMaT participants.
- See individual subcontract summaries for specific technical accomplishments.
- Presented public papers to promulgate PVMaT results (see below).

Planned FY 2000 Milestones:
- Collect capacity/cost/recapture (CCR) data from PVMaT participants, 12/99
- Analyze CCR data and report on industry progress, 03/00
- Renew 3- year Subcontracts, 09/00
- Initiate solicitation with emphasis on in-line diagnostics and intelligent manufacturing for larger capacity manufacturing lines if congressional funding is appropriated, 09/00

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

Contract #: DE-AC36-99G010337

Major Articles Published in FY 1999:

Witt, C. E., et al., "Current Status and Future Prospects for the PVMaT Project," Proceedings of the 11th International Photovoltaic Science and Engineering Conference, Sapporo, Japan, September 20-24, 1999 (to be published).

Witt, C. E., et. al., "Terrestrial Photovoltaic Technologies Update," Proceedings of the World Conference on Renewable Energy and Environmental Protection, Alexandria, Egypt, November 7-11, 1999 (to be published)

Manufacturing and System Integration Improvements for One- and Two-Kilowatt Residential PV Inverters

Contract#: ZAX-8-17647-08	**Contract Period:** 7/17/98–12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Omnion Power Engineering Corporation P.O. Box 879, 2010 Energy Drive East Troy, WI 53120	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D. Porter **Phone:** 262-642-7200 **Fax:** 262-642-7760	
Technical Monitor: Holly Thomas **Phone:** 303-384-6400 **Fax:** 303-384-6604 **E:mail**: holly_thomas@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Omnion Power Engineering, Division of S&C Electronics
	DOE Funding Allocation: 1998: $ 96,000 1999:$357,404	**Cost Share Funding:** 1998: $ 41,143 1999: $153,173

Project Objective: The objective of this subcontract is to produce two inverter products that are easily manufactured, and are suitable for use in residential PV applications. Omnion will finalize designs and evaluate one-kilowatt and two-kilowatt (kW) single-phase inverters for utility-interconnected applications suitable for high-volume production (5,000 units/year). Features of the Series 2500 inverters will include features such as:

- Integrated AC and DC Disconnects to meet NEC and UL Requirements.
- Dedicated access for AC output and DC input terminal wiring.
- Laminated bus plane integrated into printed circuit board.
- Price of less than $.50/watt for the two-kW unit and less than $.75/watt for the one-kW unit.
- An estimated mean-time-between-failure (MTBF) equal to or exceeding 60,000 hours.

Approach/Background: Omnion will complete their work in two incrementally-funded phases. Omnion uses a four-step process for designing new products. Step I is product concept, Step 2 is prototype development, followed by pilot production, and full production. During Phase I Omnion will prototype the Series 2500 one-kilowatt and two-kilowatt inverters and proceed with a pre-production version of the products. These products will use the transformerless phase leg topology used by Omnion for its Series 2200. The input to the inverter has been modified by adding a buck-boost DC/DC converter that creates the negative half voltage. This means that the input voltage range can be broadened from the Series 2400 input voltage of ±180 to ±300 to the new Series 2500 voltage range of ±180 to ±500. This larger input voltage span shall make it easier to design a system because of the broader array voltage windows.

Status/Accomplishments: Omnion finalized the topology, selecting a unique transformerless topology allowing an input voltage of 100 to 400VDC with an output voltage of 120VAC. The topology uses a different grounding scheme. UL gave verbal approval to the approach. The topology makes the discovery of a ground fault very easy. A circuit was added to allow the system to operate with small ground faults. A series of breadboards were built to check the power and control circuits, and a bench prototype was then constructed.

Planned FY 2000 Milestones: In the next year Omnion plans to re-design the control and power circuit boards to get a working prototype. Several prototypes will be built. UL will review the ground fault scheme by looking at the effect of various ground faults on a working system. The integrated AC and DC disconnects will be reviewed by UL as well. A prototype will be delivered for evaluation. Manufacturing systems will be tested with the production of the prototypes, and refined as each prototype is completed. Changes will be made to improve manufacturability based on any problems found in building the prototypes. The result will be a production-ready Model 2500 inverter.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PVMaT

Three Phase Power Conversion System for Utility Interconnected PV Applications

Contract#: ZAF-14271-02	**Contract Period:** 8/17/95 - 9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Omnion Power Engineering Corporation, A Division of S & C Electronics P.O. Box 879, 2010 Energy Drive East Troy, WI 53120	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** D. Porter **Phone:** 262-642-7200 **Fax:** 262-642-7760	
Technical Monitor: Holly Thomas **Phone:** 303-384-6400 **Fax:** 303-384-6604 **E:mail**: holly_thomas@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Omnion Power Engineering Corp., A Division of S & C Electronics
	DOE Funding Allocation: 1995: $371,873 1998: $142,127 1996: $0 1999: $62,146 1997: $258,458	**Cost Share Funding:** 1995: $98,852 1998: $0 1996: $88,351 1999:$70,079 1997: $106,557

Project Objective: The objective of this Omnion subcontract over its three phases is to make advancements in three major areas of a 100 kW, three phase Power Conversion system (PCS): cost, reliability and performance. The advancement in each category are:

<u>Cost</u>: The total manufacturing cost of a nominal 100 kilowatt PCS will be reduced from approximately $.50/watt to $.25/watt when built in production lots of 100 units. This represents a cost reduction of 50%. In addition, this development will eliminate engineering charges which are typically incurred with these products, and can range from $.10 - $.20/watt.

<u>Reliability</u>: A design goal of 40,000 hours mean time between failures (MTBF) has been established for this development. Omnion has product today that reaches this goal but also has product that does not. Omnion's intent is to bring the average MTBF up to this level.

<u>Performance</u>: Three performance goals have been established to 1) improve converter efficiency from 95.5% to 96.5%, 2) meet FCC regulations for electromagnetic interference, and 3) reduce audible noise to below 60 decibels.

Approach/Background: The objective of this phase of the subcontract is to implement design modifications from the prototype PCS 3300 into the pilot production and preproduction versions of this product, then to complete the UL testing required to qualify for listing.

Status/Accomplishments: Production of 3300's was started and two fielded units are all working well. This 100 kW, 3-phase inverter makes use of better packaging of the Insulated Gate Bipolar Transistors (IGBTs) that were developed for the motor drive industry. To support the production, an O&M Manual was developed. For internal use, an assembly manual was developed that shows each of the steps in building a 3300. A 3300 was built to send through the UL listing set of tasks. Much of the work is complete, but some of the testing still needs to be done. Omnion completed rain testing, but used a gasket material that is not UL approved. The output EMI filter is not UL listed.

Planned FY 2000 Milestone: None, subcontract completed during FY99

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PVMaT

Manufacturing of the PVI Power Grid

Contract #: ZAF-5-14271-11	**Contract Period:** 10/27/95–7/15/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Photovoltaics International 171 Commercial Street Sunnyvale, CA 94086	
	Organization Type: IN	**Congressional District:** 14
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** W. Bottenberg **Phone:** 408-746-3062 x207 **Fax:** 408-746-3890	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Photovoltaics International
	DOE Funding Allocation: 1995: $248,500 1997: $1,085,000 1996: $1,072,447 1998: $1,056,402	**Cost Share Funding:** 1995: $106,500 1997: $465,000 1996: $459,620 1998: $452,744

Project Objective: The objective of this PVMaT subcontract over its three-year duration is to advance Photovoltaics International manufacturing technology through manufacturing process research and development in order to reduce its linear concentrator module volume manufacturing costs to $2.00/Watt, increase module performance, and provide the groundwork for expansion of its production capacity to 50 MW/yr.

Approach/Background: Photovoltaics International was to meet these objectives by:
- Developing a high-volume (50 MW/yr) production technology for extruded lenses,
- Developing a (25 MW/yr) high-volume technology for the production of module sides panels and endcaps,
- Developing a parallel-process for automated receiver assembly,
- Developing a roll-forming technology for the fabrication of panel frame members, and
- Eliminating volatile organic materials in receiver fabrication and for bonding plastic collector components without solvent adhesives.

Status/Accomplishments:
- Completed optimization and testing of both the revised closed-loop process control system for lens extrusion, and a fabrication process for a revised collector with roll formed metal sides and metal endcaps
- Completed one-month long production demonstration run on the PVI concentrator module manufacturing line. This run demonstrated the scalability of the process to 50MW levels with projected manufacturing costs of less than $2.00/Watt.
- Demonstrated the first-ever ethylene-vinyl-acetate (EVA) encapsulation system for PV concentrators, thereby eliminating volatile organic compounds and hazardous materials in the PVI encapsulation process.
- Developed an in-house extrusion system and an advanced automated cell assembly station that produce high quality assemblies at low labor cost.
- Introduced roll-formed steel panel frame members into production with dramatically cost reductions.
- Developed a snap-together module assembly that provides low-cost field assembly of components and thereby also greatly reduced shipping cost.

Planned FY 2000 Milestones: None - Contract Completed in FY1999

Major Reports Published in FY 1999:
Kaminar, N.R., Alexander, T., Amaya, A., Bottenberg, W.R., Carrie, P., Chen, K., Hobden, P., Lawyer, G., Zimmerman, J., and Sherring, C., "PVMaT Improvements in the Manufacturing of the PVI Powergrid," Final Technical Report, 27 October 1997- 31 October, NREL/SR-520-26661, (October 1999**)**

Major Articles Published in FY 1999: None.

PVMaT

PowerGuard® Advanced Manufacturing

Contract#: ZAX-8-17647-12	**Contract Period:** 6/10/98–8/30/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">PowerLight Corporation
2954 San Pablo Avenue
Berkeley, CA 94710</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 9</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Tom Dinwoodie
Phone: 510-540-0550 Fax: 510-540-0552</td></tr>
<tr><td rowspan="2">Technical Monitor:
Holly Thomas
Phone: 303-384-6400
Fax: 303-384-6604
E:mail: holly_thomas@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
PowerLight Corporation</td></tr>
<tr><td>DOE Funding Allocation:
1998: $275,000 1999:$452,623</td><td>Cost Share Funding:
1998: $310,106 1999: $622,823</td></tr>
</table>

Project Objective: The objective of this subcontract is to continue the advancement of PowerLight Corporation (PowerLight) PV manufacturing technologies in order to reduce cost, increase manufacturing capabilities and provide PV systems incorporating financing options. PowerLight plans to demonstrate system costs of $3.05/W and complete manufacturing improvements for PowerGuard® tile fabrication capability of 16 MW/yr, and stimulate US PV laminate manufacturing expansion by 2 MW/year.

PowerLight plans to reduce PowerGuard® system costs through 1) improvements in manufacturing technology related to system (non-module) components, 2) product design enhancements, 3) increased production capacity, 4) enhanced system reliability and performance, and 5) strategic alliances to leverage PV module technical improvements and cost reduction.

Approach/Background: Under this planned three-phase subcontract PowerLight Corporation (PowerLight) will address the PVMaT goals of manufacturing improvements directed toward innovative, low-cost, high-return, high-impact PV products. PowerLight incorporates financing, safety and reliability in its building-integrated PV product. The approach is to introduce incremental improvements to their system components and manufacturing processes to reduce Balance of System (BOS) costs to $2.00/W. PowerLight has also selected US strategic partners to achieve additional cost reductions and leverage the PV laminate manufacturing enhancements. Finally, by the end of this subcontract PowerLight expects to expand PV laminate production capacity with a US manufacturer, due to demand for the PowerGuard® product, by approximately 2 MW/yr of laminates, with total PowerGuard® tile fabrication capacity in excess of 16 MW/yr.

Status/Accomplishments:

- Reduced total installed system costs from $5.80/W down to $4.80/W for systems of 250 kW or greater using the PowerGuard® PV system.
- Increased PowerGuard® product production capacity from 5 to 20 MW per year, exceeding this year's goal. Advancements leading to the cost reduction include semi-automating junction box attachment, reducing the assembly costs of electrical quick disconnects by 75%.
- Improved the extruded polystyrene (XPS) processing by increasing processing speed by over 50%, reduced the number of required operators by 50% and improved router cutting precision from the planned =/- 1/8 inch to a repeatable 0.002 inch.
- Other reductions included reducing the number of operators for the cementicious coating by 50%, improving uniformity of the coating by over 50%, and reducing shipping costs for pre-designed systems by 25% through packaging design improvements.
- Advanced several design improvements to the Trace Technologies grid-tied inverter control board, including controller redesign, integrated data acquisition system(DAS), and communications for audit-worthy verification of PV system performance.

PowerLight produces a PV system mounting PV modules (crystalline or thin-film) on a 3-inch-thick styrofoam board coated with a proprietary cementitious coating. The PowerGuard® system can be mounted on any flat or slightly sloped roof and installed with flat or sloped PV tiles. In July 1999, the company moved into new manufacturing facilities in California, and is completing the semi-automation of a new production line.

Contract#: ZAX-8-17647-12

Planned FY 2000 Milestones: PowerLight plans to achieve the following:

- Demonstrate system cost reduction from$4.80/Wp to $<3.80/Wp;
- Complete the updating of the manufacturing layout master plan for integration of automated component stations;
- Complete design, development and production-based assessment of automated, integrated XPS processing, PV placement, and materials handling between stations;
- Develop methods of packaging which lower packaging and shipping costs by 25%;
- Complete improvements to their Retrofit PowerCurb (RT) housing, harness assemblies and source circuit combining circuitry resulting in cost reductions (materials and labor) of 50%
- Complete wind tunnel testing of RT securement, the sloped tile assembly, and the field assembly system to confirm fluid dynamic modeling and to establish wind zone design guides;
- Submit modified system to UL and international organizations for listing/certifications on PowerGuard® improvements;
- Complete comparison testing of inverter under motor induction load and IEEE 929/UL1741 standards.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PVMaT

Specific R&D Problems in Product Manufacturing

Contract #: ZAX-8-17647-14	**Contract Period:** 6/22/98–8/21/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Siemens Solar Industries P.O. Box 6032 4650 Adohr Lane Camarillo, CA 93011	
	Organization Type: IN	**Congressional District:** 23
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. Jester **Phone:** 805-388-6500 **Fax:** 805-388-6557	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: Siemens Solar Industries
	DOE Funding Allocation: 1998: $350,000 1999: $984,438	**Cost Share Funding:** 1998: $350,000 1999: $984,438

Project Objective: The objective of this PVMaT subcontract over its three-year duration is to continue the advancement of Siemens PV manufacturing technologies in order to develop and optimize silicon ingot growth, wafer sawing, and solar cell processes (which are necessary to manufacture 125-micron wafers and cells), as well as crystal growth processes for the production of 200-mm diameter Cz silicon ingots. Additionally, Siemens will develop improved modules using the new 200-mm diameter cells, and develop and optimize processes for the reduction, and re-use of waste material from both the Siemens wafer and cell manufacturing processes.

Approach/Background: Siemens Solar Industries will meet these objectives by:
- Developing and integrating new optimized cell fabrication processes into their manufacturing line for the production of 17% efficient, 125-mm cells with a 30% reduction in the cell manufacturing cost.
- Developing a large-area cell production capability for 200-mm diameter, 4.5-watt prototype solar cells and low-cost prototype modules to reduce module manufacturing cost by 20%, and
- Initiating Siemens' Environmental, Safety and Health activities directed toward reducing their hazardous waste by over 50% through recycling and re-use of slurry materials in their wire saw process and an over 70% reduction in caustic waste.

Status/Accomplishments:
- Completed development of pilot crystal growth process for quality ingots to be cut in 150-micron wafers and produce 125-micron cells.
- Completed the development of an auto-boating process for 150-micron wafers
- Demonstrated prototype 125-micron 16% efficient solar cells.
- Completed the development of a pilot process for fabrication of 125-micron thick BSF solar cells.
- Demonstrated the ingot growth of 200-mm diameter Cz silicon and initiated development of 200-mm diameter cell fabrication processes.
- Completed proof-of-concept testing for a SiC recycling process in pilot production for the separation of caustic materials and water from cell wet-line effluent.
- Demonstrated a recycling system capable of 10% recovery and re-use of SiC in the wafer slicing process.

Planned FY 2000 Milestones:
- Implement "auto boating" in pilot production of 150-micron wafers.
- Complete the implementation of a pilot production of 125-micron thick solar cells, with an 80% mechanical yield and a 20% reduction in manufacturing cost
- Demonstrate manufacturing process for 125-micron thick, 16.5% efficient solar cells.
- Complete plan for development of tooling to handle boat to boat transfers in the production line.
- Demonstrate 200-mm diameter wafer and cell fabrication resulting in low-cost frameless modules.

Contract #: ZAX-8-17647-14

- Demonstrate a 200-mm diameter 4.0-Watt solar cell.
- Complete report on a process for the production of 200-mm diameter cells and on a module design with a 10% reduction in module manufacturing costs.
- Demonstrate 20% recycling of SiC in wafering.
- Demonstrate a 13% reduction of waste volume in cell fabrication wet-line process.
- Demonstrate prototype 125-micron thick, 17% efficient solar cells.
- Complete process development for 200-mm diameter solar cells.
- Complete design of recycling production equipment for SiC recovery and oil treatment from wafering slurry.

Major Reports Published in FY 1999:
Jester, T., "Specific PVMaT R&D on Siemens Cz Silicon Product Manufacturing," Annual Subcontract Technical Report, 22 June 1998- 21 June 1999, NREL/SR-520-27591, (submitted for publication).

Major Articles Published in FY 1999:
Jester, T., Mihalik, G., Matthaus, A., "The effects of Hotzone Modifications on Czochralski Grown Solar Cells," Ninth workshop on Crystalline Silicon Solar Cell Materials and Processes, Beaver Run Resort, Breckenridge, Colorado, August 9-11, 1999

Jester, T., Nickerson, J., "Mechanical Strength Evaluation and Plans," Ninth workshop on Crystalline Silicon Solar Cell Materials and Processes, Beaver Run Resort, Breckenridge, Colorado, August 9-11, 1999

PVMaT

High Throughput Manufacturing of Thin Film CdTe Photovoltaic Modules

Contract #: ZAI-4-11294-2	**Contract Period:** 11/16/93-3/15/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail**: Richard.King@ee.doe.gov	Solar Cells, Inc. 1702 North Westwood Ave. Toledo, Ohio 43607 **Organization Type**: IN	 **Congressional District:** 9
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** D. Sandwisch **Phone:** 419-534-3377 **Fax:** 419-534-2794	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1994: $1,189,385 1995: $100,000 1996: $500,000 1997: $1,051,391 1998: $290,230	**Cost Share Information**: Solar Cells, Inc. **Cost Share Funding:** 1994: $1,189,385 1995: $100,000 1996: $214,286 1997: $709,872 1998: $1,588,630

Project Objective: The objective of this subcontract over its three year duration is to advance Solar Cells, Inc.'s PV manufacturing technologies through manufacturing process research and development in order to reduce module production costs, increase CdTe module performance, and provide the groundwork for expansion of SCI's commercial production capacities.

Approach/Background: Solar Cells, Inc. was to meet these objectives by designing, debugging, and operating a multimegawatt/year automated, continuous PV manufacturing line that produces 60cm x 120cm thin-film CdTe coated plate and modules.

Status/Accomplishments: During this subcontract, Solar Cells, Inc. developed their Cadmium telluride (CdTe) technology and initiated scale-up of its pilot production capabilities to a multi-megawatt level. Accomplishments during the last phase of this subcontract included improvements in product definition, process definition, equipment engineering, and support programs development, including:

- Demonstrated production rate operation of the new high-throughput laminator.
- Demonstrated 60-substrates/hour production rate on 20MW deposition equipment.
- Demonstrated 15 modules/hour production rate for one week on multi-megawatt line
- Demonstrated a standard deviation for module efficiency of $< \pm 7.5\%$ on production modules
- Demonstrated 1000-ft^2/hr production rate on Advanced High-Throughput Deposition System
- Demonstrated a 60.3-W thin-film CdTe module with total-area efficiency of 8.4%;
- Improved module pass rate for interim qualification test protocol from < 20% to 100%
- Completed the specification and demonstration of two products — a grid-connected, frameless, high-voltage product that incorporates a pigtail potting design and a remote low-voltage product that may be framed and may incorporate a junction box.
- Completed definition of multi-megawatt manufacturing process and demonstrated several of key processes improvements on their 100-kW pilot line which now operates as a 250-kW production line.
- Completed conceptual design layout of new multi-megawatt CdTe production lines, and projected an optimized capacity with two-shift/day operation of greater than 25 MW at a manufacturing cost of below $1.00/W.

Planned FY 2000 Milestones: None - Contract Completed in FY1999

Major Reports Published in FY 1999:
Sandwisch, D.W., "High Throughput Manufacturing of Thin-Film CdTe Photovoltaic Modules", Final Subcontract Technical Report, 16 November 1993- 31 December 1998, NREL/SR-520-26435, (August 1999)

Major Articles Published in FY 1999: None

Improvements in Polycrystalline Silicon PV Module Manufacturing Technology

Contract #: ZAX-8-17647-05	**Contract Period:** 5/4/98–7/3/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Solarex 630 Solarex Court Frederick, MD 21701	
	Organization Type: IN	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** J. Wohlgemuth **Phone:** 301-698-4375 **Fax:** 301-698-4201	
Technical Monitor: Richard Mitchell **Phone**: 303-384-6479 **Fax**: 303-384-6604 **E:mail:** richard_mitchell@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Solarex
	DOE Funding Allocation: 1998: $470,000 1999: $928,235	**Cost Share Funding:** 1998: $489,184 1999: $879,837

Project Objective: The objective of this subcontract over its three year duration is to advance the of Solarex PV manufacturing technology in order to design and implement a process which produces polycrystalline silicon PV modules that can be sold profitably for $2.00 per peak watt or less and which increases the production capacity of the Frederick plant to at least 25MW/year.

Approach/Background: Solarex will meet these objectives by:

- Developing a process to produce silicon feedstock from commercial grade H_2SiF_6 that can be sold profitably for less than $15/kilogram in large quantities to industrial Silicon PV manufacturers,
- Improving the control of their casting process to increase yields and improve material quality through a new automated casting control system,
- Reducing their wire saw center-to-center cut distance to less than 450µm in production,
- Developing a glycol-based slurry system that does not require organic cleaners and eliminates the generation of hazardous waste material,
- Developing a method to recycle a significant fraction of their silicon carbide grit,
- Demonstrating and implementing a cost-effective, robust cell process that produces a minimum average cell efficiency of 15% and improves the cell line electrical yield,
- Developing and qualifying an encapsulation system that meets technical and reliability requirements and can be laminated and cured in less than 6 minutes in the present Solarex laminators,
- Refining three specific production line process areas for improved product and materials handling to increase production line yield and reduce labor,
- Improving process measurement and control in their production line and reduce rework through the implementation of an improved information system, and
- Developing and implementing a brick identification system.

Status/Accomplishments:

- Identified sources and procured raw materials for the H_2SiF_6/Na process
- Completed preliminary design of pilot facilities to produce SiF_4 from H_2SiF_6 and for storage and handling
- Completed installation of new automated casting control system on all stations.
- Completed the development of thinner wire in wire sawing of Silicon bricks and transferred process to the manufacturing line.
- Completed experimental evaluation the economics of silicon carbide recycling.
- Completed laboratory development of the PECVD silicon nitride AR coating process.
- Completed the development and implementation of an Al Back Surface Field process and a fine-line screen printing process and transferred both to the production line.
- Completed evaluation and initial laboratory compounding trials on fast-cure encapsulation formulations.
- Completed development of a process for SiC recycling.

- Completed preliminary evaluation of an oil recycling process.
- Completed development cell processing equipment using Shimadzu silicon nitride.

Planned FY 2000 Milestones:

- Complete laboratory and pilot line verification of process to produce Si feedstock from H_2SiF_6/Na
- Complete the initial set of experiments to determine if H_2SiF_6 and SiF_4 can be obtained economically from spent fluid catalytic cracking material and/or from fossil fuel combustion byproducts.
- Complete engineering support for design of H_2SiF_6/Na-process solar-grade-silicon production facility.
- Complete implementation of ceramic handling and slip dispensing equipment.
- Complete the first set of *Design of Experiment* casting experiments.
- Complete transfer of SiC recycling process to production.
- Complete installation of oil recycle equipment and complete and evaluate economics.
- Complete wire saw process optimization on the Solarex production line.
- Complete evaluation of candidate methods for detecting cracks in wafers and in finished cells.
- Complete cost analysis for reductions in consumable costs by at least $0.05/wafer.
- Complete environmental qualification of selective emitter process.
- Complete design and development of ultrasonic doper prototype and complete environmental testing of cells from the new doper.
- Complete design, fabrication, and installation of silicon-nitride production deposition system.
- Complete evaluation of candidate methods for in-line, non-destructive testing of cell interconnects.
- Complete the fabrication of modules incorporating fast cure encapsulant and initiate environmental and outdoor testing.

Major Reports Published in FY 1999:
Wohlgemuth, J., "PVMaT Improvements in the Solarex Photovoltaic Module Manufacturing Technology," Annual Subcontract Technical Report, 4 May 1998- 3 May 1999, NREL/SR-520-27643, (submitted for publication).

Major Articles Published in FY 1999: None

PVMaT

Post-Lamination Manufacturing Process Automation for Photovoltaic Modules

Contract #: ZAX-8-17647-04	**Contract Period:** 6/10/98-12/19/2000

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Spire Corporation
One Patriots Park
Bedford, MA 01730-2396</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Michael J. Nowlan
Phone: 781-275-6000 Fax:781-275-7470</td></tr>
<tr><td rowspan="2">Technical Monitor:
Marta Symko-Davies
Phone: 303-384-6528
Fax: 303-384-6490
E:mail: marta_symko_davies@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Spire Corporation</td></tr>
<tr><td>DOE Funding Allocation:
1998: $454,561
1999: $873,695</td><td>Cost Share Funding:
1998: $194,812
1999: $316,574</td></tr>
</table>

Project Objective: Spire Corporation is addressing the Photovoltaic Manufacturing Technology (PVMaT) project goals of PV module cost reduction and improved PV module manufacturing process technology. New cost-effective automation processes are being developed for PV module assembly after the solar cell lamination process. The development and implementation of these automated systems are expected to result in significant labor cost savings and increased throughput.

Approach/Background: The automated processes under development in this program include (1) a module buffer storage system, including conveyor load/unload and module storage, (2) an integrated edge process system, combining automated edge trimming, edge sealing, and framing capabilities, (3) a junction box installation system for attaching a junction box, and (4) an integrated module test system that combines high voltage isolation testing, ground continuity testing, and module performance testing. Proof-of-concept prototype systems will be developed and evaluated with module components from several US module manufacturers.

Status/Accomplishments: A module buffer storage with a conveyor load/unload named the SPI-BUFFER™ 350 was developed. Modules are stacked vertically on a cart for mobility and high storage density. This system has a conveyor speed of 20 cm/s, a storage capacity for modules up to 102 cm x 162 cm, and a storage depth of 51 cm. Spire also developed a system for transporting, probing, and testing modules for electrical isolation, ground continuity, and performance (I-V measurement), named the SPI-MODULE QA™ 350. Both of these developments were demonstrated to the PV industry in June, 1999, at Spire.

Spire demonstrated prototype processes for edge trimming, sealing and framing of modules. An evaluation report for the integrated test system was completed as well.

A cost study was completed during this year. It was shown that $2.37M can be justified for post-lamination automation at a production level of 10 MW/year (2 shifts/day, 5 days/week).

Planned FY 2000 Milestones: Design, build, test and evaluate an automated edge processing system for module edge trimming, sealing, and framing. This system will consist of two automated machines: an edge trimmer for trimming excess encapsulant and back cover film from module edges after lamination, and an edge sealer and framer for installing edge sealant and frames on trimmed modules. Both machines will have conveyors for module transport, allowing them to be placed together or separately as needed to suit the manufacturer's process sequence.

The edge trimmer will include a module aligner, a module lift, and a four-axis (x, y, z, θ) Cartesian robot with optical sensors for finding the glass edges and a hot knife for removing excess material. The sealer-framer will consist of a module aligner and lift, frame feeders, corner fastener feeders, dispensers for hot-melt edge sealant, a four-axis Cartesian robot with mechanical grippers for frame transport, and a two-axis frame press.

Detailed mechanical, electrical, and software designs will be completed for both machines. The machines will be fabricated, tested, and evaluated with module components from several US module manufacturers. A summary report of a technical review meeting on software and hardware designs for the edge process system is to be completed.
A junction box Design will be completed and work will begin to develop an automated junction box installation process.

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, pp. 373-376 (June 1999).

M.J. Nowlan, J.M. Murach, T.W. McCormick, E.R. Lewis, and S.J. Hogan, "Post-Lamination Manufacturing Process Automation for Photovoltaic Modules," Annual Technical Progress Report, Spire doc. ATR-10182-01 (1999).

M.J. Nowlan, J.L. Sutherland, E.R. Lewis, and S.J. Hogan, "Evaluation of an Integrated Test System," Spire doc. ER-10182-01 (1999).

Major Articles Published in FY 1999:
M.J. Nowlan, W.G. Kurth, T.D. Harmon, T.W. McCormick, J.M. Murach, W.F. Breen, S.J. Hogan, M.R. Diver, M.I. Symko, and S.R. Rummel, "A Photovoltaic Industry Survey on Post-Lamination Module Manufacturing," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference,* Denver, CO, September, 1998; AIP Conference Proceedings Vol. 462, pp. 725-730 (1999).

M.J. Nowlan, J.L. Sutherland, E.R. Lewis, and S.J. Hogan, "Evaluations of an Automated Photovoltaic Module Test System," abstract submitted to 16th European Photovoltaic Solar Energy Conference, Glasgow, UK, May, 2000.

PVMaT

Development of a Fully-Integrated PV System for Residential Applications

Contract#: ZAX-8-17647-02	**Contract Period:** 03/27/98–07/26/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Utility Power Group, Inc.
21250 Califa Street, Suite 111
Woodland Hills, CA 91367</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 24</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Gil Duran
Phone: 818-700-1995 Fax: 818-700-2518</td></tr>
<tr><td rowspan="2">Technical Monitor:
Holly Thomas
Phone: 303-384-6400
Fax: 303-384-6604
E:mail: holly_thomas@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Utility Power Group, Inc.</td></tr>
<tr><td>DOE Funding Allocation:
1998: $237,900 1999:$ 279,500</td><td>Cost Share Funding:
1998: $101,957 1999: $119,786</td></tr>
</table>

Project Objective: Objectives of this subcontract are to:

- reduce the total installed cost of residential, roof-top-mounted PV power systems;
- increase the reliability of these systems, and;
- expand the technology base which supports increasing US PV power system production capacity.

Utility Power Group (UPG) is working with its lower-tier subcontractor, Trace Technologies, Inc. to achieve a 30% reduction in total non-module related system costs through the development of a PV Array and Power Unit with direct material and direct labor costs below $\$4/ft^2$ and $0.45/W, respectively. The roof-top system will consist of a PV array, a Power Unit with a peak power maximum of 19 kW, and an optional Energy Storage Unit.

Approach/Background: The subcontract consists of two phases. During Phase I, UPG worked with its lower-tier subcontractor Trace Technologies, to design and test prototypes for each of the system elements — the PV Array, Power Unit, and Energy Storage Unit. The work included the design, development and thorough evaluation of prototypes for each element of the integrated residential PV system. Underwriter's Laboratories (UL) and other safety recognitions are planned, and UPG worked closely with UL to ensure the design meets applicable design requirements.

During Phase II, UPG is focusing on the refinement and evaluation of systems installed for beta testing. Each of the system elements will be reviewed, and Highly Accelerated Lifetime testing conducted on the Power Unit as part of the prototype evaluation. The final production prototype will be submitted to UL to apply for listing. By the conclusion of Phase II, UPG will demonstrate a low-cost, reliable, fully integrated residential PV system.

Status/Accomplishments: During FY 1999, UPG developed a Power Unit with a continuous power rating of 12 kW, with a peak power rating of 19.2 kw. UPG selected this power rating to meet large household requirements and to manage motor starts, such as air conditioners. Trace Technologies tested the prototype Power Unit and reports the continuous, full-power measured efficiency is 95.7%, exceeding the goal of 94%. UPG estimates , based upon a 100 Power Unit production run, the cost of materials and direct labor is $0.34/W, exceeding their $0.50/W goal by over 30%. The Power Unit incorporates algorithms to manage cycling and charging the Energy Storage (battery) Unit. The Power Unit is designed to charge the batteries from the utility grid or the PV array and can draw power from the PVand the batteries to meet short-term peak energy demands. The high frequency switching at 30 kHz makes this a quiet unit, well-suited for its planned application as a residential system. The Power Unit enclosure is weatherproof, NEMA-rated, and suitable for outdoor installation. Trace Technologies acquired the power engineering division of UPG in 1999 and is completing the development of the Power Unit.

The Energy Storage Unit is a 32-battery unit using Valve Regulated Lead Acid batteries employing absorbed glass mat technology. The batteries are in a tamper-proof, free-standing powder-coated enclosure, and the entire unit weighs roughly 1,000 pounds. The fan-ventilated storage unit will not be sold, but available to customers through lease. In this way, the customer does not have to deal with the batteries, and will simply call for a replacement when needed.

Contract#: ZAX-8-17647-02

The PV Array is a roof-mounted rail design using a roof-penetration method to attach the array to the roof. The array structure is designed to accommodate a variety of PV modules, including crystalline and thin film products. Each string will be rated at approximately 1.2 kW and the Power Unit will accept up to four strings, for a total PV capacity of 4.8 kW.

Planned FY 2000 Milestones: During FY 2000, the following achievements are planned:

- A fully-operational and code-compliant Power Unit and Energy Storage Unit will be delivered to Sandia National Laboratories for performance testing.
- UPG will demonstrate the performance of the modular, UL_ listed residential PV Array with a direct materials and labor cost (exclusive of PV module cost) below $\$4.00/ft^{2.}$
- Complete Highly Accelerated Lifetime Testing of the Power Unit.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None

Photovoltaic Module Thermal/Wind Performance Long Term Monitoring and Measurement

Contract #: ACQ-9-29610-01	**Contract Period:** 8/16/99–8/16/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Arizona State University
PO Box 873503
Tempe, AZ 85287-3503-</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Liang-Jun Ji
Phone: 480-727-1219 Fax: 480-727-1223</td></tr>
<tr><td rowspan="2">Technical Monitor:
Carl R.Osterwald
Phone: 303-384-6764
Fax: 303-384-6790
E:mail: carl_osterwald@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $27,479</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The purpose of this work is to aid the development of a consensus standard for rating modules by energy production by measuring the temperature of a group of photovoltaic (PV) modules as a function of wind speed, wind direction, total irradiance and possibly relative humidity. This data will be used to propose, investigate, and evaluate experimental methods for obtaining the ambient temperature and wind speed to module temperature transfer function for an arbitrary module.

Approach/Background: The current draft Institute for Electrical and Electronics Engineers energy ratings standard (IEEE PAR 1479) specifies the hourly irradiances, ambient temperatures, and wind speeds at which a module's maximum power is determined; these results are then integrated over time to obtain the energy produced during several reference days. Because each different module type may have a different thermal characteristic, a method of obtaining the actual module temperature from the ambient data is needed.

A group of modules has been installed for similar measurements at NREL's Solar Radiation Research Laboratory (SRRL) on top of South Table Mountain. The subcontract work will parallel the NREL work, with the exception that it be located in a hot, desert climate. In order to increase the confidence in any results, the measurements will be continued for as long as possible.

Status/Accomplishments: The first deliverable for this subcontract, documentation of initial installation of the test samples and operation of the data acquisition system, is due on 12/31/99.

Planned FY 2000 Milestones:
None at this time, however, if the option for an additional year of funding is exercised, additional deliverables will be specified.

Major Reports Published in FY 1999:
None.

Major Articles Published in FY 1999:
None.

Module and Array Performance and Reliability

Collector & Systems Testing Support

Contract #: 75-3058 and AK-0748A	**Contract Period:** 10/1/95–6/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	EG&G Albuquerque, NM 87119 **Organization Type**: IN	 **Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** E. Dawson **Phone:** 505-845-7111 **Fax:** 505-243-1021	
Technical Monitor: Michael A. Quintana **Phone**: 505-844-0474 **Fax**: 505-844-6541 **E:mail:** maquint@sandia.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1996: $230,000 1997: $120,000 1998: $54,000 1999: $81,000	**Cost Share Information**: **Cost Share Funding:**

Project Objective: Provide on-site technical support for module and cell testing and for module durability testing.

Approach/Background: Individual provides research and development in the areas of machining, controls, adhesion measurements, electrical and mechanical assembly of test apparatus, performance testing, and computer-aided design.

Status/Accomplishments: Contract terminated due to insufficient funding. Staff for nine months of the fiscal year with work centering on studies of Solarex adhesion and solder-joints, in addition to developing a method for cutting tempered glass.

FY 2000 Milestones: None. Contract terminated.

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None

Module and Array Performance and Reliability

Accelerated Testing of Materials and Encapsulated PV Cells

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. McMahon (Task Leader) **Phone:** 303-384-6762 **Fax:** 303-384-6790 **E:mail**: tom_mcmahon@nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **E:mail**: roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: N/A
	DOE Funding Allocation: 1999: $687,400	**Cost Share Funding:**

Project Objective: This Task is being performed in support of the PV Program to accelerate the development of PV technologies for a 30-yr service life of PV modules as targeted by DOE's *Solar 2000-A Collaborative Strategy*. The principal purposes of this task are (1) to develop and establish adequate accelerated weathering or exposure testing (*AWT/AET*) methodologies for investigating the photo, thermal, and electrical stability of various module technologies and encapsulation materials; (2) to identify by AWT/AET and to mitigate the causes or mechanisms of degradation; (3) to improve the materials, cells, interconnects, encapsulation conditions, and module processing methods; and (4) to collaborate with U.S. PV industry through (1 to 3) to improve reliability and stability.

Approach/Background: The R&D activities include performing AET studies, elucidating the photothermally and/or voltage-bias induced primary and other secondary degradation mechanisms of module materials, and testing new encapsulation materials and methods that are developed either in house, through CRADA/academic collaborations, or by PV manufacturers. The Task employs several AWT/AET methods to investigate the performance stability of a relatively large number of c-Si minimodules that are encapsulated by using various materials (e.g., superstrates, pottants, and substrates) and methods. A voltage-biased damp-heat (at 85^{O}C and 85 %RH) AET method is employed to investigate the performance reliability of commercial thin film a-Si modules. The NREL's high flux solar furnace is also used for studying EVA-laminated c-Si solar cells in collaboration with SNL. A number of analytical methods, including surface/interfacial analysis, and IV/QE measurements are employed to characterize and identify material and cell failure mechanisms resulting from AWT/ALT. Technology transfer is accomplished through presentations at professional meetings, publications of research results, and licensing negotiation of patent of the technology or materials developed.

Status/Accomplishments:

1. *Patent Application* of NREL IR#96-28 "Composition and Method for Encapsulating Photovoltaic Devices" (i.e., NREL-developed EVA formulations) was allowed in June, and issuance fee was paid in September 1999.
2. *Performance Stability of Cells, Minimodules, and Encapsulants by AET Studies.*
   We have shown that the electrical performance of encapsulated solar cells (c-Si and a-Si) exhibit irregular changes (increase or decrease) upon various AETs, and that AET conditions affect the discoloration pattern of encapsulant (of commercial EVA) over c-Si solar cells. We have upgraded the operation hardware and software for two Atlas Ci4000 weatherometers, and designed and fabricated three new special platform/chambers for AET studies using solar simulators.
   We have demonstrated that NREL-developed EVA formulations are the best among those tested in photothermal stability against discoloration without the protection of Ce-containing glass superstrate. The stability is better than (Japanese) Bridgestone EVA, and much better than Sovlux EVAs and commercial EVAs. We have also determined that some polymeric backing (substrate) foils, which are variously used in some of current modules, are not really suitable for encapsulation. The results will be conveyed through presentation/publication to PV manufacturers.
   We have overcome various technical difficulties and prepared a large quantity (~350) of encapsulated c-Si cells with different encapsulation materials (superstrates, pottants, and substrates). All the samples have been baselined with various optical and electrical characterizations that include %T (or %R), color indices, fluorescence, and Light/Dark I-V. Some selected samples were characterized additionally with Laser OBIC and impedance spectroscopic measurements. The samples will be used in various AWT and AET studies.
3. *AET Studies of Encapsulation Materials for PVMaT Contractors and CRADA Partnership.*
   We have performed various sample preparations, lamination/curing tests, chemical analyses, and photothermal stability studies by AETs for a Sovlux EVA from ECD/NREL CRADA and a (Japanese) Bridgestone EVA for Global Solar, a PVMaT contractor. The results are compared to the commercial EVA and NREL EVA formulations. Periodic reports are prepared and submitted to the participating parties. We also received a set of unencapsulated a-Si minimodules from Iowa Thin Film asking for roll-press lamination by using various encapsulation materials followed by AET studies. However, we were unable to perform the work because of equipment and manpower limitations.

Stress testing of EVA laminated, thin-film modules has begun in collaboration with the Module Testing/Tech. Validation Task by subjecting different modules to 85 C, 85% RH, and 600 V between the cells and the frame. We will monitor the leakage current to determine the charge leaking from the cell area to the frame. So far the threshold for damage is far below the values set by R.Ross years ago. We hope to develop a valid accelerated test for both module qualification and life prediction study.

Field wet hi-pot tests(FWHPTs) conducted at PVUSA showed very high current leakage with a huge temperature dependence that doubles with a 6 C rise. The bulk leakage current contribution thru the glass on these CdTe modules was calculated from values measured on an actual CdTe soda-lime superstrate glass. We find an ohmic behavior from 100 to 600 V with a bulk resisivity of 8.5 x 10^{9} ohm cm at 90 C with an activation of 0.862 eV down to 50 C. (Literature values are 15% higher with the same activation). "New" and "old" soda lime samples from AFG have about the same resistivities with the same activation energies. These values are very much less sensitive to temperature than the FWHPT currents measured at PVUSA and only account for 1/10 the leakage current. The excess leakage on PVUSA's modules must not be thru the glass and is most likely due to some other leakage path.

A collaboration between SNL and NREL was begun to study the effects of accelerated UV exposure on the adhesion properties of EVA in crystal silicon solar cell modules. We subject samples to UV radiant fluxes up to 100 times the ambient, while controlling the temperature. The *Hi-Flux Solar Furnace* uses 18 reflecting hexagonal facets to uniformly irradiate a target. In this case, dielectric mirrors reflect only the light in the spectral range from 280 nm to 450 nm. This reduces the heat load on the target, while depositing the high energy photons generally thought to be responsible for photodegradation of polymers in outdoor environments. A fixture for the furnace that allows a sample to be held in the target plane while being cooled has just been completed. A cover and flowing gas can be used to control the gas composition, temperature, and relative humidity over the sample.

4. *CdTe Reliability Activities*

   We continue to lead the reliability section of the National CdTe R & D Team in its activities.

   A summary of our AMPS device modelling was presented at a CdTe meeting. Our objective for running device simulations is to discover how a component of the cell, and variation of its electronic properties, can influence the performance of a solar cell. Causes for change in performance due to special processing or degradation as a result of environmental stress can be identified in this way. Conclusions were: 1. Roll-over, cross-over, and loss of V_{OC} can <u>all</u> be eliminated by reducing the back barrier to zero. 2. The trap concentration, depth, and crossection influence the cell performance through recombination <u>and</u> modification of the electric field profile. 3. The 0.32 eV conduction band offset between CdS and CdTe does not diminish performance. If interface states are a result of this discontinuity, then the performance may be diminished in a real device. 4. The negative curvature sometimes seen in the fourth quadrant-distinct from rollover-can be caused by an N-layer between the metal and the P-CdTe absorber. At that meeting we concluded that for reliability studies CdTe failure mechanisms from the field must be correlated with the CdTe R&D Team's accelerated stress testing results. Also we will rank order the known failure mechanisms.

5. *Subcontract Delivery and Other General Items*

   We have concluded a subcontract for "Fabricating a Portable Spectrophotometric and I-V Analyzer" by a group at the UC-Denver. The portable analyzer, a final report, software, manuals, and operation training were finally delivered in Feb. 1999. We have participated and presented 5 papers in the 15th NREL/SNL PV Program Review Meeting, the Solder-Joint Symposium at the Sandia National Laboratories, and the 41st Rocky Mountain Conference on Analytical Chemistry. We also provided various technical assistance to PV industry and academics (domestic and foreign) by the forms of paper reprints, discussion over phones, seminars, and/or e-mail communications.

Planned FY 2000 Milestones:

- Report on the Determination of the Activation Energy of I-V Performance Degradation of Encapsulated c-Si Solar Cells
- Report on the Electrical Performance Reliability of Encapsulated Solar Cells and Module Components by Accelerated Weathering Tests in Ci4000 Systems
- Publication (with Sandia) on IR Camera for Module Diagnostics.
- Update performance indicators of 30-yr. module lifetime

Major Articles Published in FY 1999:

1. F.J. Pern and S. H. Glick, "Photothermal Stability of Encapsulated Si Solar Cells and Encapsulation Materials upon Accelerated Exposures," Solar Energy Materials and Solar Cells, in press (SOLMAT #2104).
2. F. J. Pern and S. H. Glick, "Accelerated Exposure Tests of Encapsulated Si Solar Cells and Encapsulation Materials," AIP Conference Proceedings No. 462 of 15th NCPV PV Program Review meeting, Sept., 1998, Denver, Colorado, American Institute of Physics,, New York, 1999, pp. 559-564.
3. F. J. Pern, S. H. Glick, and A. W. Czanderna, "Review of the Photothermal Stability of EVA Pottants: Effects of Formulation on the Discoloration rate and Mitigation Methods." ibid, pp. 599-604.
4. Meier, S. H. Glick, and F. J. Pern, "Impedance Spectroscopy as a Non-Invasive Analytical Method for Monitoring Solar Cell Degradation." in M. Al-Jassim and J. P. Thornton ed., ibid, pp. 661-666.
5. L. Rosenthal, A. W. Czanderna, and F. J. Pern, "Performance Losses in Rooftop-Mounted PV Modules from Long-Term Environmental Exposure at Las Cruces, New Mexico.," ibid, pp. 655-660.
6. T.J.McMahon and G.J. Jorgensen, "Progress Toward a CdTe Cell Life Prediction," ibid, 1999, p. 62.

Module and Array Performance and Reliability

Module Testing and Technology Validation

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401- **Organization Type**: FF	 **Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Carl R. Osterwald **Phone:** 303-384-6764 **Fax:** 303-384-6790 **E:mail**: carl_osterwald@nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **E:mail**: roland_hulstrom@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $1,067,500	**Cost Share Information**: None **Cost Share Funding:**

Project Objective: The objective of this task is to provide module performance measurements over a range of outdoor conditions, to thoroughly investigate module reliability issues using a variety of accelerated aging tests, and to develop or improve industry-standard module qualification tests. DOE-sponsored projects such as PVMaT, PV:BONUS, the Thin Film Partnership, and the Concentrator Alliance are strongly supported, in order to help guide their technology developments, and established module manufacturers, companies with emerging module technologies, codes & standards organizations, and system users all benefit from efforts conducted in this task.

Approach/Background: Well established laboratory capabilities and expertise at NREL are used for module stability testing of thin-film and advanced PV technologies by conducting long-term exposure tests and controlled light-soaking experiments. Accelerated stress testing and analytical investigation of the resulting failure mechanisms is emphasized by this task, including efforts to correlate failure mechanisms and degradation rates observed in accelerated tests with those observed in fielded systems, particularly for newer thin-film technologies. This correlation, when achieved, will help validate the computer models being used by NREL for module service lifetime predictions. As part of this effort to correlate the effects of accelerated tests with real-time exposure, long-term ultraviolet (UV) exposure testing of commercial modules was continued. Research efforts in this task also addressed the development of a standardized "module energy rating (MER)." For individual modules, the MER will provide relative energy production at five different operating conditions, chosen to represent a range of geographic sites. The MER development has the support of industry and is envisioned to be an expansion of the "nameplate" performance information currently provided on commercial modules. The task continued its role in the development of national and international standards by participating on IEEE and ASTM committees.

Status/Accomplishments:

During fiscal year 1999, the long-term UV exposure comparison on six types of commercial modules reached the following UV dosage totals (integrated 280 - 400 nm irradiances): Xe exposure, 958 MJ/m^2; real-time outdoor exposure, 539 MJ/m^2; accelerated outdoor exposure with two-axis tracking, 625 MJ/m^2; accelerated outdoor exposure with mirror enhancement, 1156 MJ/m^2; and UVA fluorescent tube exposure, 308 MJ/m^2. Also, the a-Si Light Soak IV testing program continued throughout this period, and the results are being prepared for presentation at a Material Research Society conference. Exploratory environmental stress testing was initiated or completed on a number of PV prototype items, including: Iowa Thin Film a-Si modules (PVMaT), PowerLight PV/building laminate materials (PV:BONUS), Astro Power welded-tab junction box designs, BP Solarex large-area Si modules (PVMaT), Sovlux/ECD a-Si modules (part of a CRADA), TerraSun holographic Si modules, and Global Solar CdTe developmental prototypes. Indoor a-Si light soaking was performed on USSC triple-junction, Sovlux/ECD, and SK Corp. (Korea) modules. New modules installed into the Performance and Energy Ratings Testbed (PERT) included: EPV tandem a-Si, BP Solar CdTe, and Siemens CuInGaSe. An ongoing effort has been made to analyze and publish the results of the long-term PERT performance data. For module qualification test development, we worked on validation of a modified thermal cycling procedure, originally developed by BP Solarex, which uses dark forward current biased during thermal cycling to simulate long-term stress on solder bonds. A 400-cycle comparison test on 4 types of Si and a-Si modules was performed and showed that this is a very useful test. We have done some damp heat testing (85% RH, 85°C) on a-Si modules while the modules are biased at maximum system voltages (usually 600V) which simulates and accelerates electrochemical corrosion. This test is also being proposed as a modification to the standard qualification sequence. We have installed and are using a new UVA fluorescent tube exposure system built by Arizona State University (ASU). This system allows UVA exposure testing to be performed without using an environmental chamber to control module temperatures. A new testbed for conducting thermal measurements of modules as a function of irradiance and wind has been constructed on the mesa above the OTF. Data from this facility will be compared with data from a similar testbed at ASU Photovoltaic Testing Laboratory (PTL). Another equipment item acquired during FY1999 was a new infrared camera. This camera is fully portable and has 60 fps operation, 0.1°C temperature resolution, -10°C to 45°C operation, 2°C absolute accuracy, and a spatial resolution of 0.1 mR. Initial operation showed that its sensitivity and portability make it an extremely useful diagnostic tool for cells and modules. Hot cells are easily spotted in field modules, and attaching the close-up lens moves the object plane to 10 cm from the lens with a resolution of 100 µm. For the MER development efforts, PV performance measurements were made from NREL's Outdoor Test Facility during the calendar year 1998. These data were used to validate the procedure by comparing modeled and measured maximum power values for seven flat-plate modules representing different technologies. On an annual basis, modeled values compared within 5% of measured values. The validation study also looked at the performance of the model on days similar to five reference days, which give a module's one-day energy production in five different environments: Hot-Sunny, Hot-Cloudy, Cold-Sunny, Cold-Cloudy, and Nice. The modeled values for these types of days were within 5% for all module technologies except triple junction a-Si, which was within 9%. A technical report completes a key milestone for the Module and Array Performance and Reliability Task. The report includes a detailed test procedure that will be incorporated into IEEE PAR 1479 "Recommended Practice for the Evaluation of Photovoltaic Module Energy Production". We currently collaborating with Sandia toward comparing this method with a PV performance model developed at Sandia.

Planned FY 2000 Milestones:
Establish criteria for a 30-year service lifetime module (NREL/SNL), Key, 9/00.
Publish report covering the comparison of two alternative module energy rating methods (NREL/SNL), Key, 9/00.
Publication covering IR camera diagnostic methods and applications (NREL/SNL), Internal, 9/00.
Publish report covering the NREL Outdoor Accelerated-weathering Test System (NREL), Internal, 9/00.

Major Reports Published in FY 1999:
B. Marion, B. Kroposki, K. Emery, J. del Cueto, D. Myers, and C. Osterwald, "Validation of a Photovoltaic Module Energy Ratings Procedure at NREL," NREL/TP-520-26909.

NCPV FY 1998 Annual Report*, NREL/BK-210-25626, (June 1999).*

Major Articles Published in FY 1999:
del Cueto, J., "Method For Analyzing Series Resistance And Diode Quality Factors From Field Data; Part II — Applications To Crystalline Silicon," *Solar Energy Materials and Solar Cells*.

Osterwald, C.R., et al., "The World Photovoltaic Scale: An International Reference Cell Calibration Program," *Prog. in Photovolt: Res. Appl.*, **7**, 287-297 (1999).

Osterwald, C.R., "Accelerated and Environmental Stress Testing at NREL," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462 (1999).

del Cueto, J., "Guide to the Field Performance of c-Si PV Modules," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462 (1999).

Basso, T., "The NREL Outdoor Accelerated-weathering Tracking System (OATS) and Photovoltaic Module Exposure Results," *NCPV Photovoltaics Program Review, Proceedings of the 15th Conference, Denver, CO, 1998*; AIP Conference Proceedings, Vol. 462 (1999).

Module and Array Performance and Reliability

Collector & Systems Testing Support

Contract #: AK-0748B	**Contract Period:** 9/1/95–8/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Spectra Research Albuquerque, NM 87119	
	Organization Type: IN	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** None	
Technical Monitor: Michael A. Quintana **Phone**: 505-844-0474 **Fax**: 505-844-6541 **E:mail:** maquint@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1996: $325,000 1997: $0 1998: $99,000 1999: $110,000	**Cost Share Funding:**

Project Objective: Provide on-site technical support for module performance testing.

Approach/Background: Provide computer programming, solar resource measurements, and performance testing, and analysis support.

Status/Accomplishments: Provided module performance testing, computer programming, and solar resource measurement.

FY 2000 Milestones: None.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Module and Array Performance and Reliability

Industry-Guided Module Durability Research

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/98 – 9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic System Components Department **Organization Type**: FF	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Michael A. Quintana **Phone:** 505-844-0474 **Fax:** 505-844-1504	
Technical Monitor: James M. Gee **Phone:** (505) 845-7812 **Fax:** (505) 844-6541 **E:mail:** ljmgee@sandia.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1999: $528,000	**Cost Share Information**: **Cost Share Funding:**

Project Objective: The objective of the Module Durability Research Cooperative (MDRC) is to improve durability of commercial photovoltaic modules. This work is highly collaborative with manufacturers often participating in the research and sometimes cost sharing the expense. Module Durability Research Cooperative has been performed in collaboration with Solarex, Spire, STR, ASE Americas, AstroPower, USSC, Spire, and Siemens. Initial collaborations have been undertaken with First Solar and Evergreen.

Approach/Background: The technical approach for conducting MDRC studies has been to 1) collaboratively identify module durability issues, 2) examine the underlying physical mechanisms associated with these durability issues, and 3) feed back the resultant information to positively influence the reliability of future products. This is accomplished by utilizing expertise and resources available at Sandia National Laboratories, NREL, Southwest Technology Development Institute (SWTDI), and Florida Solar Energy Center (FSEC).

FY99 MDRC activities examined issues related to:

1. Adhesion of EVA encapsulant to the glass and cell surfaces
2. Physical characteristics of field-aged EVA
3. Adhesion of UV accelerated EVA
4. Integrity of as-manufactured and field-aged solder-joints
5. Conversion to lead-free solders
6. Infrared thermometry techniques for characterizing manufacturing line variations
7. Dark IV measurements as a method of characterizing manufacturing line variations
8. Optical characteristics of new and field-aged glass
9. Ultrasonic techniques for NDT testing of solder bonds
10. Module performance changes due to solder-joint degradation
11. Mapping moisture migration in photovoltaic laminates

Status/Accomplishments: A strong synergy is developing between durability testing and manufacturing verification. Test techniques used for durability studies have developed a set of metrics that not only describe physical changes in field-aged modules but can also assist manufacturers to characterize line variations and verify product modifications. During FY99, series resistance measurements, IR thermometry, solder joint metallography, and EVA adhesion measurements were used to characterize line variations. These and other techniques were used for verification of manufacturing modifications. Sandia's role in providing testing and analysis of solder-joints will provide additional value as the industry considers a conversion to lead-free solder. Increasing environmental regulations are motivating the elimination of lead in photovoltaics. Globally, some governments and electronic manufacturers have already announced commitments to eliminate lead in consumer products. US PV manufacturers will have to consider lead-free solders in order to remain competitive. Sandia's resources and expertise in solders and soldering processes, developed for defense related purposes, is ideally suited to assist this effort.

Contract #: DE-AC04-94AL85000

Solder Joint Durability Analysis
During FY99 the MDRC performed detailed analyses of solder-joints from several manufacturers. Analyses included physical characterization of joint locations, metallurgical evaluation of solder joint cross sections, scanning electron microscopy, shear analysis, and ultrasonic analysis. A symposium was presented on solder joint durability in February, 1999, with over forty attendees from industry, national labs, and academia. During the symposium a suggestion was made that a nondestructive technique was needed to characterize solder joints. Ultrasonic testing was investigated as a possible technology to pursue. Total solder bond area and bond geometry are key parameters that affect the ability of the joint to withstand differential thermal expansion and the subsequent shear stress. Ultrasonic detection uses acoustic energy transmitted through the bond to characterize the total bond area. Energy transmitted is dependent on the acoustic impedance mismatch of bond materials. Air at the interface causes a difference in the acoustic impedance that is an order of magnitude higher. This results in little or no acoustic energy transmitted through the bond, thereby identifying voids and dewetted areas. Ultrasonic tests were performed to quantify total bond area without destroying tabbed solar cells. Resulting sonograms have provided a glimpse of a technique that could useful to manufacturers.

Moisture Intrusion
During FY99 an initial test was conducted to verify the capability to map moisture intrusion. Moisture intrusion has been identified as a key contributor to a number of module durability issues including delamination, browning, corrosion, temporary performance degradation and ground faults. Sandia's microelectronics program has developed a moisture sensor that can be embedded in small electronic packages for integrated circuit applications. A single cell laminate similar in construction to a PV module was fabricated with an embedded moisture sensor and environmentally cycled to verify the sensor function. Results show that the sensor can be deployed in test laminates. However, several issues were identified that need to be addressed. Additional work should be conducted to identify the number and the geometrical pattern of sensors that should be placed in a laminate to accurately define a moisture intrusion pattern. Capillary moisture migration at the sensor test leads that exit the laminate needs to be examined. Finally, an economic technique, embedding cobalt chloride paper in test laminates, has been defined for manufacturers wishing to participate in similar studies without significant investment.

Module Long Term Exposure
During FY 98 the Module Long-Term Exposure (MLTE) task was initiated. The objective of this task is to examine subtle module degradation mechanisms by conducting a structured and controlled long-term (minimum of five years) outdoor exposure of commercially available modules in cooperation with module manufacturers. Manufacturers participate by submitting modules for outdoor exposure. Modules are concurrently being exposed to a hot and humid climate at FSEC and to a hot and dry climate at SWTDI. During FY99 Solarex thin-film modules were installed alongside the Siemens (crystalline and CIGS modules), USSC, and ASE Americas modules already participating in the MLTE. Modules are inspected and I-V curves are taken monthly looking for the earliest signs of field-induced degradation.

FY 2000 Milestones:

- Establish the technical requirements for a 30-year service lifetime module
- Generate multiple reports related to module durability research on encapsulant adhesion, interface chemistry, solder bond metallurgy, optical properties of field-aged glass, and moisture-induced corrosion.
- Report on new techniques for non-destructive solder bond evaluation.
- Investigate and document feasibility of new durability diagnostic techniques: acoustic microscopy, in-situ moisture migration sensors, and finite-element modeling of stress-strain in solder bonds
- Initiate experimental optimization of solder-bond fatigue life with manufacturers
- Add at least one new module manufacturer as participant in MLTE program with baseline tests completed at Sandia

Major Reports Published in FY 1999:

Multiple test reports to manufacturers on adhesion tests, solder-joints, Dark I-V tests, and IR scans, and ultrasonic tests

Major Articles Published in FY 1999:

King, D. L., M. A.Quintana, J. A. Kratochvil, D. E. Ellibee, and B. R. Hansen. *Photovoltaic Module Performance and Durability Following Long-Term Field Exposure,* Progress in Photovoltaics: Research and Applications, 1999.

Module and Array Performance and Reliability

Module/Array Performance Testing and Modeling

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/98 – 9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic System Components Department	
	Organization Type: FF	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** David L. King **Phone:** 505-844-8220 **Fax:** 505-284-3239	
Technical Monitor: James M. Gee **Phone:** (505) 845-7812 **Fax:** (505) 844-6541 **E:mail:** ljmgee@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $371,000	**Cost Share Funding:**

Project Objective: The objective of this task is to apply measurement and modeling capabilities available at Sandia to characterize the electrical, thermal, and optical behavior of photovoltaic modules and arrays. These efforts are tailored to, and conducted in close cooperation with, module manufacturers, system designers/integrators, system owners, and organizations that establish or perform module qualification testing procedures.

Approach/Background: The technical activities associated with this task can be described in three categories: (1) development and application of improved outdoor test methods for module performance, (2) development and validation of improved field testing procedures for photovoltaic array performance characterization (rating), and (3) the incorporation of improved testing and modeling procedures in both consensus standards and the software used for system design and sizing.

At industry's request, comprehensive outdoor tests are conducted that provide a combination of specific module performance characteristics not available elsewhere. Improved outdoor test methods are continually being developed at Sandia. The information gained from the testing provides not only traditional performance "calibrations" at ASTM Standard Reporting Conditions but also module parameters required for system engineering (design, sizing, rating). Specific tests provide: module temperature coefficients, direct measurements of the influences of solar spectral variation and solar angle-of-incidence, module thermal time constants, operating temperature versus wind speed, thermal "hot-spot" behavior in reverse-bias. Complementary dark current-voltage measurements provide physical parameters (series resistance, shunt resistance, saturation currents, diode factor) required for electrical modeling of cell circuits. In many cases, individual cell measurements in Sandia's Photovoltaic Device Measurement Laboratory are also used to confirm characteristics observed in outdoor module testing.

The development and improvement of field testing procedures for arrays involves adapting our outdoor module measurement procedures to large photovoltaic arrays. By doing so, a significant improvement in the accuracy and utility of performance characterizations (ratings) of large arrays has been obtained, and now integrated in field testing standards such as IEEE 1373. During the last two years, improved array testing procedures have been successfully demonstrated for virtually all commercial photovoltaic technologies; flat-plate and concentrator. Sandia's testing procedures, data analysis, and performance modeling method is being considered for inclusion in a variety of domestic and international standards (IEEE 1479, IEEE 1513, ASTM E1036, IEEE 1262, IEC 1215, IEC 1646).

Status/Accomplishments: During FY99, outdoor characterization of more than 75 commercial modules at Sandia resulted in nearly a dozen test reports to module manufacturers and users, including: Solarex, Siemens, AstroPower, USSC, ASE Americas, Spire, Solar Cells Inc., Kyocera, CIO Inc., ASU/PTL, and FSEC. In addition, comprehensive baseline testing of 12 commercial Solarex amorphous silicon modules was completed for inclusion in the Module Long-Term Exposure program at the Florida Solar Energy Center (FSEC) and the Southwest Technology Development Institute (SWTDI). At the request of module manufacturers, carefully controlled measurements of the "stabilization" trends in commercial amorphous silicon modules from USSC, Solarex, and EPV have continued with multiple modules exposed over a 12- to 36-month period at Sandia. Results from these stabilization tests are being consolidated as a paper to be submitted to the Progress in Photovoltaics journal. Through round-robin calibrations, in conjunction with NREL and ESTI in Europe, our outdoor tests provided the traceability required for accreditation of commercial testing organizations such as the Photovoltaic Testing Laboratory (ASU/PTL), and FSEC.

During FY99 in support of the thin-film industry, field performance characterization was repeated on a 25-kW Solar Cell Inc. CdTe array at Edwards AFB. The field test results were used to help interpret accelerated test results conducted at NREL on similar CdTe modules. A field performance test was also conducted on a 2-kW roof-integrated PV array of Solar Millennia (a-Si) modules in Tijeras, NM.

Considerable effort was expended in applying Sandia's PV performance modeling procedures to improve system design software, and in the development of methods for rating modules or designing systems based on energy production rather peak power. Sandia and NREL are teaming to compare alternative procedures for rating modules based on energy production. A collaborative development effort with a commercial software vendor (Maui Solar Energy Software Corporation) has resulted in the incorporation of the Sandia performance model in their sophisticated system design program (PV-DesignPro).

FY 2000 Milestones:

- Joint with NREL, publish comparison of two proposed module energy rating methods.
- Provide at least 10 industry-requested module test reports or array performance characterizations.
- Document Sandia's outdoor test procedures for IEEE, IEC, and ASTM standards committees.
- Publish report on spectral and thermal influences on the stabilization characteristics of commercial amorphous silicon modules during long-term outdoor exposure at Sandia.
- Joint with NREL, publish report on diagnostic applications for infrared (IR) imaging cameras.

Major Reports Published in FY 1999:

- Ten industry or lab-requested module performance characterization reports for AstroPower, ASE Americas, EPV, Solarex, Siemens, ASU/PTL, FSEC, NREL, Phillips Lab.
- Two array field test reports for Solar Cells Inc. (First Solar) on aging characteristics of a 25-kW CdTe array at Edwards AFB.

Major Articles Published in FY 1999: None.

PV Balance-of-System Reliability Analysis

Agreement #: DE-FC36-99GO10443	**Project Period:** 9/01/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Alec Bulawka **Phone:** 202-586-5633 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Alec.Bulawka@ee.doe.gov	Control Systems Associates (CSA) 1777 Adams Way Monterey Park, CA 91755 **Organization Type:** IN	**Congressional District:** 31
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Stanley Krauthamer **Phone:** 626-571-1203 **Fax:** 626-571-1203	
Project Manager: Robert Martin **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1999: $15,000	**Cost Share Information:** None. **Cost Share Funding:**

Project Objective: Under this award, Control Systems Associates (CSA) intends to analyze the U.S. Navy's Power Electronic Building Block (PEBB) technology to determine if it is a viable option for PV application and, if so, establish a set of recommendations on how to transfer this technology to the PV industry.

This effort will assess the issues of reliability in PV BOS and to see if the incorporation of PEBB devices will change the focus of the PV-BOS community and possibly resulting in improved reliability. The power Electronics Building Block (PEBB) Program initiated by the office of Naval Research is a new high reliability approach that simultaneously develops Science, Technology, and Engineering with a Commercialization Program for rapid insertion of products and technology into commercial and naval systems. The basic objective of this project is to report to the PV power conditioner industry the availability and characteristics of PEBB modules that will be available as a result of the PEBB program and to establish a set of recommendations on how to transfer this technology to the PV Industry. Application of PEBB devices will be reviewed and assessed. Modules developed should be available to the PV industry and will assist the industry to improve reliability, reduce costs and open a new window of opportunity for large scale manufacturer of photovoltaic systems. PEBB Program reliability efforts at PEBB will be analyzed for their applicability to improve PV Balance of System (BOS).

This task will be collaborative effort with the PEBB program and the PV industry and will result in a report that will outline the results of the PEBB Module program and associated reliability improvement. The report will identify the applicable PEBB Devices that can be used by PV-Power conditioner manufacturers in their products, and to establish a set of recommendations on how to transfer this technology to the PV industry. Furthermore, the report will identify sources and suppliers of the PEBB modules, including application recommendations. The basic objective is to improve reliability, performance and to help open new large scale markets for PV by reducing cost.

Approach/Background: This is a new solicited severable award with a duration of thirteen (13) months for the analysis and assessment of the U.S. Navy's Power Electronic Building Block (PEBB) technologies and its applicability to increasing the reliability of PV Balance-of-Systems (BOS). CSA was selected under the Broad-Based Solicitation, Supplemental Announcement 05.

Status/Accomplishments: Cooperative agreement selected and awarded.

Planned FY 2000 Milestones: Final Letter Report and technical conference publication will be issued including details of: 1) viability of PEBB modules for PV applications; 2) PEBB module characteristics; 3) PEBB module applications information; 4) PEBB module reliability issues; 5) summary of PV-PCU manufacturers requirements; 6) assessment of PEBB modules; 7) reliability issues in PV-BOS and resultant impact of PEBB; and 8) PV-PCU specifications

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

Balance-of-Systems Components Development

Battery/Controller Development and Systems Support

Contract #: AU-0556	**Contract Period:** 8/13/96–10/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Florida Solar Energy Center Cocoa, FL 32816-0150	
	Organization Type: CU	**Congressional District**: 8
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Jim Dunlop **Phone**: 407-783-0300 **Fax**: 407-783-2571	
Technical Monitor: Thomas D. Hund **Phone**: 505-844-8627 **Fax**: 505-844-6541 **E:mail:** tjhund@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1997: $100,000 1998: $100,000 1999: $122,000	**Cost Share Funding:**

Project Objective: Support U.S. PV Industry and DOE PV Program personnel.

Approach/Background: Test battery performance and charge control algorithms in small stand-alone PV systems. This work is part of DOE's Balance-of-Systems (BOS) development program designed to improve reliability, lower costs, and encourage manufacturer development of improved PV batteries and battery charge controllers.

Status/Accomplishments: Reported on the PV battery cycle-life test results. Supported drafting of an IEEE SCC-21 PV system and battery test procedure. Upgraded the battery cycle test software.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Balance-of-Systems Components Development

Power Electronic Building Block Program

Contract #: AO-5380	**Contract Period:** 2/1/95–10/15/98

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	NASA Management Office Jet Propulsion Lab Pasadena, CA 91109	
	Organization Type: FF	**Congressional District**: 27
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** S. Krauthamer **Phone**: 818-54-7740 **Fax**: 818-393-4272	
Technical Monitor: W.ard I. Bower **Phone**: 505-844-5206 **Fax**: 505-844-6541 **E:mail:** wibower@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1995: $105,000 1996: $0 1997: $0 1998: $0 1999: $0	**Cost Share Funding:**

Project Objective: Support US PV industry and DOE PV Program personnel with Power Electronic Building Block liaison and information transfer.

Approach/Background: Participation in the US Navy Power Electronic Building Block Program, information transfer, and education for inverter manufacturers.

Status/Accomplishments: Contract ended. Final invoice submitted.

FY 2000 Milestones: None.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Balance-of-Systems Components Development

Inverter Reliability

Contract #: AU-5805A	**Contract Period:** 10/1/96–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Omnion East Troy, WI 53120-1357	
	Organization Type: IN	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** H. Meyer **Phone:** 414-642-7200 **Fax:** 414-642-7760	
Technical Monitor: Russell H. Bonn **Phone:** 505-844-6710 **Fax:** 505-844-2890 **E:mail:** rhbonn@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: Omnion
	DOE Funding Allocation: 1996: $75,000 1997: $75,000 1998: $200,000 1999: $40,000	**Cost Share Funding:** 1996: $60,000

Project Objective: To improve the reliability of fielded PV systems by 1) developing a quality assurance program 2) preliminary development of a systems engineering capability and 3) development of a reliability database.

Approach/Background: PV BOS component manufacturers are mostly small companies with no structured procedures in place. Both quality and reliability suffer due to the fact that products vary from unit to unit, the supply of parts has inconsistent quality, and the design process is generally bench testing a prototype before requirements are defined. As with all small businesses, they eventually reach a size where they are large enough to support a professional quality engineer. The purpose of this contract was to accelerate this normal process by providing funding for a quality engineer and a quality/reliability program for two years.

Status/Accomplishments: The quality programs are completed. Dramatic changes have been made in their operations. Among these changes are:

- Developing controlled procedures for all parts of the manufacturing process
- Screening of incoming components to ensure consistent quality
- Tracking field experiences to aid in defining quality problems
- Developing a systems engineering approach to product design.

At this point, this company is on the verge of achieving ISO 9000 certification. They have confirmed that the MTBF for fielded units increased from 30,000 hours in 1996 to 114,000 hours in 1998.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Balance-of-Systems Components Development

PV Battery and Charge Controller Testing and Development

Contract #: DE-AC04-94AL85000	Contract Period: 10/1/98 – 9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
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E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Sandia National Laboratories
Photovoltaic System Applications Department</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
Tom Hund
Phone: 505-844-8627 Fax: 505-844-1504</td></tr>
<tr><td rowspan="2">Technical Monitor:
Christopher P. Cameron
Phone: (505) 845-8161
Fax: (505) 844-6541
E:mail: cpcamer@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $303,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: PV system field test evaluations have identified the battery as one of the highest life-cycle cost components. Many times battery life-cycle cost is well over 1/3 of the initial capital costs of the system. In some cases the frequent battery replacements and added costs make the PV system unsustainable. Field test data has shown that inappropriate battery design/installation, improper battery charging, and a lack of maintenance were the predominate contributors to capacity loss and early failure. In an effort to reduce PV system life-cycle costs, the Balance-of-Systems Components Development project at Sandia is working to educate PV system designers on PV battery requirements, identify PV battery charging requirements with laboratory and field testing, and promote improved battery designs and charge controllers in fielded PV systems.

Approach/Background: Work is progressing in education, laboratory and field battery testing, and charge controller development. Maintaining a good line of communication with battery manufacturers, charge controller manufacturers, and system integrators is key to the success of this effort. Many times battery manufacturers do not understand the unique requirements of a PV system and need a technical interface between them and the PV industry. In turn, most charge controller manufacturers and system integrators do not have effective communications with the battery manufacturers. Sandia has and continues to facilitate improved communications among different segments of the industry. To quantify battery performance, laboratory test procedures have been developed to test batteries in small stand-alone PV systems and in PV hybrid systems. These test procedures make it possible to understand why PV batteries are not performing as expected by quantifying the degradation caused by common PV use environments. The laboratory testing also identifies improved management strategies usually with minimal or no additional costs to the system. Field testing is used for verification of new battery technology and/or improved charge control. It's always a key element in any laboratory testing program. Many times the work in the lab has shown that commercially available charge controllers do not use the regulation voltage that is appropriate or that the engine generator battery charge control in PV hybrid systems is inadequate. In these cases Sandia works with the charge controller manufacturers to upgrade and/or test their product. Examples of this support where significant improvements were made are Morningstar, Pulse Energy, and Digital Solar charge controller manufacturers.

Status/Accomplishments:

1) A factory visit at East Penn (Deka) battery and onsite meetings with East Penn, GNB, C&D, and Yuasa battery to promote educational communications concerning the needs and requirements of their batteries in PV systems were facilitated.
2) Numerous phone conversations with the battery and PV industry discussing PV battery charging requirements were conducted.
3) IEEE SCC21 standards work to develop a PV battery test procedure was conducted.
4) Two E-publications on the laboratory test results were published. These include PV battery cycle-life and PV battery capacity loss.
5) Extensive laboratory testing on the East Penn 8G30H gel VRLA, G-75 gel VRLA, Unigy II AGM VRLA, and M-75 Maintenance Saver vented battery has demonstrated the need to properly choose and maintain batteries for optimum performance. Very good batteries can be quickly damaged without proper charging. The new G-75 gel is now being field tested at Mt. Washington telecommunication site.

6) Test results on the GNB Absolyte IIP have provided quantifiable performance results and identified battery performance degradations that are typically seen in fielded systems.
7) PV battery cycle testing for the World Bank has identified PV performance characteristics for the Sri Lankan batteries. This work makes it possible to establish a level of confidence in developing country batteries.
8) As a result of Sandia testing on the new Pulse Energy PM series charge controllers, Sandia was able to help Pulse debug programming errors and improve performance and reliability.
9) Sandia funding and laboratory testing of Digital Solar's MPR-9400 has resulted in an advanced microprocessor based system controller with improved charge control, data logging, and remote communications. This unit is now being field tested at the Mt. Washington telecommunication site.

FY 2000 Milestones:

1) Report on PV battery evaluations (East Penn Battery and Trojan Battery)
2) Report to manufacturers on test results from charge controller testing and Golden Genesis refrigerator testing.

Major Reports Published in FY 1999:

1) *Test Results from the PV Battery Cycle-Life Test Procedure* – published on Sandia's PV web site
2) *PV Battery Capacity Loss and Recovery Procedures* – published on Sandia's PV web site

Major Articles Published in FY 1999:

1) *Battery Evaluations for Hybrid Photovoltaic Systems*, Quarterly Highlights of Sandia's Photovoltaics Program, Volume 3, 1998.

Balance-of-Systems Components Development

PV Power Processing (BOS) Program

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/98 – 9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic Systems Applications Department	
	Organization Type: FF	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Russell Bonn **Phone:** 505-844-6710 **Fax:** 505-844-2890	
Technical Monitor: Christopher P. Cameron **Phone:** (505) 845-8161 **Fax:** (505) 844-6541 **E:mail:** cpcamer@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $1,080,000	**Cost Share Funding:**

Project Objective: The Sandia balance-of-systems (BOS) program analyzes BOS components to evaluate performance and to identify methods for improving performance and reliability. Additionally the program strives to lower the life-cycle-cost by improving product designs, developing new technologies, and enhancing reliability. Program goals are to:

- Promote development of advanced BOS components
- Advance reliability and reduce life-cycle cost.
- Remove implementation barriers to PV.
- Assist component manufacturers with the development of more reliable, cost effective systems

Approach/Background: In 1999 the Sandia BOS team addressed the following goals:

- A variety of new inverters were evaluated in the laboratory. These ranged in power from 1 kW to 100 kW and included products that had been developed with support from the DOE PVMaT program.
- The reliability of BOS components was improved by HALT (accelerated reliability) tests on Trace and Omnion inverters and by quality contracts that reduced field failures: (1) Trace reported a failure rate of SW inverters at 2% versus 14% in 1997, and (2) Omnion reported an MTBF of 114,000 hours versus 30,000 reported in 1996.
- Grid-tied implementation barriers were reduced by developing a single-inverter anti-islanding test that will identify inverters that previously would have islanded when placed in parallel with another inverter of a different brand, and by evaluating the Omnion inverter response to 24 anomalous waveforms at the request of a group of New York electric utilities.
- To assist manufacturers in developing more robust systems, surge evaluations were initiated on several inverters. The purpose was twofold. First, to improve reliability by making the inverters less susceptible to nearby lightning and switching transients. Second, to assure utilities that if a failure does occur, the failure is in a safe mode. This means that the inverter must not island, and that its anti-islanding circuitry must not be damaged.

Status/Accomplishments:

<u>Testing Identifies Problem with IEEE 929 Before Release</u>

Islanding, the run-on of a grid-tied inverter after the utility is removed, is prohibited by US utilities. Last year the SNL BOS laboratory discovered that inverters from different manufacturers interfered with each other's anti-islanding schemes and that some combinations of inverters would island. As a result, IEEE Standard 929 was rewritten with new criteria for evaluation. The SNL BOS laboratory developed the methodology for evaluating single inverters so that inverters with this islanding problem could be identified. The test circuit consists of a local RLC load with a resonant frequency of 60 Hz. As well as developing the initial test, further research established that inverters with non-unity power factor require a special evaluation configuration. The impact of this research is to establish more confidence in photovoltaics by utilities.

Surge Testing of Inverters
Nearby lightning and capacitor switching can result in surges on ac and dc inverter power wiring and diagnostic cables that have the potential to shorten inverter lifetime. Inverter manufacturers have stated that this issue is a concern. In addition, the potential for such surges to disable the anti-islanding technology of the inverter is of concern to utilities. For these reasons SNL has initiated a surge-testing program. IEEE C62.41-1991 (category B) and C62.45-1992 define the pulses that are applied to the hardware. Initial testing has been limited to PV inverters. Criteria for successful completion of a test are 1) no failures at agreed-to open-circuit surge generator voltages and 2) no impairment of anti-islanding circuitry. Note that this is a design evaluation test and that the stress to the inverter can be much more severe than it might be in a screening or qualification test. In tests done specifically to determine compliance with a utility requirement, the voltage will be limited to the utility requirement. Some products have already been modified as a result of this testing.

PVMaT Evaluations
Omnion Power Engineering Company developed a 100 kW grid-tied inverter, the Series 3300. A prototype was evaluated for a variety of operational parameters. These included efficiency, power factor, harmonic distortion of the output current, conducted and radiated radio-frequency interference, maximum-power-tracker functionality, anti-islanding functionality under a wide range of load conditions, dc and ac operating range, acoustic noise, temperature, and performance over a typical day. The inverter performed well and met or exceeded all of its design specifications. An interesting evaluation was the three-phase anti-islanding test. The test methodology used was the same as that discussed in the new IEEE 929 for small inverters (<10 kW). The RLC load was placed on all three phases. First,all 3 phases were interrupted simultaneously, and then a single phase was interrupted. The inverter passed both tests.

Advanced Energy Systems developed a nominal 1000-watt grid-tied inverter, the GC 1000. Testing has identified a few development problems; an updated inverter is expected soon, and the evaluation will be completed when that unit arrives.

Trace Engineering developed a 2.5 kW inverter, the PS2512. This inverter has grid-tied capability and utilizes batteries to provide power to local loads during a utility outage. Again some problem areas were discovered that were still being addressed at the time this report was being prepared. A replacement unit is expected soon, and the replacement inverter will be retested.

Additional In-house inverter testing
Inverters with a variety of power ratings, applications, and topologies were evaluated. Manufacturers included Raytheon, Trace Engineering, Trace Technologies, Omnion, Statpower, and AES. . All of these inverter evaluations identified problem areas that resulted in the manufacturer's redesign. A report was prepared on the Statpower inverter and was placed on the Sandia WEB site. A report on the Omnion 2400 is in preparation and will be on the WEB soon. Reports are placed on the WEB with the concurrence of the manufacturer once the product has moved beyond the development stage and become a commercial product.

Other PV Industry Support
The requests for support ranged from simple recommendations on charge set-points and inverter efficiency to elaborate laboratory tests. Two of the more time consuming tests performed were the special waveform tests for KeySpan Energy, a New York utility, and hybrid tests for Arizona Public Service.

KeySpan was concerned that 24 "anomalous" waveforms that had been recorded as part of a relay test project could result in improper operation of the anti-islanding circuitry. The evaluation required programming each waveform into a waveform synthesizer and coupling that signal through a linear amplifier to the inverter. The inverter evaluated, the Omnion 2400, did operate properly. The support for APS involved evaluating and coordinating changes to a 30 kW Trace hybrid inverter in the APS PV Hybrid facility.

Additionally Sandia staff traveled to the APS STAR hybrid test facility to review the performance of the 90-kVA Trace Technologies inverter that was to be installed at San Juanico hybrid village project

FY 2000 Milestones:
- Award at least two R&D contracts for new technology
- Evaluate five grid-tied inverters for islanding
- Installation in BOS lab of at least one small PV system for reliability evaluation
- Conduct HALT tests and conduct quality audits
- Publish (on PV website) product evaluations, as appropriate

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999:
Ginn, J. W. "Testing and Development of a 30-kVA Hybrid Inverter: Lessons Learned and Reliability Implications," *Progress in Photovoltaics: Research and Applications*, Vol. 7, Number 3, May-June 1999.

Balance-of-Systems Components Development

Reliability Program Development

Contract #: AU-5805B	**Contract Period:** 10/1/96–3/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Trace Engineering Arlington, WA 98223	
	Organization Type: IN	**Congressional District**: 2
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** C. Frietas **Phone:** 360-435-8826 **Fax:** 360-435-2239	
Technical Monitor: Russell H. Bonn **Phone:** 505-844-6710 **Fax:** 505-844-2890 **E:mail:** rhbonn@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1996: $75,000 1997: $75,000 1998: $150,000 1999: $209,000	**Cost Share Funding:**

Project Objective: To improve the reliability of fielded PV systems. This project consists of three components 1) development of a quality assurance program 2) development of systems engineering capability and 3) development of a reliability database.

Approach/Background: PV BOS component manufacturers are mostly small companies with no structured procedures in place. Both quality and reliability suffer due to the fact that products vary from unit to unit, the supply of parts has inconsistent quality, and the design process is generally bench testing a prototype before requirements are defined. As with all small businesses, they eventually reach a size where they are large enough to support a professional quality engineer. The purpose of this contract was to accelerate this normal process by providing funding for a quality engineer and a quality/reliability program for two years.

Status/Accomplishments: The quality programs are completed. Dramatic changes have been made in their operations. Among these changes are:

- Developing controlled procedures for all parts of the manufacturing process
- Screening of incoming components to ensure consistent quality
- Tracking field experiences to aid in defining quality problems
- Developing a systems engineering approach to product design.

At this point, Trace is on the verge of achieving ISO 9000 certification. Trace reported a failure rate of SW inverters at 2% in 1998 versus 14% in 1997.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

System Engineering and Applications

Photovoltaic System Performance and Engineering

PV Interconnection Issues

Contract #: AS-3621	**Contract Period:** 2/25/96–2/25/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Ascension Technology Lincoln Center, MA 01773	
	Organization Type: IN	**Congressional District:** 7
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Ed Kern **Phone:** 781-684-6101 **Fax**: 781-684-2050	
Technical Monitor: John W. Stevens **Phone:** 505-844-7717 **Fax:** 505-844-6541 **E:mail:** jwsteve@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1996: $16,000 1997: $0 1998: $4,000 1999: $5,400	**Cost Share Funding:**

Project Objective: Install grid-tied 30KW inverter for existing PV system. Establish monitoring technique to provide data for reliability project.

Approach/Background: Communicate with reliability project leader to determine exact data requirements for reliability project. Configure data monitoring system to provide that information.

Status/Accomplishments: Reliability data logged and annual reporting begun.

FY 2000 Milestones: Continue to provide annual data reports.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507a	**Contract Period:** 5/12/99-9/15/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Ascension Technology, Inc.
Lincoln Center, MA 01773</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 7</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
Miles Russell
Phone: 781-890-8844 Fax: 781-890-2050</td></tr>
<tr><td rowspan="2">Technical Monitor:
Larry M. Moore
Phone: (505) 845-9191
Fax: (505) 844-6541
E:mail: lmmoore@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $30,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507c	**Contract Period:** 5/11/99-9/15/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Enersol Associates, Inc.
North Chelmsford, MA 01863-1561</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 7</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
Lynn Wiles
Phone: 978-251-1828 Fax: 978-251-5291</td></tr>
<tr><td rowspan="2">Technical Monitor:
Larry M. Moore
Phone: (505) 845-9191
Fax: (505) 844-6541
E:mail: lmmoore@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $22,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

Field Module Durability and System Rating

Contract #: AP-7660	**Contract Period:** 9/3/95–10/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Florida Solar Energy Center Cocoa, FL 32816-0150	
	Organization Type: CU	**Congressional District:** 8
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** J. Ventre **Phone:** 407-638-1000 **Fax**: 407-638-1010	
Technical Monitor: Michael A. Quintana **Phone**: 505-844-0474 **Fax**: 505-844-6541 **E:mail:** maquint@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1996: $180,000 1997: $350,000 1998: $150,000 1999: $188,000	**Cost Share Funding:**

Project Objective: Assist Sandia and the U.S. PV industry to identify and study PV module durability issues.

Approach/Background: FSEC continues to provide critical support to Sandia and the U.S. PV industry by providing expertise and resources necessary to address module durability. Leveraging this work by taking advantage of Florida University system test facilities and links to think-film as well as crystalline technologies provides exceptional value.

Status/Accomplishments: Continued module long-term exposure study. Performed adhesion and/or surface characterization studies on twenty-year-old modules from Natural Bridges array. Supported NREL and Sandia in collaborative effort to determine the effects of accelerated UV testing on encapsulant adhesion. Increased the database of adhesion measures by adding measurements from at least one manufacturer.

FY 2000 Milestones: None.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999:

Dhere, N. G. and N. R. Raravikar. *Adhesional Strength and Surface Analysis of a PV Module Deployed in Harsh Coastal Climate*, Solar Energy Materials and Solar Cells, Proceedings, 11th International Photovoltaic Science and Engineering Conference (PVSEC-11), Sapporo City, Japan, September 1999.

Photovoltaic System Performance and Engineering

SERES Field Evaluation

Contract #: AV-5590	**Contract Period:** 5/1/95–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
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E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Florida Solar Energy Center
Cocoa, FL 32816-0150</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 8</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
J. Ventre
Phone: 407-638-1470 Fax: 407-638-1010</td></tr>
<tr><td rowspan="2">Technical Monitor:
Michael G. Thomas
Phone: 505-844-1548
Fax: 505-844-6541
E:mail: mgthoma@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1996: $380,000
1997: $650,000
1998: $600,000
1999: $440,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Support US PV Industry and DOE PV Program personnel.

Approach/Background: Regional assistance with agencies and utilities, integration of buildings program at FSEC with PO, education and training for regional customers, and development of statewide programs in Florida.

Status/Accomplishments: Developed PV Buildings Program with Florida Energy Office and Sandia National Laboratories.

FY 2000 Milestones:

- Installation of minimum of 50 residential rooftop systems through Florida Buildings Program
- Partnerships with a minimum of six municipal utility companies and two investor-owned utilities in the state of Florida
- Host Quarterly Million Solar Roofs meeting, and conduct workshop on developing concurrent state programs

Major Reports Published in FY 1999:

- Florida Solar Buildings Program notebook.
- Young, William R., Jr. "User Evaluation of Prototype PV Equipment Disasters," Florida Solar Energy Center, August 1999.
- Parker, D. S., et al. "Field Evaluation of Energy Efficient Building Technology with Photovoltaic Power Production in New Florida Residential Housing," FSEC-CR-1044-98, Florida Solar Energy Center, November 1998.
- Ventre, Jerry. "A Program Plan for Photovoltaic Buildings in Florida," FSEC-PD-25-99, Florida Solar Energy Center, January 1999.
- Ventre, Jerry. "Statewide Green Pricing Program," FSEC-PD-25.C-99, Florida Solar Energy Center, January 1999.
- Ventre, Jerry. "Acceptance Testing of PV Systems," FSEC-PD-25.G-99, Florida Solar Energy Center, January 1999.
- Ventre, Jerry. "Interconnecting Small PV Systems to Florida's Utility Grid," FSEC-PD-25.P-9, Florida Solar Energy Center, January 1999.

Major Articles Published in FY 1999:

- Ventre, G. G. "A Program Plan for Photovoltaic Buildings in Florida," *Progress in Photovoltaics: Research and Applications*, Volume 7, Number 3, May-June 1999.

Photovoltaic System Performance and Engineering

Photovoltaic Solar Radiometric Measurements

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd Golden CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** D.R. Myers **Phone:** 303-384-6768 **Fax:** 303-384-6790 **E:mail**: daryl_myers@nrel.gov	
Technical Monitor: Roland Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6481 **E:mail**: roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $485,100	**Cost Share Funding:**

Project Objective: The PV Solar Radiometric Measurements task supports the radiometric needs of the NREL PV research program tasks, measurement and characterization activities, and the PV industry . The project performs optical radiation broadband and spectral calibrations (metrology) and measurements, and provides technical expertise in the subject areas as requested. The project strives to meet the requirements for appropriate levels of uncertainty in areas of solar and optical radiometry directly applicable to PV research, development, production, and deployment.

Approach/Background: Accurate solar irradiance and optical radiation measurements are essential to the national labs' role in supporting internal PV research and development activities and the evolving PV industry. This accuracy is required both in the laboratory during calibration and performance testing of cells and modules, in the production environment for quality control and production monitoring, and in the field during performance characterization and monitoring of photovoltaic arrays. The project maintains measurement instrumentation, expertise, and traceability to organizations such as the National Institute for Standards and Technology (NIST), the World Meteorological Organization (WMO/WCRP), and the recently proposed World Photovoltaic Scale (WPVS). This internationally established traceability is continually transferred to industry by NREL and Sandia via several activities.

These activities include: calibration of broadband and spectral solar irradiance sensors; optical metrology for cell and module calibrations for manufacturers and universities; technical support in the field of optical radiometry and solar radiometry for standards committees (ASTM, IEEE, IEC, etc.); and radiometric calibrations for accreditation of commercial test laboratories (PowerMark, ASU/PTL). Specific technical activities include the maintenance and operation of the NREL Optical Metrology Laboratory for spectral radiometry and optical radiation research; operating the NREL Solar Radiation Research Laboratory (SRRL) for monitoring the solar and meteorological environment in support of PV testing under prevailing conditions and radiometric sensor calibration and characterization; the calibration and measurement of solar simulators for PV performance testing; measurement of natural and artificial sunlight in outdoor and indoor accelerated (high flux) testing ; and measurements for the validation of radiometric aspects of consensus national and international standards and codes developed to support the PV industry.

Status/Accomplishments: We replaced an obsolete paper based calibration history recording system, implementing an electronic historical calibration data base system for all broadband and (significantly more complex) spectral calibrations.

Analysis of Reference Meteorological and Irradiance System (RMIS) Cavity Radiometer 29219 versus NREL Pyrheliometric Comparison Reference irradiance during NREL Pyrheliometric Comparisons Oct 11-16 of 1998 confirmed RMIS deviations at less than 0.05%, maintaining NREL traceability to the World Meteorological Organization World Radiometric Reference to 0.3%

The instrumentation of the Solar Radiation Research Laboratory (SRRL) was upgraded to World Meteorological Organization Baseline Surface Radiation Network Standards. Design and functionality of the internet access to SRRL data was significantly improved, to include real time data access, hourly archived all sky photographs, and access to historical data. See **http://srrl.nrel.gov/**

The project performed optical calibrations on 48 NREL and PV industry systems devoted to PV performance and qualification testing, materials research and development, and PV production. Two thirds of these systems involved spectral measurement of continuous and pulsed solar simulators and ultraviolet sources. Both NREL and industry (MV Systems, Golden, Co., Solarex, Frederick, MD) systems were characterized. The remaining systems involved solar broadband and ultraviolet radiometric measurements, instrument characterizations, and calibrations applicable to PV systems testing, materials testing, and accelerated ultraviolet exposure.

We evaluated three new techniques to measure the spectral distribution of pulsed solar simulators. The most accurate new technique, reduces measurement time from 90 minutes to 25 minutes. The other two techniques were faster, but compromised the measurement accuracy. Using the best new technique, we made periodic measurements to monitor the NREL Spire 240A simulator for significant spectral changes on a monthly basis, without compromising lamp life.

We developed software to apply the Perez Anisotropic Diffuse radiation model to Typical Meteorological Year-2 (TMY2) and National Solar Radiation Data Base (NSRDB) data to plot the annual average energy available in various tilt/azimuth. This allows optimization of geometry for flat plate collectors based on available energy at various tilt and azimuth orientations

At the request of the concentrating PV industry, we implemented the NREL Simple Spectral Model, SPCTRL2, and the NREL Clear Sky Broadband models of Bird and Hulstrom into a user friendly Microsoft Excell® Spreadsheet environment to assist the industry in tuning and optimizing concentrator and module parameters.

We provided technical input, review, and voted for the approval of 8 ASTM Standards under the E-44 committee on Photovoltaics. In addition we published articles describing issues related to module energy ratings, outdoor conditions for PV performance ratings, and higher accuracy diffuse component measurement during broadband radiometer calibrations.

Planned FY 2000 Milestones: Milestones to be completed by September, 2000 are:

- Consolidation of Optical Metrology Lab with NREL Metrology and Solar Radiation Research Facility upon completion of new Solar Radiation Research Laboratory building, replacing the current SRRL on South Table Mountain;
- Publication on techniques applied to, and results of, periodic re-calibration and measurement of solar simulators and radiometric sensors for PV Performance and PV production applications;
- Publication on applications of well documented and technically supported moderate resolution radiative transfer code [MODTRAN] to evaluate the impact of terrestrial solar spectral variations on PV technologies;
- Refurbish and install operational Atmospheric Optical Calibration System developed at NREL to quantify prevailing PV test conditions with respect to standard reporting conditions.

Major Reports Published in FY 1999:

R.D. McConnell, A. Hansen, eds. *NCPV FY 1998 Annual Report*, NREL/BK-210-25626, (June 1999). "Photovoltaic Solar Radiometric Measurements and Evaluation" pp. 403-406

I. Reda and D. Myers, "Calculating the Diffuse Responsivity of Solar Pyranometers," NREL Technical Paper TP/560-26483. July 1999 15 pp.; NICH Report No. TP-560-26483.

Marion, B.; Kroposki, B.; Emery, K.; del Cueto, J.; Myers, D.; Osterwald, C. (1999). "Validation of a Photovoltaic Module Energy Ratings Procedure at NREL". 97 pp.;NICH Report No. TP-520-26909.

Major Articles Published in FY 1999:

Myers, D. R. (1998). "Silicon Cell Pyranometers: The Cost of Accuracy". *Solar Spectrum: Newsletter of the Resource Assessment Division of the American Solar Energy Society*. Vol. 11(2), November 1998; pp. 1+; NICH Report No. 26199.

Myers, D.R., S. Kurtz, C. Whitaker, T. Townsend, A. Maish, "Objective Method for Selecting Outdoor Reporting Conditions for Photovoltaic Performance". R. Campbell-Howe, B. Wilkins-Crowder, eds. *Solar '99 Conference , Proceedings of American Solar Energy Society Annual Conference*, Portland Maine, June 12-16, 1999. pp. 267-272 ; NICH Report No. CP-520-26229.

Myers, D. R. (1999). "Module Energy Rating Candidate Reference Days: Criteria and Selection Process". Al-Jassim, M.; Thornton, J. P.; Gee, J. M., eds. *NCPV Photovoltaics Program Review: Proceedings of the 15th Conference*, 9-11 September 1998, Denver, Colorado. AIP Conference Proceedings 462. Woodbury, NY:American Institute of Physics; pp. 649-654; NICH Report No. 27445.

Kurtz, S.R., D. Myers, T. Townsend, C. Whitaker, A. Maish, R. Hulstrom, K. Emery. Outdoor Rating Conditions for Photovoltaic Modules and Systems. Submitted to *Solar Energy Materials*, Sep, 1999. NICH Report No. JA-520-27160.

Photovoltaic Systems Performance and Standards

Contract #: DE-AC36-98-GO10337	Contract Period: 10/1/98–9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
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E:mail: Richard.King@ee.doe.gov</td><td colspan="2">National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Richard DeBlasio
Phone: 303-384-6452 Fax: 303-384-6491</td></tr>
<tr><td rowspan="2">Technical Monitor:
Roland Hulstrom
Phone: 303-384-6420
Fax: 303-384-6481
E:mail: roland_hulstrom@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1997: $83,000 1999: $905,000
1998: $843,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The overall objective of the Photovoltaic System Performance and Standards task is to address PV system, subsystem, and component technical and infrastructural issues and provide solutions that support the DOE PV Program five year plan (1996-2000) goals, and accelerates PV technology readiness and commercialization. Specific objectives are to provide engineering solutions and approaches that will reduce technical barriers to commercialization and advance photovoltaic system, subsystem, and component performance, safety, and quality.

Approach/Background: The technical approach to achieving task objectives include: (1) conducting system, subsystem, and component interface performance characterization outdoor testing and establishing standardized measurement and test procedures; (2) verifying PV system, subsystem and component development and advances through baseline outdoor performance testing, evaluation, and comparative analysis; (3) developing and documenting engineering best practices and technical guidelines for standardized system, subsystem, and component design and interface criteria and test procedures; (4) leading and supporting the development of national and international PV consensus standards and codes; (5) participating and supporting the development, implementation, and operation of domestic and international system and component certification and test facility accreditation programs; (6) facilitating information exchange and technology transfer through topical meetings, forums, and workshops; and (7) providing technical assistance and support to the domestic and international PV community for PV technology development and systems engineering and applications.

Status/Accomplishments: Task members coordinated and conducted with Sandia the annual PV Performance, Reliability, and Standards Workshop held in Vail, CO. The workshop provided a venue for technical discussions on four topical areas: module ratings, module qualification, power processing, and systems testing. Both tutorial presentations and open discussion on individual concerns, issues, and solutions was the focus of the workshop. Activities included morning presentation sessions that were followed by afternoon standards development meetings to address the needs and requirements established in the morning. The workshop was a major success in that participants endorsed the venue and informal interactions of all 65 participants. Inter-comparison of small system tests to validate interim test methods was a major effort in FY99. Two small PV lighting systems were selected to validate the small PV system test procedures that were previously developed at NREL. The four participating laboratories (NREL, FSEC, SWTDI, and PVUSA) completed the validation. A report detailing the results of this testing was presented at the Standards and Codes Forum. A technical report titled "Procedures for Determining the Performance of Stand-Alone PV Systems" (NREL/TP-520-27031) was completed and published. The revised procedures have become Draft 1 of IEEE PAR1526 "Recommended Practice for Testing the Performance of Stand-Alone PV Systems." Operations at the NREL Outdoor Test Facility (OTF) included conducting validation performance tests on 20 operational systems and two new intalled systems. The two new installed systems included a 1-kW CIGSS system from Siemens Solar. This array consists of 28 modules that averaged 41.6 watts and had an average efficiency of 11.4% at standard test conditions and is configured as a DC operational array with peak-power trackers. A Solarex 1.5kW system was installed on the OTF (lower front roof) and is connected to the electric utility via the OTF electrical distribution system. This system contains 36 dual-junction amorphous silicon Millennia modules. Both systems are being monitored for long term performance and reliability. PVMaT and PVBonus testing support of deliverables included testing of the 200W MAPPS system from SES. This system operated for more than 14 months with an availability of 98%. Two AC modules from Ascension Technologies were installed in the field array area at the OTF and are being monitored for long-term performance. A study was conducted by task members to determine system design and performance analysis needs and included the evaluation of several PV system design software packages to determine in what areas they might need improvement. The design of both grid-tied and stand-alone PV systems was evaluated. The software packages evaluated were PV Designer, PV Design Pro, PVFORM, PVCAD, and SolarSizer. Results are being further considered by the IEEE SCC21 for the development of a standards project on PV systems sizing design. Over the past year task members lead IEEE and IEC standards development committees focusing on P929, P1526, P1373, P1479 and expanding TC82 . This included chairing IEEE SCC21, IEEE SCC21 working groups, and IEC TC82, and providing leadership in system/utility interconnection, energy rating, concentrator qualification tests, and system test standards development. In recognition of the PV lead efforts under SCC21, the IEEE Standards Board expanded the scope of IEEE SCC21 to address all dispersed generation and energy storage technologies. The IEEE Standards Board approved the PAR 1547 "Standard for Distributed Power Resource(s) Interconnection with the Electric Power System(s)." The proposed standard, when completed, will provide a uniform standard for interconnection of distributed resources (including PV) with electric power systems. It will also provide requirements for the performance, operation, testing, safety considerations, and maintenance of the interconnection. IEEE-P929 is a recommended practice for PV interconnection is nearing completion, and expected to provide some basis for the P1547 standard. Approval was also given for the balloting committees in reaffirming IEEE 1145 and IEEE 1013 (PV Battery recommended practices). IEC TC82 was expanded to include working groups on Quality and Certification, BOS, and concentrators. Preparation for the U.S. to host the IEC-TC82 general meeting in FY 2000 were initiated with plans to have the meeting at ASU (Arizona State University) in May 2000 . Support for domestic and international accreditation and certification included the certification of two photovoltaic module manufacturers (Solarex and United Solar Systems) who completed the quality and qualification testing requirements for PowerMark Corporation (PMC) certification. This is the first time that module certification has been given to PV manufacturers based on third-party certification (PMC) within the United States. Internationally PMC will also be the first point of contact for the PVGAP application process in the USA and will facilitate the NSI (National Supervisory Inspection) through UL (USA/NSI). Task members represented the DOE and PV program during the PVGAP World Bank sponsored summit meeting held in Geneva, Switzerland on May 3 and 4, 1999, to review with member nations the PV quality and training manuals for in-country application and for World Bank use in funding UNDP projects. A meeting of the PVGAP Board of directors was also held following the World Bank meeting on May 5, 1999, and was also attended Task members also participated and provided technical assistance to the PVUSA technical review committee, UPVG engineering and specification working group; supported through reviews and testing PVMaT, PV Bonus, thin-film partnerships, million solar roofs; and interface for task activities with DOE, industry, and internationally **.** Major activities included participation in the PVUSA proposal review with the DOE Golden field office for FY 1999 activities at the PVUSA Davis, California site . Participation in the UPVG UPEX meetings and providing an overview (IEEE P929) for PV system interconnection requirements and presenting IEC TC82 standards status at the Soltec PVGAP workshop on PV international system certification . A PV Standards and Codes Forum was conducted in June 1999 at Winter Park, CO . The organizations involved were IEEE Standards Coordinating Committee 21, ASTM subcommittee E44.09, and the U.S . Technical Advisory Group (TAG) for IEC Technical Committee 82 . Over 45 participants attended the 3 day meeting and were given the opportunity to meet the organizational leaders and become aware of IEEE, ASTM, IEC, and NEC activities for PV standards and codes development and to get involved. Overview meetings were followed by concurrent working group meetings that discussed individual standards and codes documents . During the workshop task members lead working group meetings for IEEE projects P1526 and P 1479 on module energy rating and system performance testing.

Planned FY 2000 Milestones: Milestones include: 1. Conducting validation of systems testing procedure in coordination with international round robin. (9/00); 2. Hosting the IEC TC82 PV International Standards meeting in the US at ASU. (5/00); 3. Installing a 1kW PVI concentrator system. (7/00); and 4. Initiating the development of small systems qualification testing procedures. (9/00)

Major Reports Published in FY 1999:
STR98USR.001 - Final Test Report on USSC dual-junction amorphous silicon prototype roof mounted array
STR98SCI.002 -Three year update on the performance of the SCI CdTe system
STR99SES.001 - Final report on the performance of a metal-halide PV lighting system
STR99USR.001 - Performance of the United Solar Roofing system over the first six months of operation
STR99SSI.001 - Final report on the second Siemens CIGSS array
STR99SCI.001 - Performance of the Solar Cells, Inc. 1kW CdTe system up to March 1999
STR99SSI.002 - New CIGSS system's performance to March 1999.
STR99SSI.003 - Updated the Siemens CIS system performance over the last nine months.

Major Articles Published in FY 1999:

- *"PV Systems: An End-of-Millennium Review,"* M. Thomas, H. Post, and R. DeBlasio, "Progress in PV: Research and Application," January 1999.
- *"Performance of Amorphous Silicon Photovoltaics for Building-Integrated Applications,"* B. Kroposki and R. Hansen, ASES conference June 12-16, Portland, Maine.
- *"Procedures for Determining the Performance of Stand-Alone PV Systems,"* (NREL/TP-520-27031), P. McNutt, R.Hansen, B. Kroposki, and R. DeBlasio, September 1999.

Photovoltaic System Performance and Engineering

Solar Resource Characterization

Contract #: DE-AC36-99GO10337	**Contract Period:** 10/1/98–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** David S. Renné **Phone:** (303) 275-4648 **Fax:** (303) 275-4675 **E:mail**: david_renne@nrel.gov	
Technical Monitor: R. Hulstrom **Phone**: 303-384-6420 **Fax**: 303-384-6490 **E:mail:** roland_hulstrom@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1998: $500,000 1999: $500,000	**Cost Share Funding:**

Project Objective: The goal of this project is to develop and disseminate key information on solar energy resources to the U.S. industry and to energy planners in order to facilitate and accelerate the deployment of their technologies domestically and world-wide. To achieve this goal, the following objectives were addressed in FY 1999:

- Improve ability to produce time-series and statistical estimates of solar resources from world-wide meteorological data;
- Improve ability to provide accurate and reliable maps and underlying climatological data of world-wide solar resources at high spatial resolution;
- Provide a centralized, interactive source of quality assessed non-proprietary resource data and information.

Approach/Background: This project consisted of three tasks:

Task 1: Evaluate meteorological data for modeling hourly values of solar radiation at stations throughout the world;

Task 2: Evaluate and enhance capabilities for producing high-spatial resolution world-wide maps of solar resources using ground-based and satellite-based data;

Task 3: Maintain the Renewable Resource Data Center web site.

Status/Accomplishments: Under Task 1, a technique was developed to estimate solar resources (global horizontal, direct normal, and diffuse) at over 20,000 stations around the world using the surface global meteorological data base called DATSAV2. This data base was acquired from the National Climatic Data Center, and is used jointly by the wind and the solar resource assessment teams at NREL. For each station, over twenty years of three-hourly or six-hourly weather observations (including cloud cover and characteristics, temperature, relative humidity, etc.) are available. For stations where data quality is adequate, the data can be input into a modified version of the METSTAT Model (the model used to calculate solar resources for the National Solar Radiation Data Base). A draft report was completed summarizing the use of this technique in the southern Africa region. For 7 locations in Southern Africa, modeled global horizontal solar radiation compared with measured data to within $\pm$10% for monthly averages and to within $\pm$26% for daily values. This is comparable accuracy to that of the National Solar Radiation Data Base for the United States. We concluded that it is now possible to produce multi-year data sets of hourly solar radiation and meteorological to support the analysis and deployment of renewable energy systems at the majority of the DATSAV2 stations.

Also in Task 1, PVWATTS was added to the Renewable Resource Data Center (RReDC) in September. PVWATTS is an internet-accessible model that calculates the performance of grid-connected PV systems. Based on subroutines from Sandia's PVFORM, PVWATTS reads Typical Meteorological Year (TMY2) data and performs an hour-by-hour simulation for a one-year period. Users may select any of the 239 TMY2 stations from a clickable station map, and may select default PV system parameters, or specify their own. Parameters that may be specified include PV system size, fixed or tracking PV array, PV array tilt angle, PV array azimuth angle, and local electric cost. PVWATTS outputs a table of monthly and annual energy production in AC kWh and energy value in dollars.

Contract #: DE-AC36-99GO10337

Under Task 2, we have finished the installation of all 14 tilted surface algorithms into the Climatological Solar Radiation (CSR) model. We have evaluated the model results against the NSRDB hourly statistics, and produced data grids for all 14 surfaces over the United States, Mexico, Central America and the Caribbean basin.
Results of the evaluation were somewhat better than expected. Mean bias error of the CSR technique vs. the NSRDB is about 3% (over-prediction) for tilted flat-plates, and almost 0 for the concentrating collectors. Root-mean-square (RMS) error is about 1.5% for most surfaces.

The errors are slightly larger, as expected, using data grid inputs to the model. For flat-plate collectors, the bias error is about 2.6% and the RMS error is 2-3%. For concentrating collectors, the bias error is -1.2% (model under-predicts) and the RMS error is about 3.5%. These results indicate that the data grids, with 40 km spatial resolution, can be used for estimating the solar resource at various collector orientations and types.

Under Task 2, NREL hosted the 2nd Workshop on Satellites for Solar Energy Assessments, which was held at the Golden Hotel on February 3-4, 1999. The theme of the workshop was to review the current status of techniques and products of solar data derived from weather satellite imagery. Of the more than 40 participants, many were representatives from U.S. government, laboratory, and university researchers, including the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, and NREL, and experts in the use of solar energy for building design and concentrating solar power technologies. In addition, researchers from seven other countries (Canada, France, Switzerland, Germany, Mexico, Brazil, and Japan) as well as Puerto Rico, attended the workshop. Many of these foreign visitors were invited to give presentations on the status of research in their country. Presentations on new techniques for developing climatological estimates of the solar resource at all locations on earth at a resolution of 100 km, and of developing estimates at half-hour intervals at resolutions of 10 km or less in specific locations were made. A major conclusion of this workshop is that satellite techniques have become so advanced that they now represent a reasonably-accurate tool for developing large area solar resource assessments. These assessments are of particular value in locations where ground data are limited, and for developing high resolution site/time-specific data that can be used for assessing the performance of PV technologies.

Under Task 3, we continue to add new solar-related data sets and other features to the Renewable Resource Data Center web site at NREL. The home page has been restructured, and easier links to the NCPV and to the EREN home pages established. There is also a new “Kidzlinks” site to provide answers to popular questions from school-age visitors. We have also established links to the solar data being collected at Southwest Technology Development Institute, and the Florida Solar Energy Center. The site continues to grow in popularity, receiving as many visits as other web sites at NREL, resulting in numerous enquiries from the public on solar resource data.

Also under Task 3 we have formed a cooperative arrangement with the Global Atmopsheric Watch, a program of the World Meteorological Organization, to obtain access to the high-quality solar resource data being collected at a number of GAW stations around the world. We have visited two GAW sites in South America to work with local personnel on data quality assessment procedures, and have hosted GAW station personnel to provide training in our data quality assessment software. These quality assessment and archiving procedures will ultimately be used to transfer the data to the world archive at the World Radiation Data Center in Russia.

Planned FY 2000 Milestones: This project will achieve two major milestones in FY 2000:
- North American Solar Atlas (electronic version), Version 1
- Monthly and annual 40-km solar resource data grid maps for Alaska and Hawaii

Major Reports Published in FY 1999:
NREL, 1999: “Presentations of the 2nd Workshop on Satellites for Solar Energy Assessments”, February 3-4, 1999.

Major Articles Published in FY 1999:
- Brady, Elizabeth H. and Buckley, David J., “Using GIS to Deploy a Climatological Solar Radiation Model” *Solar ’99 Conference Proceedings, Portland, ME, June 12-16, 1999.*
- George, Raymond I. and Eugene I. Maxwell, “High Resolution Maps of Solar Collector Performance Using a Climatological Solar Radiation Model”, *Solar ’99 Conference Proceedings, Portland, ME, June 12-16, 1999.*
- Renné, David S., Zelenka, Antoine, Perez, Richard, Whitlock, Charles, and DiPasquale, Roberta, “Recent Advances in Assessing Solar Resources over Large Areas”, *Solar ’99 Conference Proceedings, Portland, ME, June 12-16, 1999.*
- Renné, David S., Richard Perez, Antoine Zelenka, Charles Whitlock, and Roberta DiPasquale, “Use of Weather and Climate Research Satellites for Estimating Solar Resources”, Chapter 6 in *Advances in Solar Energy, Volume 13,* Edited by D. Yogi Goswami and Karl W. Boer, American Solar Energy Society, Boulder, CO.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507h	**Contract Period:** 5/11/99-9/15/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	National Rural Electric Coop Association (NRECA) Arlington, VA 22203-1860	
	Organization Type: TA	**Congressional District:** 8
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Pete Smith **Phone:** 703-907-5532 **Fax:** 703-907-5673	
Technical Monitor: Larry M. Moore **Phone:** (505) 845-9191 **Fax:** (505) 844-6541 **E:mail:** lmmoore@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $27,000	**Cost Share Funding:**

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

Field Module Durability Support

Contract #: BE-2538	**Contract Period:** 12/15/98-10/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">New Mexico State University (Southwest Technology Development Institute)
Las Cruces, NM 88003</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 2</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
Gabriela Cisneros
Phone: 505-646-2438 Fax: 505-646-3841</td></tr>
<tr><td rowspan="2">Technical Monitor:
Michael A. Quintana
Phone: 505-844-0474
Fax: 505-844-6541
E:mail: maquint@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $33,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Assist Sandia and the PV industry to identify and study module durability issues.

Approach/Background: Provide support by conducting module long-term exposure tests.

Status/Accomplishments: Continued to provide monthly performance tests and visual inspections.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507g	**Contract Period:** 5/11/99-9/15/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Planergy, Inc.
Austin, TX 78746</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 10</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
John Hoffner
Phone: 512-327-6830 Fax: 512-327-2553</td></tr>
<tr><td rowspan="2">Technical Monitor:
Larry M. Moore
Phone: (505) 845-9191
Fax: (505) 844-6541
E:mail: lmmoore@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $25,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507e	**Contract Period:** 5/11/99-9/15/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	PowerLight Corporation Berkeley, CA 94710	
	Organization Type: IN	**Congressional District:** 9
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Dan Shugar **Phone:** 510-540-0550 **Fax:** 510-540-0552	
Technical Monitor: Larry M. Moore **Phone:** (505) 845-9191 **Fax:** (505) 844-6541 **E:mail:** lmmoore@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $27,000	**Cost Share Funding:**

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

PV Certification and Accreditation Management Support

Contract#: AAX-7-16821-01	**Contract Period:** 11/18/98–11/17/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Power Mark Corporation 4044 East Whitton Phoenix, AZ 85018-5940 **Organization Type:** IN	 **Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** S. Chalmers **Phone:** 602-955-7214 **Fax:** 602-955-7295	
Technical Monitor: Richard DeBlasio **Phone:** 303-384-6452 **Fax:** 303-384-6490 **E:mail**: dick_deblasio@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1996: $49.970 1998: $60,000 1997: $35,000 1999: $60,000	**Cost Share Information:** None **Cost Share Funding:**

Project Objective: To support Power Mark Corporation to manage and administer the operation of a component and system certification and laboratory accreditation program. Administer corporate board and committee activities, and liaison activities with domestic and international organizations associated with certification, accreditation, standards, codes, and test method development and validation.

Approach/Background: The development of a domestic PV system and component certification and test facility accreditation program that is recognized, has reciprocity between other organizations and has testing conducted by accredited test facilities and products manufactured in a quality environment is a key to a PV component and system quality system. Power Mark Corporation was created to implement and manage a PV module certification program based on the ASU/ NREL/DOE study and has expanded it's role to include systems /components.

Status/Accomplishments: The PowerMark Corporation (PMC) board, technical, accreditation, and quality subcommittees have been in operation for over three years. The Board membership includes representatives from ASE Americas, BP Solarex, AstroPower, EBARA Solar, Trace Engineering, Siemens Solar, Endicon Engineering and United Solar Systems. Two major module manufactures have modules that have passed the PMC testing and quality certification requirements.One manufacturers facility has been approved by IECQ for module production and the ASU/PTL. Laboratory has also been approved by IECQ. AL2A has audited ASU/PTL and found conditions favorable for continued module testing. Module test performed at the laboratory are recognized internationally . Integration with the international PV Global approval Program (PVGAP) is progressing to harmonize the national and international certification activities with IECQ and the Supervising Inspectorate (SI) Underwriters Laboratories (UL). Three PMB Board members are on the PVGAP board and committees. PV-GAP has designated Solar Energy Industries Association (SEIA) as the licensee in the US. PMC will perform all the administrative functions for SEIA and collect the fees.

Planned FY 2000 Milestones: Hold monthly meetings (Tele-conferences) of the PMC Board. Increase industry representation on the board and committees from component and systems sectors. Exert best efforts to encourage reciprocity protocols from associated certification programs. Maintain a PMC web site. Provide presentations of PMC and PVGAP at technical and industry meetings. Facilitate the IECQ approval of U.S. laboratories and manufactures. Sponsor a workshop for PV manufacturers that defines the process for obtaining IECQ approval of their facilities and products.

Major Reports Published in FY 1999:
FY 1998 Photovoltaic Energy Program Contract Summary, DOE/10099-721 (1999). Subcontract monthly reports, travel reports, meeting minutes and annual reports.

Major Articles Published in FY 1999:
Promotional material describing the PMC organization and benefits of PMC certification were provided during presentations at the IEEE SCC21 meetings and SOLTECH 2000 meeting.

Photovoltaic System Performance and Engineering

Combining Satellite and Ground Measurements for the Production of Site/Time Specific Solar Irradiance

Contract #: XAH-5-15222-01	**Contract Period:** 6/16/95–2/28/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
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E:mail: Richard.King@ee.doe.gov</td><td colspan="2">The Research Foundation of the State University of New York, Albany
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Albany, NY 12203</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 21</td></tr>
<tr><td>Directing Organization:
DOE Office of Solar Energy Technology
1000 Independence Ave., SW
Washington, DC 20585</td><td colspan="2">Principal Investigator (s)
Richard Perez
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David. S. Renné
Phone: (303) 275-4648
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E:mail: david_renne@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1998 $30,000
1999: $30,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objectives:

Building upon accomplished satellite model development and validation tasks, the FY 99 objectives of this project are:

1. To continue receiving and archiving GOES-8 and GOES-9 visible channel northern hemisphere frames on a regularly scheduled basis; processing these frames into a 10-km grid with normalized values acceptable to our satellite-to-irradiance model; and forwarding processed data to NREL.
2. To derive and test a one-step satellite-to-direct beam algorithm, using GOES-8 data for the northeastern US and ground measurements from the Atmospheric Sciences Research Center.
3. To compare the results against the "classical" modeling approach, which consists of first deriving global irradiance using the Zelenka/Perez/Satellight model, and then applying the DIRINT (modified DISC) algorithm.
4. To provide an initial evaluation of how the algorithm could be improved in the future (i) by using a measured regional clear sky turbidity rather than a default or time-averaged regional turbidity and (ii) by using widely available ground based meteorological measurements.

Approach/Background

Archiving of Goes Data: Visible channel GOES-8/10 data broadcasted by UCAR to its member universities are acquired and processed into $.1^o \times .1^o$ grid archives (i.e. ~ 10 km). Every frame archived is visually inspected. Each image including visual defects (e.g., tainted with black, white streaks or distortion patterns) is flagged as questionable.

The one step model: Ineichen and Perez (1999) introduced a one-step approach to model other than global solar components directly from the satellite counts This task represents an initial validation of this one-step model against high quality hourly ground measurements in Albany, NY, covering a 9-month period.

Comparison with the classical approach: Results are compared to the traditional approach of compounding two models to derive direct and diffuse irradiance. The benchmarks of performance assessment include (1) Root mean square mean bias errors (resp. RMSE and MBE); (2) Effective accuracy; (3) Frequency distribution comparison between measured and modeled components

Use of auxiliary data: Two versions of the classical model augmented with auxiliary input are investigated: (1) the first version refines the dynamic range-tracking algorithm by adding available external information to help picking up fast evolving ground albedo situations. Using external information readily available from the National Weather Service -- ***cloud cover*** -- we modify the algorithm to only allow pixels corresponding to a "clear sky" signal from the closest National Weather Service site into the calculation of the current's dynamic range's lower bound. (2) The second version uses additional external information: measured current regional Linke turbidity replaces the seasonal look-up table. Regional turbidity is estimated from direct irradiance measurements in Albany. The average turbidity corresponding to the pixels used to define the lower bound of the dynamic range is used in the algorithm's clear sky model.

Status/Accomplishments

Archiving of Goes Data: As of this writing, we have archived 27 month of gridded satellite images covering the northern hemisphere from the western Atlantic Ocean to Hawaii.

One-step Model development &Validation: Our preliminary investigation in the one step modeling of direct and diffuse irradiance demonstrates substantial performance improvement potential. The performance of this model betters that of the classical model using any of the performance evaluation benchmarks, and approaches the performance of the latter when this uses external information. In particular, the one step model shows little seasonal bias variations. The results of this investigation are detailed in a completed article to be presented next month at the annual AMS meeting.

These encouraging preliminary results ought to be pursued in the following directions:

- Investigating and minimizing site-dependency by expanding the analysis to other climates/environments.
- Implementing effective albedo tracking in the one-step model, and making use of readily available auxiliary data.

Use of auxiliary data: We showed that the use of readily (or potentially) available, information consisting of cloud cover from meteorological services and regional turbidity resulted in measurable performance improvement, particularly in winter, at times of rapidly evolving ground albedos.

Planned FY 2000 Milestones:: Letter Report: "Assessment of high resolution solar mapping technique for North America using GOES imagery," 9/00.

Publications in FY 1999

- Ineichen P., R. Perez, and D. Renné, (1999): Generalized Cloud Indices for the Production of Solar Irradiance and Daylight Illuminance Data from Geostationary Satellites. Proc. Eumetsat Conference, Copenhagen, Denmark.
- Ineichen, P. and R. Perez, (1999): Derivation of Cloud Index from Geostationary Satellites and Application to the Production of Solar Irradiance and Daylight Illuminance Data Theoretical and Applied Climatology *(accepted for publication 2/99)*
- Zelenka, A., Perez R, Seals R. and Renné D., (1999): Effective Accuracy of Satellite-derived irradiance, Theoretical and Applied Climatology, 62, 199-207
- Perez R., (1999), Jul 6th, 1999 Heat Wave, Peak Demand Records & Outages in New York City...PV Would Have Worked! Custom study posted at: http://lunch.asrc.cestm.albany.edu/~perez/
- *Ineichen, P., R. Perez, M. Kmiecik and D. Renné, (2000): Modeling direct irradiance from goes visible channel using generalized cloud indices. 80th AMS Annual Meeting, Jan 9-14, 2000, Long Beach, CA*

Photovoltaic System Performance and Engineering

Systems Engineering

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/98 – 9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Sandia National Laboratories Photovoltaic Systems Applications Department	
	Organization Type: FF	**Congressional District**: 1
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Hal Post **Phone:** 505-844-2154 **Fax:** 505-844-6541	
Technical Monitor: Christopher P. Cameron **Phone:** (505) 845-8161 **Fax:** (505) 844-6541 **E:mail:** cpcamer@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $1,880,000	**Cost Share Funding:**

Project Objective: The program provides system, subsystem, and component-level information and technical assistance to the photovoltaic community, primarily through the Photovoltaic Systems Assistance Center (PVSAC), and work on standards and codes, especially as they relate to IEEE and the National Electrical Code. The goal is to provide value-added engineering on both fielded and prototypical systems and components. Sandia has primary responsibility within DOE's PV program for developing and disseminating technical information on PV systems engineering. Goals and objectives are:

- reducing the life-cycle cost of PV systems
- reducing barriers to systems acceptance
- providing systems engineering best practices and guidelines
- leading the national effort in performance and reliability testing,

with the overall goal of ensuring that PV systems meet customers' needs by working as expected.

Approach/Background: The systems engineering program seeks to improve PV system design, deployment, and operation, thereby achieving the goal of lower cost, more reliable systems

Status/Accomplishments:

- Sandia's expertise in the systems engineering field was recognized this year by an invitation from the prestigious international journal, Progress in Photovoltaics, to publish an article entitled Photovoltaic Systems: An End-of-Millennium Review. This is the first time this journal has published an invited review on PV systems. The article summarized 20 years of experience in PV systems engineering at Sandia and identified a major deficiency (quantifying recurring costs of PV systems) in our current understanding. A major R&D initiative was begun to examine the reliability and life-cycle costs of PV systems as a result.
- FY99 saw the culmination of an extremely successful five-year partnership with federal agencies. The Renew series reported on Sandia's work with federal agencies to document agency experience with PV, identifying barriers to deployment, and providing technical assistance in deploying new systems. Over 2 megawatts of PV was installed on federal lands through the Renew partnership (over 300kW) and work with the Department of Defense. One result was *Renew the Government*, a document featuring over 100 systems and applications.
- Established formal support to Remote Power Initiative projects in Utah (large facility power), Virginia, and Maryland (multiple agricultural applications). This effort focuses Sandia's engineering expertise on assistance to state energy offices.

Performed economic analyses that evaluated alternative strategies for improving hybrid systems. Analyses shoed that recurrent capital replacement and maintenance costs drive hybrid economics, and that operational strategies have second-order impact on these costs.

Contract #: DE-AC04-94AL85000

- Drafted and achieved consensus on IEEE P929 (Recommended Practice for Utility Interconnection of Photovoltaic (PV) Power System) to the point where it is ready for submission to the IEEE standards board.
- First-ever regional assistance provided to DOE/DOI's Green Energy Parks initiative.
- Assistance in evaluating PVMaT and proposals continued; serves on monitoring team;
- Coordinated input for the next version of the NEC
- Participation in the International Energy Agency's Task V work on Photovoltaics continued.
- Co-hosted the annual Performance and Reliability Workshop at Florida Solar Energy Center, attended by more than 100 members of the PV industry. This workshop continues to be the only national forum for the discussion of PV systems-level issues.

FY 2000 Milestones:

- Study the operations and maintenance costs of both grid-tied and stand-alone systems to establish a benchmark for life-cycle costs
- Develop qualified database for long-term maintenance and reliability of systems
- Continue our assistance to the Navajo Nation
- Continue our assistance to the State of Florida (buildings program)
- Conduct technical assessments for PV opportunities at federal facilities
- Continue to provide outside assistance to hundreds of individuals in the PV industry, generally in the form of direct technical assistance
- Develop data for web-based battery handbook
- Participate in periodic workshops on the National Electrical Code for state electrical inspectors
- Publish a PV industry program marketing tool to identify the wide range of applications for which PV can be used
- Document outreach activities through publication distribution and website activity
- Continue to serve on PVMaT monitoring teams

Major Reports Published in FY 1999:

Renew the Government: Summary of Projects and Lessons Learned. Sandia National Laboratories SAND98-1943, October 1998.

Utility Aspects of Grid Interconnected PV Systems, IEA-PVPS Report, IEA-PVPS T5-01: 1998, Dec 1998. (Printed and Distributed in 1999)

Post, Hal, Mike Thomas, and Jerry Ventre. "An Assessment of Renewable Energy Options at Brooks Camp, Katmai National Park and Preserve," August 1999.

Major Articles Published in FY 1999:

Thomas, M., H. Post, and R. DeBlasio. "Photovoltaic Systems: An End-of-Millennium Review," *Progress in Photovoltaics: Research and Applications*, Vol. 7, Number 1, January-February 1999.

Bower, W. and R. DeBlasio. "Code Requirements and Standards for Installations of Photovoltaic Systems in the US," *Progress in Photovoltaics: Research and Applications*, Vol. 7, Number 3, May-June 1999.

Maish, A. "Defining Requirements for Improved Photovoltaic System Reliability," *Progress in Photovoltaics: Research and Applications*, Vol. 7, Number 3, May-June 1999.

Bower, Ward. "Task V of the IEA Photovoltaic Power Systems Program: Accomplishments and Activities," *Proceedings of the NorthSun99 Conference*, Edmonton, Alberta, Canada, August 1999.

Wiles, John and Ward Bower. "What Changed in Article 690 - Solar Photovoltaic Systems- of the 1999 National Electrical Code," *Journal of the International Electrical Inspectors Association*, Spring 1999.

Photovoltaic System Performance and Engineering

Management and Administration of the IEC TC82

Contract #: ACD-9-29429-01	**Contract Period:** 4/26/99–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Solar Energy Industry Association Solar Energy Research & Education Foundation 1111 N. 19th St.–Suite 260 Arlington, VA 22209	
	Organization Type: IN	**Congressional District:** 8
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J. Anderson **Phone:** 828-495-1274 **Fax:** 828-495-3441	
Technical Monitor: Richard DeBlasio **Phone:** 303-384-6452 **Fax:** 303-384-6490 **E:mail**: dick_deblasio@nrel.gov	**B&R Code:** EB22	**Cost Share Information:**
	DOE Funding Allocation: 1997: $ 65,000 1998: $ 65,000 1999: $ 65,000	**Cost Share Funding:**

Project Objective: To support an appropriate organization (SEIA/SEREF) designated by the ANSI USNC (American National Standards Institute, United States National Committee) to manage and administer Secretariat responsibilities for the International Electrotechnical Commission (IEC) PV/Technical Committee (TC) 82 for PV Solar energy systems standards, and coordinate and support U.S. technical participation in the IEC PV/TC82 and its working groups.

Approach/Background: The IEC TC-82 is an international standards making committee on solar PV energy systems. The committee prepares consensus international standards and publishes them for the PV industry and community. The committee consists of 6 working groups on glossary, modules, systems, certification, BOS components, and concentrators plus a seventh group on batteries, which is shared with TC21.

Status/Accomplishments: There are 21 participating (voting status) and 12 observing (commentary status) countries involved in TC-82 work. A complete listing is given in Table 1. The number of working groups and the number of international experts participating in this work has nearly doubled in size during the past 5 years. Currently, the Working Groups (WG) and the participants are distributed as follows: WG 1. (Glossary)–9 experts; WG 2. (Modules) - 18 experts; WG 3. (Systems) - 25 experts; WG 4. (refer to joint WG TC21/TC82 on batteries); WG 5. (Quality) - 11 experts; WG 6. (Components) - 7 experts; and joint WG TC21/TC82 - 5 TC 82 experts.

TABLE 1

Country Membership for IEC/TC82

Australia (P)	Hungary (O)	Singapore (P)
Austria (P)	India (P)	South Africa (P)
Belgium (O)	Indonesia (P)	Spain (P)
Brazil (O)	Italy (P)	Sweden (O)
Bulgaria (O)	Japan (P)	Switzerland (P)
Canada (P)	Netherlands (P)	Ukraine (O)
China (P)	New Zealand (O)	United Kingdom (P)
Czech Republic (P)	Norway (O)	United States of America (P)
Denmark (P)	Poland (P)	Yugoslavia (O)
Finland (O)	Portugal (P)	
France (P)	Romania (P)	**P** = (Participating)
Germany (P)	Russian Federation (P)	**O** = (Observing)

Contract #: ACD-9-29429-01

Currently, 26 standards have been published. Work is underway on a PV safety standard, a PV module power and energy rating standard, a comprehensive Part 2 to the glossary technical report, a system standard for small stand-alone systems, an inverter safety standard, a total quality program standard for product certification and laboratory accreditation, and an environmental test standard for the type approval of BOS components.

Planned FY 2000 Milestones: To conduct TC82 and working group meetings, and to establish two new working groups: one for the interconnection and integration of distributed energy systems, and another for energy storage system requirements, including, but not limited to battery requirements.

Major Reports Published in FY 1999:

NREL Photovoltaic Program FY 1998 Annual Report, NREL/BK-210-26626, (June 1999). TC82 committee and working group meeting reports, and subcontract monthly, quarterly, and annual reports.

Major Articles Published in FY 1999:

Published IEC TC82 standards during this reporting period:

IEC 61883: 1999, PV Systems - Power Conditioners-procedure for measuring efficiency.

IEC 62111: 1999, General Directives for the use of REN in Decentralized Rural Electrification

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507d	**Contract Period:** 5/11/99-9/15/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Soluz, Inc. North Chelmsford, MA 01863-1561	
	Organization Type: IN	**Congressional District:** 7
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** John Rogers **Phone:** 978-251-5290 **Fax:** 978-251-5291	
Technical Monitor: Larry M. Moore **Phone:** (505) 845-9191 **Fax:** (505) 844-6541 **E:mail:** lmmoore@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $30,000	**Cost Share Funding:**

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

SWRES Field Evaluation

Contract #: AV-5589	**Contract Period:** 3/19/97–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Southwest Technology Development Institute Box 30001, Dept. 3SOL Las Cruces, NM 88003-0001	
	Organization Type: CU	**Congressional District**: 2
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** A. Rosenthal **Phone**: 505-646-1323 **Fax**: 505-646-3841	
Technical Monitor: Michael G. Thomas **Phone:** 505-844-1548 **Fax:** 505-844-6541 **E:mail:** mgthoma@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1994: $263,000 1995: $404,000 1996: $400,000 1997: $780,000 1998: $600,000 1999: $467,000	**Cost Share Funding:**

Project Objective: Utilize field experience to monitor performance of systems.

Approach/Background: Systems installed are monitored for initial performance, performance changes, and safety issues.

Status/Accomplishments:
- Documented technical assistance to Tucson UPVG project.
- Conducted six PV/NEC workshops for state electrical inspectors.
- Training workshops conducted in Arizona, North Carolina, Idaho, Washington, Maine, and New Mexico.
- Provided assistance to Tucson Coalition partners; Global Solar in developing UL listing of products; Tucson Electric in developing a design for the Ward 4 Building and electrical inspection training.
- Developed 32 proposed changes for the 2002 National Electrical Code

FY 2000 Milestones:
- Update and revise Suggested Practices for the 1999 NEC
- Develop SWTDI web page, emphasizing codes and standards
- Prepare bi-monthly electronic newsletters on off-grid applications

Major Reports Published in FY 1999:
- Rosenthal, A., et al. "Procedures for Determining the Performance of Stand-Alone PV Systems," National Renewable Energy Laboratory, September 1999.
- Rosenthal, A., et al. "Dangling Rope Marina PV Hybrid Power System: 1998 Annual Performance Report." Produced for the State of Utah, Office of Energy and Resource Planning, April 1999.
- Rosenthal, A., et al. "Field Test Report: Grand Canyon National Park North Rim Visitor Center and Tuweep Ranger Station," National Park Service report, June 1999.
- Rosenthal, A., et al. "PV Hybrid System Test Report: Joshua Tree National Park and Mojave National Preserve," National Park Service report, July 1999.

Major Articles Published in FY 1999:
- Wiles, John. "Code Corner," *Home Power Magazine*. [six columns every year]
  Rosenthal, A. L. "Evaluation of Hybrid Power System Alternatives: A Case Study," *Progress in Photovoltaics: Research and Applications*, Vol. 7, Number 3, May-June 1999.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507b	**Contract Period:** 5/14/99-9/15/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Winrock Repso Brazil Lauro de Freitas Bahia, Mexico	
	Organization Type: ZZ	**Congressional District**:
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** William E. Howley **Phone:** 557-379-1759 **Fax:** 557-379-1759	
Technical Monitor: Larry M. Moore **Phone:** (505) 845-9191 **Fax:** (505) 844-6541 **E:mail:** lmmoore@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $41,000	**Cost Share Funding:**

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Photovoltaic System Performance and Engineering

Reliability Database Development

Contract #: BF-4507f	**Contract Period:** 5/11/99-9/15/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	World Water, Inc. Pennington, NJ 08543-2000	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Quentin Kelly **Phone:** 609-818-0700 **Fax:** 609-818-0720	
Technical Monitor: Larry M. Moore **Phone:** (505) 845-9191 **Fax:** (505) 844-6541 **E:mail:** lmmoore@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $25,000	**Cost Share Funding:**

Project Objective: This contract represented a survey to determine available and appropriate data for construction of a reliability database.

Approach/Background: Several small contracts were let (this being one of them) to allow as broad a range of survey participants as possible.

Status/Accomplishments: Data was provided from their fielded systems.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PV Domestic Applications and Markets

Pentagon PV System

Contract #: ACQ-9-29769-01	**Contract Period:** 3/1/99–8/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: R. King **Phone:** 202-586-1693 **Fax:** 202-586-8148	Ascension Technology 235 Bear Hill Rd. Waltham, MA 02451-1003	
	Organization Type: IN	**Congressional District:** 7
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Ed Kern **Phone:** 781-684-6101 **Fax:** 781-890-2050	
Technical Monitor: John P. Thornton **Phone**: 303-384-6469 **Fax**: 303-384-6490 **E:mail**: john_thornton@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $176,000	**Cost Share Funding:**

Project Objective: The object of this subcontract was to install a 15 KW_{pk}, grid connected photovoltaic (PV) system at the Pentagon outside of Washington, DC. The PV system was designed, manufactured and installed under a Memorandum of Understanding established between the U.S. Department of Energy and the U.S. Department of Defense Headquarters Services in March 1999. The Pentagon PV system was designated DOD's first showcase renewable energy project. The project was initiated in January 1999 and accepted by the Pentagon in a dedication ceremony in June 1999.

Approach/Background: The system consists of 60 ASE Americas SunSine 300 AC modules developed under NREL's PVMaT Initiative. The system is grid connected and utilizes no storage – all energy is used by the Pentagon as it is produced, thus reducing energy needed from the local utility, Virginia Power.

At its rated capacity of 15 KW_{pk}, the system is expected to produce about 24,502 kWh annually. With the electricity produced by the PV array each year, the emission of approximately 34,627 pounds of CO_2, 106 pounds of SO_2 and 51 pounds of NO_X can be avoided. The carbon dioxide emissions alone are equivalent to driving about 43,284 miles in an average passenger car, or equivalent to the CO2 absorbed by about five acres of trees in one year. The production of electricity and the savings in emissions will actually be about 13% higher to the use of SunSine modules with higher than rated output.

Status/Accomplishments: Installation was completed in June 1999 and the system was dedicated on June 28, 1999. It has been operating successfully since. Under a grant from the Federal Energy Management Program, an additional 15 KW_{pk} has also been added. Eventually, the total capacity of the array may be increased to as much as 75 KW_{pk}.

Planned FY 2000 Milestones: None

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None. An article on the system is expected to appear in the January/February 2000 issue of *Solar Today*.

PV Domestic Applications and Markets

Programming Support for Energy-10

Contract #: TAR-8-18416-01	**Contract Period:** 3/30/98–3/29/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
R. King
Phone: 202-586-1693
Fax: 202-586-8148</td><td colspan="2">CDI Corporation
P.O. Box 840354
Dallas, TX 75284-0354</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
Norm Weaver
Phone: 970-870-1710 Fax: 970-870-1710</td></tr>
<tr><td rowspan="2">Technical Monitor:
J. Douglas Balcomb
Phone: 303-384-7507
Fax: 303-384-7540
E:mail: doug_balcomb@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $30,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective of this subcontract was to provide programming services to develop the Energy-10 computer program, a tool for designing low-energy buildings. The funding support from the PV in Buildings Task was to develop the PV module that will be incorporated into the software. The PV module will evaluate both the system electrical output as well as the impact on other building energy loads, such a thermal and lighting loads, of a building-integrated PV system.

Approach/Background: Energy-10 is a PC-based building energy simulation program that focuses on the integration of daylighting, passive solar design, low-energy cooling, and energy-efficient equipment into both residential and nonresidential high-performance buildings. Developed specifically as a design tool, the program facilitates quick evaluations. Its simulation engines perform whole-building energy analysis for 8760 hours per year that include. The target audience for the program is building designers, architects, heating, ventilation, and air-conditioning engineers, utility officials, and architecture and engineering students and professionals. It is the people in this audience that has the most influence on whether or not PV is included in the building design. By incorporating PV into Energy-10 will introduce the possibility of using building-integrate PV systems, help the designers evaluate the impact the PV system will have on the building, and provide a tool for designers to optimize the building-integrated PV system design.

Status/Accomplishments: The subcontractor completed programming the interface between the user and the PV module code. The interactions between the PV module and other modules in the Energy-10 code have been identified and codes to complete these interactions are currently being completed.

Planned FY 2000 Milestones: Complete integration of the PV module into the Energy-10 code.

Major Reports Published in FY 1999: N/A

Major Articles Published in FY 1999: N/A

PV Domestic Applications and Markets

Renewable Energy Analysis, Applications, and Domestic Market Opportunities

Contract #: ACQ-9-29770-01	**Contract Period:** 9/1/99–3/1/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: R. King **Phone:** 202-586-1693 **Fax:** 202-586-8148	Clean Power Research, L. L. C. 10 Glen Ct. Napa, CA 94558	
	Organization Type: IN	**Congressional District**: 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** T. Hoff **Phone:** 707-224-9992 **Fax:** 707-224-9993	
Technical Monitor: C. Herig **Phone**: 303-384-6546 **Fax**: 303-384-6490 **E:mail**: christy_herig@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $70,000	**Cost Share Funding:**

Project Objective: The objective of this work is to research and analyze the economics, financial mechanisms, business opportunities and intangible value propositions for consumers, building industry, and utilities, as the energy industry changes through restructuring.

Approach/Background: Energy service and supply are rapidly changing. Relationships of electric service providers, regulatory/legislative bodies, the financial and building industry are transitioning with this change. State and local environmental and economic health are considered in electric utility industry restructuring resulting in policies favorable to renewables. Both utilities and builders/developers are defining micro-grids as reliable low cost approaches to meeting new load. And micro-grids meet the environmental and reliability concerns of policy makers. The following tasks will be completed in this subcontract:

- Expand a web based PV value tool which can be used by policy makers, builders/developers, consumers, and utilities to the additional three top value states, IL, NC, HI. It has already been developed through other funding to CA and NY.
- Construct an Excell spreadsheet model to determine value of micro-grids to builders and utilities.
- Construct a market demand curve for PV by metropolitan area
- Perform two case studies with utilities or builders.

Status/Accomplishments: Clean Power Estimator is an economic evaluation software program for customer-owned clean energy systems. The program gives a personalized estimate of the costs and benefits of a PV system for a specific homeowner. The program was tailored to work in 2,000 cities through Illinois, Hawaii, and North Carolina. The following agencies received versions to post on the Internet: (1) Illinois Department of Commerce and Community Affairs/Renewable Energy Resources Program; (2) Hawaii's Energy, Resources, and Technology Division, Energy Branch; and (3) North Carolina Solar Center.

Planned FY 2000 Milestones: Publish paper and brochure on value of distributed resource reliability value to utility grid

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None

PV Domestic Applications and Markets

Domestic PV Applications and Markets

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/01/98–9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: richard.king@ee.doe.gov</td><td colspan="2">National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
J. Thornton
Phone: 303-384-6469 Fax: 303-384-6490</td></tr>
<tr><td rowspan="2">Technical Monitor:
Roland Hulstrom
Phone: 303-384-6420
Fax: 303-384-6481
E:mail: roland_hulstrom@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $1,310,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective:
The goal of the Domestic PV Markets and Applications Project is to foster widespread acceptance of PV in numerous market sectors where significant penetration has not been attained. These sectors include the insurance and disaster mitigation industries, residential and commercial buildings, electric utilities and the agricultural/ranching industry.

Approach/Background: Tasks within this project area include:

- Training, Education and Technical Assistance - This subtask supports the Photovoltaics Program through training, education and technical assistance for domestic applications. The client base includes other NREL research and development activities, the DOE and other federal agencies and programs, the U.S. photovoltaic industry, and specific application sectors, such as the insurance industry.
- Market and Policy Value Analysis - With the energy industries competitive transitioning and the high capitol cost of PV, past work has shown an acceleration of domestic grid-tied PV through state and local policy funding. This task will continue to develop value analysis for policy justification. However, as often happens in accelerated markets, market support infrastructure is lagging. This task also identifies infrastructure weaknesses or opportunities and supports development through value analysis, and assessment tools.
- PV:BONUS Support - The DOE Golden Field Office asked the labs (NREL and SNL) to provide technical support to the PV:BONUS2 program, which began its second phase at the start of FY99. This program is supporting a variety of building-integrated products, and most of the projects are with companies which have had, or do now have, PVMaT subcontracts. The technical support for these seven DOE agreements is being managed in the same manner as the PVMaT technical support teams.
- Photovoltaics in Buildings (PVB) - In partnership with industry, the task fosters the widespread acceptance of PV-integrated buildings by overcoming technical and commercial barriers and by facilitating the integration of PV into the built environment for the PV and buildings industries and their customers. All activities are conducted in cooperation with current PV/buildings activities at the National Center for Photovoltaics (NCPV), both at NREL and SNL, the NREL Center for Buildings and Thermal Systems (CBTS), and in other federally funded locations such as the Florida Solar Energy Center (FSEC) and the Southwest Technology Development Institute (SWTDI).

Status/Accomplishments:
Continued Million Solar Roofs support included technical assistance to all but four of the forty MSR communities.
Workshops:

Conducted curriculum workshops for teachers.
Co-sponsored workshop on use of renewables for prevention, mitigation or response to disasters caused by global climate change.
Conducted consumer workshops in AZ, CO, DC and WA.

Contract #: DE-AC36-98-GO10337

Technical Facilitation:

Provided technical management for the installation of a 3 KW PV system at the Forrestal Building and a 15 KW PV systemat the Pentagon, both in the Washington, DC area.

Technical support to the Smithsonian Institution's *Under The Sun* exhibition

Presentations

"Renewables as an Infrastructure Element," Midwest Legislative Conference

"Photovoltaics: A Tool for Building Community Sustainability," Colorado Economic Development Council, November 1999.

"Photovoltaics: A Utility Tool for Managing Emergencies," American Power Conference, April 1999.

Planned FY 2000 Milestones: Install PV- oriented public display on Mall
Host FEMA Technology for Emergency Management Conference
Update customer-sited PV value analysis
Complete analysis of distributed resource incentives and barriers within restructuring legislation
Publish paper and brochure on value of distributed resource reliability value to utility grid
Support PV:BONUS2 product development
Complete Energy-10 PV module development

Complete building performance case study

Major Reports Published in FY 1999:

"Counting on Solar Power for Disaster Relief," Technical Assistance Information Sheet, DOE/GO-10099-729, April 1999.

A. Deering and J.P. Thornton, "Solar Technology and the Insurance Industry: Issues and Applications,"NREL/TP-520-26490, July 1999.

"Making the Most of Residential Photovoltaic Systems," DOE/GO-10099-918, September 1999.

"Distributed Generation," DOE/GO-10098-657, September 1999.

Consumers Guides to Buying Solar Electric Systems for National, Mid Atlantic, NY, CO, CA, NC and OH.

Major Articles Published in FY 1999:

Thornton, J.P., "Renewables on Main Street," NREL/JA-520-26228, November 1999. To be published in the January 2000 issue of *Public Works Management and Policy*.

PV Domestic Applications and Markets

Sunrayce 99 Management

Contract #: AAX-8-29767-01	**Contract Period:** 01/01/99 – 8/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	New Resources Group 12 Cedars Freeman, MO 64746	
	Organization Type: IN	**Congressional District**: 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Dan Eberle **Phone:** 816-899-5511 **Fax:** 816-250-5430	
Technical Monitor: B. Stafford **Phone**: 303-384-6426 **Fax**: 303-384-6490 **E:mail**: byron_stafford@nrel.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1998: $266,040 1999: $463,025	**Cost Share Funding:**

Project Objective: The primary goal of Sunrayce is to promote solar energy and energy efficiency to the general public. An additional goal is to educate future engineers and business leaders on the use of photovoltaics and energy efficiency. Sunrayce 99 was held June 20-29, 1999, from Washington, DC, to Orlando, FL. The subcontract objectives were

- Staff and operate Sunrayce Headquarters as the principal contact for all inquiries from the public and students. This objective also includes making Headquarters mobile during the race.
- Write, edit, publish and distribute a monthly newsletter for the students and organizers.
- Finalize the new route from Washington, DC, to Orlando, FL. Develop and distribute a Route Book for the students and organizers.
- Perform community relations work with the communities along the route for community awareness and local support.
- Plan and manage Preliminary and Last Chance Scrutineering and Qualifier events in Detroit, MI, and Winchester, VA, before the race.
- Select and train an Observer Corps to participate as the official observers during the race.
- Plan and manage a Safety and Medical Response Team to respond to safety and medical issues during the race.
- Plan and manage a Meal Plan during the race for students and staff.

Approach/Background:
Sunrayce 99 is a public/private collaboration between US DOE, General Motors and EDS as the major sponsors. As a colloboration each sponsor is responsible for certain aspects of the race planning and execution. Joint planning meeting were held every three months to coordinate and assign the responsibilities. Both General Motors and US DOE/NREL used the same subcontractor, New Resources Group, to execute certain complimentary but non-overlapping responsibilities. NRG was funded under NREL Subcontract Number AAX-8-18646-01 for $266,040 for advance planning and management of Sunrayce 99 activities during FY 98.

Planning for Sunrayce 99 began in October 1997. A letter of invitation was issued in November 1997 announcing Sunrayce 99 A workshop for almost 400 students and faculty advisors was held in Atlanta, GA, in March 27-29, 1998. A test run of the route from Washington, DC, to Epcot© in Orlando, FL, was held during June 1998 with one solar car from Rose-Hulman Institute of Technology, Terre Haute, IN, completing the entire route on solar power only. Community relations and public relation meeting were organized by NRG, NREL Public Affairs, DOE, GM and EDS.

The origins of Sunrayce can be traced to the 1987 World Solar Challenge in Australia when GM's Sunraycer won the first transcontinental race of solar-powered vehicles. That victory led GM to approach the Department of Energy about creating a biennial collegiate competition to race solar-powered vehicles resulting in the first Sunrayce -- GM Sunrayce USA -- in 1990. EDS joined as a sponsor in 1993. Since its inception, more than 6,000 students from more than 175 colleges and universities have participated in vehicle design, testing or actual racing.

Contract #: AAX-8-29767-01

Status/Accomplishments:
All tasks were completed and all objectives were met by NRG making Sunrayce 99 a very successful event. Sunrayce 99 started at the U.S. Capitol in Washington, DC, and ended 10 days later at Epcot in Orlando, FL. Sunrayce continues to grow every year in public visibility and educational outreach to college students. At least 1,000 students were directly impacted by Sunrayce 99. During June 1999 over 6 million potential hits were documented in newspapers mentioning Sunrayce 99. Over 500 television stations broadcast stories about Sunrayce 99 including CNN, ESPN2 and all the major networks. EDS reported over 6 million hits on the official Sunrayce homepage during the 10-day race. Also, local radio stations and NPR carried stories about Sunrayce. The major news networks also included stories on their Internet news homepages.

Sunrayce Headquarters was managed by Bryan Arnold, NRG. Community relations with the cities along the route were coordinated by Kate von Reis, NRG. During the race, headquarters was stationed in an RV that traveled along with the racers. Over 40 adults were recruited, many were science teachers, as observers to ride with the teams during the race to observe any infractions of the racing regulations. NRG subcontracted Premier Event Management, Denver, Colorado, to manage the safety and medical response during the race. Five motorcycle marshals and a command vehicle escorted the racers using a traveling zone coverage. There were no major injuries or accidents during Sunrayce 99. Teams were well prepared by NRG and Premier Event Management to reduce the risk of injury or accidents while racing.

The race got underway June 29th in Washington, DC, and has covered five states -- Virginia, North Carolina, South Carolina, Georgia and Florida -- under consistently cloudy and often rainy skies. Sunrayce 99 was the fifth biennial intercollegiate solar car race and the 1425-mile route was the most difficult because of the terrain and inclement weather conditions. The University of Missouri -- Rolla took first place with an overall winning race time of 56 hours, 16 minutes and 44 seconds (56:16:44) and an average speed of 25.30 mph for the 10-day race. Placing second was Queen's University (Kingston, Ontario) with a time of 57:04:02, and an average speed of 24.95 mph. Rose-Hulman Institute of Technology (Terre Haute, IN) achieved the third best time of 64:08:10 and an average speed of 22.10 mph. It was the best finish ever by the five-time veteran Sunrayce team.

Planned FY 2000 Milestones: none

Major Reports Published in FY 1999:
Sunrayce 99 Rayce Program, distributed during the race, limited quantities available.
Sunrayce 99 Route Book, distributed during the race, limited quantities available.

Major Articles Published in FY 1999:
Sunrayce Dateline newsletter, http://www.sunrayce.com/sunrayce.

State PV Models

Contract #: AU-8436	Contract Period: 10/23/96–9/30/97

Sponsoring Office Code: EE-11	Performing Organization(s)	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	North Carolina State University Raleigh, NC 27695-7401	
	Organization Type: CU	**Congressional District:** 2
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** B. Brooks **Phone:** 917-515-7147 **Fax:** 917-515-5778	
Technical Monitor: Roger R. Hill **Phone:** 505-844-6111 **Fax:** 505-844-6541 **E:mail:** rrhill@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1996: $19,000 1997: $0 1998: $0 1999: $0	**Cost Share Funding:**

Project Objective: Summarize experiences and lessons learned with PV projects at state agencies around the country.

Approach/Background: By a survey, a count of the number of systems installed and the experiences gained will be tabulated. An analysis will be performed on this data.

Status/Accomplishments: Report written and posted to North Carolina Solar Center web site. Salient portions incorporated into a Sandia publication entitled *Photovoltaics for the States: Lessons Learned and Project Summaries*, SAND 99-0927.

FY 2000 Milestones: None. Contract terminated.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PV Domestic Applications and Markets

U.S. Representation in the IEA PVPS Task 7, "Photovoltaic Power Systems in the Built Environment"

Contract #: AAR-9-29426-01	**Contract Period:** 2/8/99–9/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: R. King **Phone:** 202-586-1693 **Fax:** 202-586-8148	Solar Design Associates Harvard, MA 01451-0242	
	Organization Type: IN	**Congressional District**: 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Steven J. Strong **Phone:** 978-456-6855 **Fax:** 978-456-3030	
Technical Monitor: Sheila Hayter **Phone**: 303-384-7519 **Fax**: 303-384-7540	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1998: $49,232.00 1999: $39,851.00	**Cost Share Funding:**

Project Objective: The objective of this subcontract was to support representation by the US on the International Energy Agency PV Power Systems Task 7, "Photovoltaic Power Systems in the Built Environment." US involvement with this task leads to a better understanding of international PV in buildings activities and an opportunity for the US to become competitive in the worldwide PV in buildings industry.

Approach/Background: The International Energy Agency (lEA) is an organization that promotes the collaborative research, development, and demonstration of new energy technologies between nations. IEA PVPS Task 7, "Photovoltaic Power Systems in the Built Environment," is a 5-year effort involving approximately 15 countries. The objective of the task is to enhance the architectural quality, technical quality, and economic viability of PV systems in the built environment and to assess and remove non-technical barriers for their introduction as an energy-significant option. The US participated in the previous related task, lEA SHC Task 16, "Photovoltaics in Buildings." This task concluded in the spring of 1996. The US has also been involved with lEA PVPS Task 7 since its inception in the fall of 1996.

Status/Accomplishments: 1) The US representative completed requirements for supplying information to fulfill requests by the various Task 7 activity leaders. 2) The US representative met with Task 7 members at Task 7 meetings and met with individual Task 7 members throughout the year. 3) The US representative participated in international conferences related to Task 7 activities. These conferences included the "PV Integration Concepts Workshop" held February 11-12, 1999 in Lausanne, Switzerland and the Workshop on Solar Thermal-PV Hybrid Systems held September 16-17 in Amersfoort, Holland. 4) The US representative encouraged the Kawneer Company to construct a pavilion demonstrating their building-integrated photovoltaic products to be displayed at the DemoSite in Lausanne, Switzerland.

Planned FY 2000 Milestones: Continue to represent the US on IEA PVPS Task 7 and provide information as needed to the activity leaders.

Major Reports Published in FY 1999:
N/A

Major Articles Published in FY 1999:
N/A

PV:BONUS Two - PV String Inverters

Agreement #: DE-FC36-97GO10261	**Project Period:** 9/30/97–12/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Robert.Hassett@ee.doe.gov	Advanced Energy Systems, Incorporated (AES) Riverview Mill Wilton, NH 03086	
	Organization Type: IN	**Congressional District:** 2
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Dr. Robert H. Wills **Phone:** 603-654-9322 **Fax:**	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Advanced Energy Systems, Inc.
	DOE Funding Allocation: 1997: $44,999 1998: $90,833 1999: $171,316	**Cost Share Funding:** 1997: $13,527 1998: $90,833 1999: $171,316

Project Objective: Advanced Energy Systems, Inc. proposes to design and manufacture a low cost String Inverter System (SIS), which will minimize the cost of the electrical BOS (i.e., the inverter and the PV output circuit wiring). The SIS is an inverter and associated wiring that is designed to operate with a single string of photovoltaic (PV) modules. By using a single string, the need for an expensive string-combiner is eliminated. The paralleling of multiple strings is accomplished on the utility or AC side of the system, lending to inexpensive installation costs.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which Advanced Energy Systems (AES) was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. The key concept is a String Inverter Module or SIM rated at 250 V dc input, at about 4 amps. Its output is 12OV, 8 Amps or 1 kW per module. These power modules use similar construction and packaging to AC module micro-inverters. Up to four SIMs can be mounted in one enclosure which also houses DC source circuit fuses and disconnects, and the AC output circuit breaker. The SIM units are cooled via an integral natural convection "chimney" built into the enclosure - no fans are used and all electronic components are isolated from the environment. In the second part of the project, Advanced Energy Systems will develop low cost wiring and interconnection components for the complete PV system including cables, connectors, disconnect and GFI protection devices. SIM refers to the standardized, modular systems designs coming out of this work as String Inverter Systems (SISs). Advanced Energy Systems has proposed a six (6) month Phase 2 (July 1, 1998 through December 31, 1998) followed by a two (2) year Phase 3 period (January 1, 1999 through December 31, 2000).

Status/Accomplishments: During Phase 1, AES designed and constructed a prototype unit which will be simple and inexpensive to manufacture and incorporates the inverter, DC source circuit string combiner, DC ground fault interrupter and disconnect, and an optional AC output circuit breaker, all in one enclosure, named this unit the "GC-1000". The GC-1000 is cooled via an integral natural convection duct built into the back mounting plate - no fans are used and all electronic components are isolated from the environment. During Phase 2, AES refined the inverter design, developed prototypes, which were UL tested and certified, and field tested pre-production units.

Planned FY 2000 Milestones: none

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

Building-Integrated Photovoltaics

PV:BONUS Two - Ballast-Mounted PV Arrays

Agreement #: DE-FC36-97GO10257	**Project Period:** 9/30/97–09/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Robert Hassett **Phone:** 202-586-8163 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Robert.Hassett@ee.doe.gov	Ascension Technology, Incorporated 235 Bear Hill Road Waltham, MA 01773	
	Organization Type: IN	**Congressional District:** 7
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Edward C. Kern Jr. **Phone:** 617-684-6101 **Fax:**	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Ascension Technology, Incorporated
	DOE Funding Allocation: 1997: $44,160 1999: $0 1998: $43,328	**Cost Share Funding:** 1997: $11,200 1999: $0 1998: $43,500

Project Objective: Ascension Technology for the development of analytic and experimental capabilities for quantifying the balance between driving (wind, seismic) forces and the restraining (gravitational/frictional) forces that must exist for the ballast-mounting approach to succeed. Ascension Technology and its partners to address wind loading on solar panels and the suitability of using frictional forces between ballast trays and roofing materials to resist wind on the PV arrays. The primary goal of the project is to capture the potential cost savings made possible by ballast-mounting by showing under what conditions it can satisfy wind loading concerns with a secondary goal is to address the more geographically constrained concern regarding withstanding seismic forces.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which Ascension was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. Ascension Technology and its partners to address wind loading on solar panels and the suitability of using frictional forces between ballast trays and roofing materials to resist wind on the PV arrays. Ascension Technology to will validate analytic methods for predicting wind speed thresholds for ballasted PV arrays sliding across roofs and develop means to improve the frictional resistance of ballast mounting techniques. Additionally, under Phase 2, Ascension Technology will develop and test new array attachment concepts as successors to our present ballast tray and flat Roof-Jack products.

Status/Accomplishments: In Phase 1 of this project, Ascension Technology developed the analytic and experimental capabilities for quantifying the balance between driving (wind, seismic) forces and the restraining (gravitational/frictional) forces that must exist for the ballast-mounting approach to succeed. During Phase 2, Ascension completed a full-scale demonstration at a coastal Massachusetts test site. The demonstration quantified coefficients for a single-ballast-mounted photovoltaic module and contributed to the development of an analytical model to determine the minimum ballast requirements for various module configurations and wind speed.

Planned FY 2000 Milestones: none

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

PV:BONUS One - Integrated Modular Homes

Agreement #: DE-FC36-93CH10568	**Project Period:** 08/01/93–06/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King Robert Hassett **Phone:** 202-586-1693 **Phone:** 202-586-8163 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Robert.Hassett@ee.doe.gov	Fully Independent Residential Solar Technology (FIRST) 66 Syndertown Road Hopewell, NJ 08525-2705	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Lyle Rawlings **Phone:** 609-466-4495 **Fax:** 609-466-3631	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Fully Independent Residential Solar Technology (FIRST)
	DOE Funding Allocation: 1994: $193,589 1996: $177,265 1995: $275,265 1997: $24,660	**Cost Share Funding:** 1994: $237,000 1997: $125,683 1995: $295,964 1998: $75,000 1996: $164,124

Project Objective: The prime objective of the project is to design, develop, and introduce to the residential market a line of integrated, modular solar homes designed for photovoltaic power. The intent of the project is to optimize home designs for least-cost construction, high performance, reliability, and to put in place the necessary marketing and distribution networks, financial products, and utility sector encouragement to ensure product success.

Approach/Background: The product concept is a factory-manufactured home which is designed from the ground-up to integrate PV power, high-efficiency appliances and light, passive solar heating and cooling architecture, and offers solar hot water as an option. The home, including the solar systems, wiring and controls, key appliances, and lights, will be produced by a major manufactured housing company, which specializes in modular homes.

Status/Accomplishments: Phase 1 (6/1/93-6/1/94) included design and initiation of pilot home construction. Phase 2 included final design and completion of six pilot homes. Phase 3 planned activities include: the implementation of PV-integrated modular homes into sustainable communities and low-income housing projects; establishment of partnerships with the EPA Energy Star Home Program for "Energy Star Mortgages"; investigation of PV/wind hybrid systems; development of a 48 V direct-current ballast for compact fluorescent lamps; and development of large, lightweight, roof-integrated modules. Nine townhouses in a Philadelphia low-income housing project, seven homes for the New Alchemy Farms Sustainable Community (Cape Cod, MA) and completion of the Long Island home are planned during Phase 3. FIRST installed a factory-built home featuring photovoltaic hardware and passive solar/energy efficient design features in the Washington area during the Solar Energy Forum held April 1997. A low-income home was completed in Jersey City in conjunction with a minority housing development and training corporation who may utilize the PV-integrated home concept in future developments. Three integrated, modular solar homes have been completed as part of the New Alchemy Farms Sustainable Community with eighteen planned for the Philadelphia low-income housing project. The three new Alchemy homes resulted in substantial lower costs ($20 per foot less) than conventional homes in the community. Large-area module development has been completed with prototypes planned for November 1997. Solarex is considering including the roof-integratable large-area module into their product line. The pre-framed large-area modules incorporate numerous cost reduction advancements by using a plastic framing assembly which allows interlocking of the modules, reduces weight, provides water-tight seals, simplifies plug wiring, negates grounding requirements, and reduces the installation time.

Planned FY 2000 Milestones: Complete the construction of the 18 PV integrated modular homes as part of Philadelphia's low-income housing project.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

PV:BONUS Two - PowerRoof 2000

Agreement #: DE-FC36-97GO10247	**Project Period:** 9/30/97–09/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King, **Phone:** 202-586-1693, **Fax:** 202-586-8148; Robert Hassett, **Phone:** 202-586-8163, **Fax:** 202-586-8148; **E:mail:** Richard.King@ee.doe.gov; **E:mail:** Robert.Hassett@ee.doe.gov	PowerLight Corporation 2954 San Pablo Avenue Berkeley, CA 94710	
	Organization Type: IN	**Congressional District:** 9
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Thomas L. Dinwoodie **Phone:** 510-540-0550 **Fax:** 510-540-0552	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** PowerLight Corporation
	DOE Funding Allocation: 1997: $60,844 1998: $57,162 1999: $397,132	**Cost Share Funding:** 1997: $ 67,000 1998: $101,041 1999: $702,957

Project Objective: PowerLight Corporation, in cooperation with AstroPower; Solarex; BP Solar; and Siemens Solar, propose to development of an innovative Building-integrated PV roofing system called PowerRoof ™. PowerGuard® is the first core product in the PowerRoof family and has been successfully developed under prior programs. The PowerRoof ™ 2000 proposal targets development of two next-generation core PowerRoof building products, HeatGuard ™ and PowerTherm™. Each builds upon the proven technological approach of the PowerGuard solar electric roofing system.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which PowerLight was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. The HeatGuard PV roofing assembly is a patent-pending core product in the PowerRoof line. In addition to generating clean solar electricity, Building-integrated HeatGuard PV systems provide roof protection from solar thermal loads in the cooling season and block radiant building losses in the heating season. This yields significant reductions in building HVAC loads - leading to reductions in energy consumption, energy costs, and system equipment sizing. The PowerTherm PV roofing system pursues existing PowerLight patent claims for hybrid PV/thermal. PowerTherm is a Building-integrated PV/thermal hybrid system designed to couple the benefits of PV power with the collection of thermal energy. The parallel development of HeatGuard and PowerTherm as extensions of the PowerGuard approach is essential, as detail refinement of both projects will yield mutually beneficial technological advancements.

Status/Accomplishments: Under Phase 1, PowerLight accomplished the following: 1) received, prototyped, and tested leading advanced thin film materials into PowerRoof assemblies from seven leading manufacturers; 2) optimized and validated HeatGuard to improve the contribution to the building thermal envelop by reducing the rooftop solar absorptance to zero; 3) developed the PowerTherm concept prototype; 4) identified hybrid products using the HeatGaurd and PowerTherm systems. Phase 2 accomplishments associated with the PowerTherm system include: 1) development of software for simulating PV/thermal hybrid performance; 2) validated simulation results through preliminary field-testing; 3) finalized preliminary PowerTherm tile design; and 4) developed a PowerTherm system prototype. During Phase 2, PowerLight identified radiant barriers and optimized the sloped tile design for the HeatGuard system, evaluated the field performance of the sloped tile design, and established the value of the HeatGaurd radiant barrier through Energy -10 simulations.

Planned FY 2000 Milestones: To be determined based on funding availability.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

PV:BONUS Two - Photovoltaic Powered Electrochromic Windows

Agreement #: DE-FC36-97GO10251	**Project Period:** 9/30/97–09/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Robert Hassett — **Phone:** 202-586-8163 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Robert.Hassett@ee.doe.gov	Sage Electrochromics, Incorporated 501 Hoes Lane, Suite 208 Piscataway, NJ 08854-0278 **Organization Type:** IN	**Congressional District:** 6
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** John Van Dine **Phone:** 908-699-1100 **Fax:** 908-699-1101	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail:** robert_martin@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1997: $60,000 1998: $200,331 1999: $120,000	**Cost Share Information:** Sage Electrochromics, Incorporated **Cost Share Funding:** 1997: $42,918 1998: $230,409 1999: $138,065

Project Objective: Sage Electrochromics, in conjunction with Solarex, propose to develop and commercialize photovoltaic (PV) powered electrochromic (EC) "smart windows" EC windows control the amount of sunlight and solar heat by dynamically switching between darkened and clear states and anywhere in-between. They provide a unique opportunity to realize significant energy savings and reduce peak electrical demand in buildings. The low-power DC voltage required to power the EC window glazing can be supplied by PV solar cells incorporated in the double pane insulating glass unit (IGU) so that no external hard-wired connections are needed.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which SAGE was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. The project is segmented into three phases over 60 months. In Phase 1, Sage proved the viability of the PV-EC concept and fabricated several 0.1 m^2 windows demonstrating operational performance, including wireless control, over a range of solar conditions. In Phase 2, Sage plans to achieve the capability to fabricate limited numbers of full-sized demonstration PV-EC prototype windows, which will be used for field demonstration and performance verification. The participant group expanded to include Glass Technologies, world leader in large-area sputtering technology and high performance architectural window fabrication, and Libbey-Owens-Ford, leading producer of conductive glass substrates. During Phase 3, the development of equipment, processes, partnerships, and distribution channels to initiate commercial production and introduction of the PV-EC window product for sale into targeted building markets will be finalized.

Status/Accomplishments: In Phase 1, Sage proved the viability of the PV-EC concept and fabricated several 0.1 m^2 windows demonstrating operational performance, including wireless control, over a range of solar conditions. The results support a marketing strategy that targets skylights and overhead glazing as first applications. Phase 1 defined the capabilities of this product, which led to defining a large size PV-EC window product that can be used for a variety of architectural window applications. Under Phase 2 Sage has: 1) developed variable control of the EC device and simplified construction; 2) built remotely-controlled PV-EC prototypes; 3) displayed an electrochromic window at Epcot; 3) defined the first product as a skylight; 4) completed pilot line industrial coater for dispositioning of substrates; 5) designed and built large-area solution coater and heater; and 6) processed skylight sized substrates in pilot line.

Planned FY 2000 Milestones: To be determined based on funding availability.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

Building-Integrated Photovoltaics

PV:BONUS One - AC PV Module and Curtain Wall Application

Agreement #: DE-FC36-93CH10572	**Project Period:** 06/01/93–06/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 — **E:mail:** Richard.King@ee.doe.gov Robert Hassett — **Phone:** 202-586-8163 — **Fax:** 202-586-8148 — **E:mail:** Robert.Hassett@ee.doe.gov	Solar Design Associates (SDA) P.O. Box 242 Harvard, MA 01451-0242	
	Organization Type: IN	**Congressional District:** 5
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Steven Strong **Phone:** 508-456-6855 **Fax:** 508-456-303	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Solar Design Associates (SDA)
	DOE Funding Allocation: 1994: $625,000 — 1996: $1,077,176 1995: $1,953,736 — 1997: $333,374	**Cost Share Funding:** 1994: $605,315 — 1996: $1,171,098 1995: $1,967,635 — 1997: $362,442

Project Objective: The objective of the project is to develop and commercialize a large-area photovoltaic (PV) module with a dedicated, integrally-mounted, DC to AC power inverter, with an electrical output of 60 Hz AC power for compatibility with the utility grid. In addition, an integrated PV curtain wall product specifically for commercial building facades will be developed for commercialization. The AC photovoltaic module will nominally be 4 x 6 feet (24 square feet) in size and designed for direct building integration into the vertical facades and sloped-roof construction of residential, commercial or institutional buildings, replacing the traditional building skin.

Approach/Background: Under Phase 1 and 2 of PV:BONUS, a large-area PV module with a dedicated, integrally-mounted, DC to AC power inverter, whose electrical output is 60 Hz AC power which is fully compatible with the utility grid was developed. The module's output is connected directly to the building's AC distribution system without need for any DC wiring, string combiners, DC ground-fault protection or additional power conditioning equipment. The AC module is nominally 4 x 6 feet (24 square feet) in size and designed for direct building integration into the vertical facades and sloped-roof construction of residential, commercial and institutional buildings, replacing the traditional building skin. A framed version of the AC module has also been developed for systems employing tracker and rack mount systems.

Status/Accomplishments: In Phase 1, Solar Design developed a prototype of the AC module inverter, while Mobil Solar Energy Corporation worked on developing a nominal 50-Volt, 240-Watt, 24 square foot photovoltaic module. During the Phase I effort, Mobil Solar was closed by Mobil Oil and Solarex Corporation, the largest US manufacturer of photovoltaics and the second-largest in the world, agreed to continue the development work in lieu of Mobil Solar. During Phase 2, the Kawneer Company, a leading manufacturer of architectural curtain wall systems, also joined the SDA team along with the Maryland Energy Administration and Baltimore Gas and Electric. In addition to designing and manufacturing a new large-area PV module to accept the SDA modular inverter, the Solarex / SDA team also developed an integrated PV curtain wall system specifically for commercial building facades and sloped-roof glazing applications. One of the first applications of this new technology was the new entry canopy designed by SDA, for the natatorium complex at the Summer Olympic Games in Atlanta. Here, 18 large-area Solarex AC modules with clear backskins are mounted in a custom, arched support structure by Kawneer, to form the skin of the canopy. The AC Module has received UL approval and is being marketed through Solarex and Kawneer. High-visibility, high-leverage early demonstrations are presently under way at the Olympic village and at the Sacramento Municipal Utility District (SMUD) where the first two-rooftop residential AC modules systems of 4 kWh each were fielded. The integration of a large-area thin-film array is planned for the south face of the 12-story high cube at the new Discovery Center, a non-profit science center, was completed August 1999.

Planned FY 2000 Milestones: Development and submittal of the final report.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

PV:BONUS Two - Hybrid Photovoltaic/Thermal Collector

Agreement #: DE-FC36-97GO10250	**Project Period:** 9/30/97–12/31/01

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Robert Hassett — **Phone:** 202-586-8163 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Robert.Hassett@ee.doe.gov	Solar Design Associates, Incorporated (SDA) 252 Old Littleton Road Harvard, MA 01451-0242	
	Organization Type: IN	**Congressional District:** 5
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Steven J. Strong **Phone:** 508-456-6855 **Fax:** 508-456-3030	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Solar Design Associates, Incorporated (SDA)
	DOE Funding Allocation: 1997: $49,969 1998: $185,148 1999: $689,938	**Cost Share Funding:** 1997: $82,762 1998: $450,770 1999: $1,680,983

Project Objective: Solar Design Associates, Inc. (SDA), United Solar Systems Corporation, and SunEarth, Inc., propose to design, develop, demonstrate, manufacture and commercialize a Hybrid Flat-plate Photovoltaic/Thermal (PV/T) Collector to deliver both electricity and thermal energy. The PV/T collector design will employ liquid thermal transfer medium and closely resemble conventional flat-plat solar thermal collectors in size, appearance, installation and function. However, in place of the normal thermal absorber plate, it will employ a PV element of triple-junction amorphous silicon alloy solar cells made with United Solar's proprietary UNISOLAR ™ technology whose material and thermal characteristics are uniquely well suited for combined PV/T applications.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which Solar Design Associates was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. During Phase 2, Solar Design Associates (SDA), in conjunction with United Solar Systems Corporation, and Sun Earth, Incorporated, propose to design and develop a Hybrid Flat-Plate Photovoltaic / thermal (PV/T) Collector to deliver both electricity and thermal energy. The hybrid collector will be fabricated, demonstrated, and verified during Phase 3.

Status/Accomplishments: During Phase 1, SDA, in conjunction with United Solar Systems Corporation and SunEarth, Inc., developed the conceptual design for the PV/T collector product and fabricated a full-scale conceptual PV/T collector based upon the standard SunEarth thermal collector. To date, SDA has accomplished the following: 1) initiated thermal performance of the full-scale prototype at FSEC; 2) initiated outdoor exposure testing at UniSolar; 3) validated the bypass diode scheme; 4) recorded initial performance curve; 5) estimated thermal performance as a function of application; and 6) initiated UL listing.

Planned FY 2000 Milestones: To be determined based on funding availability.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

Building-Integrated Photovoltaics

PV:BONUS Two - Solarex Thin Film Photovoltaics

Agreement #: DE-FC36-97GO10245	**Project Period:** 9/30/97–06/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Robert Hassett **Phone:** 202-586-1693 / **Phone:** 202-586-8163 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Robert.Hassett@ee.doe.gov	Solarex 630 Solarex Court Frederick, MD 21703 **Organization Type:** IN	**Congressional District:** 6
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** John H. Wohlgemuth **Phone:** 301-638-4375 **Fax:** 301-698-4201	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22 **DOE Funding Allocation:** 1997: \$57,368 1999: \$521,588 1998: \$164,436	**Cost Share Information:** Solarex **Cost Share Funding:** 1997: \$43,680 1999: \$525,777 1998: \$165,518

Project Objective: With the support of subcontractors Kawneer, Solar Design Associates (SDA) and Velux, Solarex will develop building-integrated photovoltaic products using tandem-junction amorphous silicon modules. Major objectives of the program include: 1) developing a commercial photovoltaic curtain wall module (Spandrel Module); 2) developing a commercial photovoltaic sunshade for curtain walls (PowerTint Window); and 3) developing an opaque PV sunshade (PowerShade).

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which Solarex was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development.

Under PV:BONUS One, the team of Solarex, Kawneer and Solar Design Associates (SDA) developed a crystalline silicon photovoltaic curtain wall module that integrated into Kawneer's standard curtain wall system and commercialized and is sold through Kawneer's network of salesman and dealers. During PV:BONUS One, a potential demand for a Building-Integrated Photovoltaic (BIPV) product based on thin film PV modules was identified. Advantages of using thin film PV modules in BIPV applications include: 1) cosmetics; 2) lower cost per unit of area than crystalline modules; and potential for a controlled amount of light transmission through the module. Under PV:BONUS Two, Solarex supported by Kawneer, SDA, and Velux, propose to develop BIPV products including curtain walls, skylights and sunshades using tandem junction amorphous silicon plates now being produced by Solarex in its Toano, VA factory. The commercial products will be developed in conjunction with Kawneer, mounting directly into Kawneer curtain wall framing and installed by glazers using the same methods used to install curtain walls. The residential products will be developed in conjunction with Velux, a major worldwide manufacturer of skylights, for installation directly into the skylights and roof windows manufactured in the Velux factory in South Carolina.

Status/Accomplishments: Solarex, competitively selected, was awarded Phase 2 funding July 1, 1998 for continued development of these three thin film PV products. During Phase 1, Solarex reduced the number of products developed under PV:BONUS Two from five to three and completed conceptual designs on each. Phase 2 accomplishments include: 1) development of a water jet process to cut plates after deposition for size flexibility; 2) completed demonstration of thin film processing on heat strengthened glass; 3) developed a laser ablation process to remove thin film layers (holes or lines in almost any pattern); 4) developed BIPV software; and 5) initiated planning for a demonstration at the University of Wisconsin at Green Bay.

Planned FY 2000 Milestones: To be determined based on funding availability.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

Building-Integrated Photovoltaics

PV:BONUS Two - Field Applied PV Membrane

Agreement #: DE-FC36-98GO10249	**Project Period:** 9/30/97–09/30/02

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King Robert Hassett **Phone:** 202-586-1693 **Phone:** 202-586-8163 **Fax:** 202-586-8148 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Robert.Hassett@ee.doe.gov	United Solar Systems Corporation 1100 West Maple Road Troy, MI 48084	
	Organization Type: IN	**Congressional District:** 12
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Dr. Subhendu Guha **Phone:** 248-362-4170 **Fax:**	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** United Solar Systems Corporation
	DOE Funding Allocation: 1998: $213,205 1999: $400,026	**Cost Share Funding:** 1998: $214,800 1999: $403,239

Project Objective: United Solar Systems Corp. in collaboration with Energy Conversion Devices Inc. the National Association of Home Builders, Phasor Energy, Arizona Public Service, Southern California Edison Co., Southern Cal Roofing, ATAS International, Elk Corp and San Diego Gas & Electric intend to develop a field applied, flexible photovoltaic (PV) membrane product for the 'built-environment". The UNI-SOLAR PV Membrane, a flexible PV laminate, will ship directly to the site for field application or to a building product company for integration with their own products. It uses United Solar multi-junction a-Si stainless steel PV cells laminated in flexible UL approved materials.

Approach/Background: The objective of the PV:BONUS Two solicitation, issued April 2, 1997, is for the development of commercial building products through three phases as follows: 1) concept development and business planning; 2) product and business development; and 3) product demonstration and marketing. Under Phase 1, sixteen Cooperative Agreements were awarded, each with a duration of nine months (September 30, 1997 through June 30, 1998). A total of seven projects were competitively selected for Phase 2 funding of which United Solar System Corporation was one. The activities to be undertaken in Phase 2 include: 1) product development and testing; 2) market planning; and 3) business development. For the commercial sector, a 250 watt, 30" x 18' PVM design is planned for retrofitting onto flat commercial roofs and existing metal roof shade structures (covered parking). For residential and light commercial markets with sloped roofs, a narrower 125 watt, 16" x 18', PVM is needed for conform to conventional metal roofing shapes. For concrete tile roofs, prevalent in the southwest, the 125 watt PVM will be designed as a PV "Shingle Membrane" for use in an integrated manner with flat tiles.

Status/Accomplishments: The conceptual design of the product has been completed and key product development tasks identified including PV Membrane size, electrical characteristics, termination designs, mounting methods for flat commercial roofs, covered parking, metal and tile shingle roofs. The PVM uses United Solar Triple-Junction PV cells on a flexible substrate, laminated in UL approved weather resistant materials to provide a flexible PV "membrane". During Phase 2, Uni-Solar accomplished the following: 1) completed the Photovoltaic Membrane (PVM) design; 2) fabricated prototypes; 3) verified the prototype performance at NREL; 3) resolved roofing/building interface issues; 4) developed a peel and seal field installation method; 5) finalized PVM termination design; 6) obtained UL recognition; 7) established PVM manufacturing process; and 8) initiated outdoor testing.

Planned FY 2000 Milestones: To be determined based on funding availability.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

TUSD PV for Schools

Agreement #: DE-FC36-99GO10465	**Project Period:** 9/01/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov Dan Ton **Phone:** 202-586-4618 **Fax:** 202-586-8148 **E:mail:** Dan.Ton@ee.doe.gov	Tucson Unified School District (TUSD) 2025 East Winsett Tucson, AZ 85719	
	Organization Type: CU	**Congressional District:** 2
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Douglas Crockett **Phone:** 520-617-7086 **Fax:** 520-617-7130	
Project Manager: Lizana Pierce **Phone:** 303-275-4727 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:**
	DOE Funding Allocation: 1999: $100,000	**Cost Share Funding:** 1999: $139,357

Project Objective: Tucson Unified School District (TUSD), in conjunction with the Tucson Coalition for Solar (TCS), will design and implement a program for establishing solar energy as a viable choice for satisfying community energy needs, specifically in schools. Through an integrated set of learning opportunities for students, teachers, school support staff, and the wider community of neighbors, family and local industry, the critical role of solar energy will be more firmly established in the Tucson metropolitan area. Further, a curriculum for the development of "solar learning opportunities" will be created to serve as a guide for other communities to design a solar initiative tailored to their needs and conditions, while building on the experience of others.

The purpose of the TUSD PV for Schools Initiative is to: increase community awareness of, and commitment to solar energy applications in schools and the community at large, by establishing a continuum of photovoltaic education for: middle to high school students and teachers; school faculty support staff and management; and the wider community. TUSD PV for Schools Initiative is a campaign designed to integrate photovoltaic technologies/applications into the immediate and wider school community. The immediate school community includes both support staff (administration, facilities managers, and maintenance staff), and curriculum (teachers, students and curriculum support personnel). The wider community includes the business and residents neighboring the schools, parents and extended family, the local union chapter of the school maintenance staff, and the community at large.

Approach/Background: Tucson Unified School District's (TUSD's) Photovoltaics (PV) for Schools Initiative was selected under the PV for Schools Supplemental Announcement. Under the Supplemental Announcement, DOE solicited Applications to develop and demonstrate a model for integrating photovoltaics into middle and high school buildings and education programs. The PV installations are intended to produce electricity for the reduction of utility costs and to serve as teaching aids for the introduction of renewable energy into each schools science programs. The activities to be undertaken under TUSD's PV for Schools project are: 1) developing capacity and enhancing political support for solar energy infrastructure through briefings for School Facilities' Managers, Board of Education, District Management and the interested public, maintenance staff and local union members, and the installation of 4kW in each of two schools; 2) establishing a solar energy awareness and value in the education continuum including a widespread solar education for the Stafford Middle School through the animated website at the "Sunsite/Funsite"; 3) building solar energy capacity in the education continuum by establishing a PV technical framework and skills within the Engineering Magnet Program at Palo Verde Engineering and Technology Magnet High School.

Status/Accomplishments: Cooperative agreement selected and awarded.

Planned FY 2000 Milestones: Install a 4 kW photovoltaic system at Stafford Middle School and 4 kW at Palo Verde Engineering and Technology Magnet High School and develop a curriculum for the middle and high schools.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

Million Solar Roofs Community Partnership Planning, Coordination, Education, and Infrastructure Development for the City of Albuquerque

Contract #: ABW 8-18667-01	**Contract Period:** 6/98–6/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** richard.king@ee.doe.gov	City of Albuquerque Development Services Division 2708 Central SW Albuquerque, NM 87104	
	Organization Type: ST	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Kim Kalender **Phone:** 505-764-0037 **Fax:** 505-764-1782	
Technical Monitor: Christy Herig **Phone**: 303-384-6546 **Fax**: 303-384-6491 **E:mail**: christy_herig@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $25,000	**Cost Share Funding:**

Project Objective: This subcontract is directed towards community partnership development activities for the Million Solar Roofs Initiative (MSRI) implementation. The MSRI plans to install one million solar thermal and photovoltaic installations on US buildings by 2010. The plan is to accomplish this through community partnership teams, which may involve the utility/energy service provider, industry (building/solar), state and local governments and other potential stakeholders. The MSRI community teams will coordinate planning education, business alliances, value analysis and infrastructure development to identify the participation approach which best fits the community needs. This flexible approach to implementation of the MSRI should allow the community teams to create a solar technology commercialization plan of highest value and therefore highest potential for sustainability beyond the initiative.

Approach/Background: The City of Albuquerque plans to use an infill, mixed income, sustainable development as the basis for infrastructure and public outreach.

Status/Accomplishments: The City has held design charettes and public meetings. **:** The City held a workshop to educate city agencies in Feb1999. Additionally, the City developed a video script with this funding (video will be completed with other funding) based on concerns from a builders survey questioning codes financing and energy ratings.

Planned FY 2000 Milestones: None

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PV for Utility Applications

Renewable Energy Analysis, Applications, and Domestic Market Opportunities

Contract #: ACQ-9-29770-01	**Contract Period:** 9/1/99-3/1/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** richard.king@ee.doe.gov	Clean Power Research, L. L. C. 10 Glen Ct. Napa, CA 94558	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Tom Hoff **Phone:** 707-224-9992 **Fax:** 707-224-9993	
Technical Monitor: C. Herig **Phone**: 303-384-6546 **Fax**: 303-384-6490	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $70,000	**Cost Share Funding:**

Project Objective: The objective of this work is to research and analyze the economics, financial mechanisms, business opportunities and intangible value propositions for consumers, building industry, and utilities, as the energy industry changes through restructuring.

Approach/Background: Energy service and supply are rapidly changing. Relationships of electric service providers, regulatory/legislative bodies, the financial and building industry are transitioning with this change. State and local environmental and economic health are considered in electric utility industry restructuring resulting in policies favorable to renewables. Both utilities and builders/developers are defining micro-grids as reliable low cost approaches to meeting new load. And micro-grids meet the environmental and reliability concerns of policy makers. The following tasks will be completed in this subcontract:

- Expand a web based PV value tool which can be used by policy makers, builders/developers, consumers, and utilities to the additional three top value states, IL, NC, HI. It has already been developed through other funding to CA and NY.
- Construct an Excell spreadsheet model to determine value of micro-grids to builders and utilities.
- Construct a market demand curve for PV by metropolitan area
- Perform two case studies with utilities or builders.

Status/Accomplishments: Clean Power Estimator is an economic evaluation software program for customer-owned clean energy systems. The program gives a personalized estimate of the costs and benefits of a PV system for a specific homeowner. The program was tailored to work in 2,000 cities through Illinois, Hawaii, and North Carolina. The following agencies received versions to post on the Internet: (1) Illinois Department of Commerce and Community Affairs/Renewable Energy Resources Program; (2) Hawaii's Energy, Resources, and Technology Division, Energy Branch; and (3) North Carolina Solar Center.

Planned FY 2000 Milestones: Publish paper and brochure on value of distributed resource reliability value to utility grid

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None

Utility On-Grid Photovoltaic Applications

Agreement #: DE-FC36-94GO10007	**Project Period:** 8/16/94–12/31/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King Dan Ton
Phone: 202-586-1693 Phone: 202-586-4618
Fax: 202-586-8148 Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Dan.Ton@ee.doe.gov</td><td colspan="2">Edison Technology Solutions
6040 N. Irwindale Avenue
Irwindale, CA 91702</td></tr>
<tr><td>Organization Type: IN</td><td>Congressional District: 28</td></tr>
<tr><td>Directing Organization:
Golden Field Office
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
Jim Reilly
Phone: 626-815-0501 Fax</td></tr>
<tr><td rowspan="2">Project Manager:
Robert Martin
Phone: 303-275-4763
Fax: 303-275-4753
E:mail: robert_martin@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Edison Technology Solutions</td></tr>
<tr><td>DOE Funding Allocation:
1994: $ 500,000
1995: $1,500,000
1996: $ 500,000</td><td>Cost Share Funding:
1994: $2,000,000</td></tr>
</table>

Project Objective: The major objective of the SCE program is to validate the use of PV as a circuit-specific peaking support resource. The ultimate benefit of a successful on-grid PV program would be more rapid commercialization of the potentially large domestic on-grid PV market.

Approach/Background: The proposed application involves using PV to meet peak load requirements on selected SCE electric distribution circuits. The circuits of interest are old, underground 4 kV circuits, which have reached the limit of their load-carrying capability. The circuits serve residential areas, which have seen recent growth in peak load requirements, so that the circuits will soon exceed their limit during the summer peak load period. Without PV, the main alternative is to replace the circuits by excavating city streets and landscaping to install new underground, high-capacity cable. Since SCE estimates that the replacement of underground cable costs approximately $600,000 per mile, installing PV to meet the peak load requirements on these circuits results in the deferment of this significant cable replacement expense. SCE estimated that replacement of about 200 miles of underground 4 kV circuits in their system could be deferred by the use of grid-connected PV. This would require approximately 25 MW of PV to meet the peak loads on these circuits. The program has been proposed in two separate phases. In Phase I, a feasibility assessment would be performed to address issues such as load and solar resource coincidence, load growth, alternatives to PV, and the size, scope, configuration, and available roof space for PV systems. Some initial installation and testing would also be performed on a pilot scale to establish data for the areas to be considered for the project. Phase II would include the final design, procurement, installation, and monitoring stages.

Status/Accomplishments: Maintenance and data collection continued for the following sites: 1) covered reservoir (98.3 kW) at Huntington Library; 2) rooftop application (112 kW) at Monterey Hills Elementary School; 3) patio cover (5.76 kW) at University of California, Irvine, 4) rooftop systems (31.5 kW) at Knotts Berry Farm Amusement Park; 5) Pacific Park Solar Farris Wheel (41.3 kW) at Santa Monica Pier; 6) covered lunch/assembly area (10.9 kW) at Glenmeade Elementary School in Chino Hills; 7) covered lunch/assembly area (12.6 kW) at Alamitos Intermediate School located in Orange County, CA; 8) rooftop system (9.45 kW) at Boys Republic in Chino Hills; 9) rooftop application (4.8 kW) at Montara Avenue Elementary School; 10) affordable housing site rooftop system (7.2 kW) at Elizabeth Court Apartments in Cudahy; 11) PV system (1.6 kW) at Straw Bale Greenhouse, Cal Poly at Pomona; 12) affordable housing site carport (4.8 kW) at Elizabeth Court Apartments in Cudahy; and 13) carport system (31.2 kW) at Santa Monica Civic Auditorium.

Planned FY 2000 Milestones: Transfer agreement to Southern California Edison. Continue monitoring and data collection and document results. Complete Discovery Science Center.

Major Reports Published in FY 1999: Quarterly project reports.

Major Articles Published in FY 1999: none

PV for Utility Applications

Million Solar Roofs Community Partnership Planning for the Island of Hawaii

Contract #: AAD 8-18664-01	**Contract Period:** 6/98–12/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** richard.king@ee.doe.gov	Hawaii Electric Light Company 1200 Kiluaea Avenue Hilo, HI 96720	
	Organization Type: IN	**Congressional District**: 2
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Steve Burns **Phone**(808)969-0136	
Technical Monitor: Christy Herig **Phone**: 303-384-6546 **Fax**: 303-384-6491 **E:mail**: christy_herig@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $25,000	**Cost Share Funding:**

Project Objective: This subcontract is directed towards community partnership development activities for the Million Solar Roofs Initiative (MSRI) implementation. The MSRI plans to install one million solar thermal and photovoltaic installations on US buildings by 2010. The plan is to accomplish this through community partnership teams, which may involve the utility/energy service provider, industry (building/solar), state and local governments and other potential stakeholders. The MSRI community teams will coordinate planning education, business alliances, value analysis and infrastructure development to identify the participation approach which best fits the community needs. This flexible approach to implementation of the MSRI should allow the community teams to create a solar technology commercialization plan of highest value and therefore highest potential for sustainability beyond the initiative.

Approach/Background: Hawaii Electric Light Company, Inc (HELCO) has been a leader in the commercialization of solar technology in the state of Hawaii and specifically in the County of Hawaii. They will therefore take the lead in this partnership development project.

- Identify the community partnership team.
- Request a short statement from each team member, identifying or proposing the individual's, company's, or government entity's responsibilities and activities for the long-term (through 2010) MSR program on the big island of HI.
- Merge these statements into a document to be the initial MSR plan for the Big Island
- Identify the coordinating committee for the Hawaii Island Million Solar Roofs Kick-off Project (a subset of the community partnership team.
- Explore additional funding for the project
- Make recommendations on appropriate sites for the exhibit
- Develop a design concept and education and outreach approach for the exhibit

Status/Accomplishments: HELCO has completed the plan.

Planned FY 2000 Milestones: None

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Development of the Tucson Photovoltaic Coalition to Promote & Support Photovoltaic Installations

Contract #: RBW 8-18685-01	**Contract Period:** 6/98–6/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** richard.king@ee.doe.gov	Learning Village Project Post Office Box 42708 Tucson, AZ 85733 **Organization Type**: IN	 **Congressional District**: 5
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Valerie Rauluk and David Fuller **Phone**(520) 326-3195 **Fax:** (520) 326-3195	
Technical Monitor: Christy Herig **Phone**: 303-384-6546 **Fax**: 303-384-6491 **E:mail**: christy_herig@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1998: $25,000	**Cost Share Information**: None. **Cost Share Funding:**

Project Objective: This subcontract is directed towards community partnership development activities for the Million Solar Roofs Initiative (MSRI) implementation. The MSRI plans to install one million solar thermal and photovoltaic installations on US buildings by 2010. The plan is to accomplish this through community partnership teams, which may involve the utility/energy service provider, industry (building/solar), state and local governments and other potential stakeholders. The MSRI community teams will coordinate planning education, business alliances, value analysis and infrastructure development to identify the participation approach which best fits the community needs. This flexible approach to implementation of the MSRI should allow the community teams to create a solar technology commercialization plan of highest value and therefore highest potential for sustainability beyond the initiative.

Approach/Background: The following activities and planned for the Tucson coalition:

1. Facilitate membership in TPVC and establish mission, objectives, and operating structure.
2. Establish a Buying Cooperative for Photovoltaic devices for installers, developers, and contractors in the region.
3. Establish relationships with funding authorities for more efficient financing of solar devices.
4. Research and recommend best possible structures for a Community Energy Cooperative or Energy Service Organization which supports wide-spread dissemination of PV technologies and other solar devices (solar thermal, especially solar water heaters).
5. Solidify the inclusion of renewable energy and sustainability criteria for programs, policies, and projects at the local government level, in particular, the City of Tucson and Pima County.

Status/Accomplishments: All activities have been completed

Planned FY 2000 Milestones:

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Renewable Energy Applications and Economic Analysis for Electric Power

Contract #: AAX-5-15330-01	**Contract Period:** 8/23/95–12/31/98

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** richard.king@ee.doe.gov	Pacific Energy Group 32 Valla Court Walnut Creek, CA 94596 **Organization Type**: IN	**Congressional District**: 10
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** H. Wenger, T. Hoff **Phone:** 925-937-1750	
Technical Monitor: Christy Herig **Phone**: 303-384-6546 **Fax**: 303-384-6491 **E:mail**: christy_herig@nrel.gov	**B&R Code**: EB22 **DOE Funding Allocation:** 1995: $120,000 1997: $167,000 1998: $85,000	**Cost Share Information**: Pacific Energy Group. **Cost Share Funding:** 1998: $50,000

Project Objective: The objective of this work is analysis of PV applications, financials, and market opportunities in the changing electric service provider environment.

Approach/Background: This subcontract has developed broad-based analysis for financial risk valuation of utility investments, customer sited PV value, policy value, and alternative electric service provider operating scenarios. The broad-based analysis has then been targeted to regions, states, municipalities, utilities and consumers for the purpose of identifying values and developing markets.

Status/Accomplishments: Analyzed financial "Risk Management Using Renewable Energy Attributes" for a variety of electric power investment scenarios; developed user-friendly software for distributed utility valuation; provided initial analyses of "Niche Markets for Grid-Connected Photovoltaics" (residential) and an architects perspective for market deployment of building integrated PV; provided analyses of commercial building integration value and microgrid and load leveling strategies. Developed a more detailed report on the initial niche market analysis approach; expand and detail the niche market analysis to include additional application and customer segmentation; analyze the financial community's view of the electric industries' investment in renewables and the effects on specific company financial status; determine the state revenue impact for legislation and policies which favor renewable deployment; support the Million Solar Roofs Initiative; provide custom analysis for the electric industry, state energy offices, legislatures, regulatory commissions, and consumer advocates as requested; and apply risk management financial analysis to actual utility case studies. Additionally, the following case studies were completed.

- Salt River Project - A possible alternative to existing solar portfolio standards (called a revenue-based solar portfolio standard) and investment opportunities in PV were identified from a utility's perspective. Final report: *An Analysis of the Solar Portfolio Standard and Solar Electric Investment Opportunities* (January, 1998)
- Okanogan Electric Coop - Evaluated the technical and economic feasibility of using distributed resources to supply the energy needs of 1,500 new homes in the Mazama Valley. Final report: Distributed Resources: *A Potentially Economically Attractive Option to Satisfy Increased Demand on Okanogan County Electric Cooperative's "Mazama Feeder" Line* (October, 1998).
- Block Island - Performed an analysis of the potential for Block Island Power Company to use renewable energy and clean distributed resources to supply power to its customers. Final report: Preliminary Analysis of Block Island Power Company's Use of Clean Distributed Resources to Provide Power to Its Customers (August, 1998)

Planned FY 2000 Milestones: Subcontract has ended. But reports on the case studies will be posted on the web

Major Reports Published in FY 1999:
NREL Photovoltaic Program FY 1997 Annual Report**,** NREL/BK-210-23607, (June 1998).

Contract #: AAX-5-15330-01

Major Articles Published in FY 1999:

"Clean Distributed Resources in the U.S. Residential Market," T. E. Hoff and C. Herig, *IEEE Power Engineering Review* (1999).

"Reducing Carbon Emissions Using Clean Distributed Resources," T. E. Hoff, J. P. Weyant, and C. Herig, 19th USAEE/IAEE Annual Conference (1999).

"Using Distributed Resources to Manage Risks Caused by Demand Uncertainty," T. E. Hoff, *Energy Journal Special Issue*:63-83 (1998).

"Reduce, Reuse, and Renew: One Possible Approach to Global Climate Change," T. E. Hoff, H. J. Wenger, J. P. Weyant, and C. Herig, *International Journal for Global Energy Issues* (2000).

PV for Utility Applications

Financing Residential PV Systems in California

Contract #: AAF-9-29611-01	**Contract Period:** 6/21/99–12/21/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** richard.king@ee.doe.gov	Renewable Energy Development Institute 383 S. Main Street, #234 Willits, CA 95490	
	Organization Type: IN	**Congressional District:** 1
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Keith Rutledge **Phone:** 707-459-1256 **Fax:** 707-459-0366	
Technical Monitor: C. Herig **Phone**: 303-384-6546 **Fax**: 303-384-6490 **E:mail**: christy_herig@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $35,000	**Cost Share Funding:**

Project Objective: The objective of this subcontract is to determine what is required by the market, infrastructure, and communications to develop a direct link between the home financing industry and the residential PV industry.

Approach/Background: Utility industry restructuring policy in California resulted in a $3/Watt buy-down incentive administered through the California Energy Commission. With this buy-down, the cost effectiveness is very close for the residential market, but still needs low interest financing such as first mortgage home financing. Currently, real estate agents can qualify home mortgages with a phone call. Through the following approach, a similar mechanism will be developed for the PV industry.

- Develop a network of PV manufacturers and installers to work out the PV industry issues in California.
- Develop a network of mortgage lenders, appraisers and real estate professionals to identify home mortgage industry issues.
- Conduct seminars in major population centers (Los Angeles, San Francisco, and Sacramento) to work out issues.
- Develop a spreadsheet tool for over the phone qualification.

Status/Accomplishments: Networks and seminars have been completed. Reports and spreadsheet tool should be completed soon.

Planned FY 2000 Milestones: Spread sheet tool for PV financing qualification in California

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None

PV for Utility System Applications (PVUSA)

Contract #: DE-FC04-96AL89744, A002	**Contract Period:** 10/01/98 - 09/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E-mail: Richard.King@ee.doe.gov</td><td colspan="2">Sacramento Municipal Utility District
P. O. Box 15830
Sacramento, CA 95852-1830</td></tr>
<tr><td>Organization Type: ST</td><td>Congressional District: 5</td></tr>
<tr><td>Directing Organization:
DOE/AL/TDD
P.O. Box 5400
Albuquerque, NM 87185</td><td colspan="2">Principal Investigator(s)
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Phone: 916-732-6679 Fax: 916-732-6423
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<tr><td rowspan="2">Technical Monitor:
D. Sanchez
Phone: 505-845-4417
E:mail: dsanchez@doeal.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Sacramento Municipal Utility District</td></tr>
<tr><td>DOE Funding Allocation:
1998: $600,000
1999: $600,000</td><td>Cost Share Funding:
1998: $640,000
1999: $427,000</td></tr>
</table>

Project Objective: Operate PVUSA's main Davis, CA facility and provide support for related technology transfer activities at Davis and at nine other affiliated host sites across the U.S. Evaluate the performance of the variety of PV systems and components installed at the Davis and host sites. Share findings with a core membership consisting of two-dozen utilities and government agencies, and distribute a subset of summary information in response to requests from the public. Meet technology transfer objectives via several avenues: training workshops at Davis and across the country; codes and standards development; publish data, reports and technical papers; provide presentations and expert information at numerous policy and technical forums; and public and membership access website.

Approach/Background: PVUSA began conducting side-by-side PV systems research in 1989. The number, size, and variety of systems being evaluated has expanded steadily over the past decade and now includes two dozen grid-connected systems totaling 2.3 megawatts of peak generating capacity. These systems range in size from 2 kW rooftop scale systems to 500 kW utility line-support systems. The focus of this Cooperative Agreement continues to be on grid-connected systems. After a change in ownership from founding utility Pacific Gas & Electric Co. to a joint ownership/ management team of the California Energy Commission (CEC) and the Sacramento Municipal Utility District (SMUD) in 1997, PVUSA developed a 5-Year Plan to guide project efforts. Several changes pursuant to the Plan are being implemented. For example, within the general area of grid-connected systems, PVUSA has widened its scope over the past two years to include a Small Systems Test Center (SST) featuring rooftop-scale systems, an increasingly important market sector. PVUSA's constituents have indicated that short-term evaluations of small systems, coupled with ongoing long-term operation of earlier vintage systems, are collectively yielding a valuable mix of lessons learned and recommendations.

Status/Accomplishments: System status is presently at 26 active systems, with a combined capacity of 2.3 megawatts. Combined, the total project lifetime generation rose by 2 million kWh during FY1999 and stands at 15.2 million kWh as of the end of FY1999. This energy represents an offset of 25,000 barrels of oil for conventional fossil-based generation, or enough electricity to meet the needs of over 2,500 homes for one year. During FY1999, a marketing coordinator was hired and an aggressive campaign to boost membership began. Four new utility members joined this year, increasing the number of participating organizations from 20 to 24. Our close relationship with UPVG was affirmed with the introduction of a UPVG Affiliate Membership, making it easier for organizations to leverage their photovoltaic R&D investments. The site continued its public visibility, hosting approximately 500 visitors during FY1999, including a group of 100 that took part in a local segment of the October 1998 National Solar Homes Tour. A display rack containing several dozen manufacturers' brochures was installed in the Visitor Center, along with descriptive signs alongside each of the PV systems along the Davis site's tour path. PVUSA also enhanced its website with the help of the CEC, who hosted the site and generated new graphics and layout.

Installation was completed on the three new rooftop class systems for a total of six SST systems. These latest systems represent the newest technologies procured under SMUD's Sustained Orderly Development (SOD) PV Pioneer program. Both utilities and manufacturers have again contracted with PVUSA to conduct nearly $100,000 in proprietary R&D work on a Fee for Service basis.

Contract #: DE-FC04-96AL89744, A002

These activities support new PCU and PV module development, on- and off-site performance evaluation, and system acceptance testing. The Fee for Service PCU testing initiates the Power Conditioning Unit Testbed (PCUT) at Davis with testing underway on three new 2 kW, 10 kW, and 100 kW varieties of PCUs. Two-day workshops on Code Compliant system design in conjunction with the Florida Solar Energy Center. Over its first year, the monthly workshop series at Davis attracted over 100 participants, and a similar number of one-day workshops were held for another 100-plus participants across the country. Requests for more hands-on field work led to the expansion of the workshop to three days at the end of FY1999.

There were other notable accomplishments as well. PVUSA continued support for the California Energy Commission's PV Buydown Program. In FY1998, PVUSA established and now periodically updates a database of approved PV modules and PCUs, along with the method for calculating a system's rating and its associated rebate. Another accomplishment involved installing and instrumenting a small system test rack for very small (<100 W) systems. This small system testing is being done in association with a team of researchers led by NREL. The group was convened to perform a Round Robin evaluation of a proposed new standard small system test procedure. Results from this international and national standards development effort were presented at two forums during FY1999, one in Winter Park, CO, hosted by NREL, and another in Phoenix, AZ, hosted by IEEE. Lastly, PVUSA's soiling test station began to yield substantial results and attract interest during FY1999. Installed at the beginning of 1998, the soiling test station showed that commonly cited annual energy losses of about 4% may be expected in locales similar to Davis only during exceptionally wet precipitation years. The losses increase to 7% during normal years such as FY1999, and are expected to exceed 10% during drought years.

Planned FY 2000 Milestones: None

Major Reports Published in FY 1999:

- "A Simple Method for Estimating PV Energy Production," ASES Solar 99.
- "Objective Method for Selecting Outdoor Reporting Conditions for Photovoltaic Performance," ASES Solar 99.

Major Articles Published in FY 1999:

- *"The Impact of Efficiency on Area-related System Costs*," 1999 Performance and Reliability Workshop and in Progress in Photovoltaics, Volume 7, Number 3, May-June 1999.

Photovoltaic Market Valuation and Load Matching

Contract #: XAD-8-17671-1	**Contract Period:** 11/21/97–8/19/00

<table>
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Albany, NY 12222</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 21</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
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Phone: 518-437-8751</td></tr>
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Christy Herig
Phone: 303-384-6546
Fax: 303-384-6491
E:mail: christy_herig@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
State University of New York., NYSERDA</td></tr>
<tr><td>DOE Funding Allocation:
1998: $85,000
1999: $70,000</td><td>Cost Share Funding:
1998: $50,000
1999: $50,000</td></tr>
</table>

Project Objective: Building upon accomplished PV load matching and customer-sited valuation tasks, the current objectives of this subcontract are:

1. To develop and test a remote resource monitoring/performance modeling service for domestic sited PV installations to provide comparison with metered performance
2. To provide utility/builder/customer with load carrying capacity / load matching analysis and/or to provide briefs on solar resource when large grid peaks or outages occur
3. To expand analysis of commercial building sited PV to include environmental, replacement material, emergency value and enhanced load management value, and apply to case studies as requested
4. To continue testing, development and economic evaluation of the solar load controller (SLC) and to analyze the potential of SLCs to enhance the value of micro-grids which include PV or PV distributed generation

Approach/Background:
Remote sensing of solar radiation from geostationary satellites may offer a solution to the "mass monitoring" of PV systems. Using appropriate models, the real time output of PV system anywhere in the US could be adequately estimated from satellites. The viability of this approach is assessed by comparing PV simulations from geostationary satellite data -- GOES 8/10 acquired as part of another NREL project -- against ground truth PV output from UPVG systems distributed throughout the country.

Upon request, PV load matching analyses, that, until recently, had to be limited to 1987-1988, can now be performed at any point/time in the US using the ongoing GOES8/10 data mentioned above. This data set may also be used upon request to look at the solar resource during high peak load and grid congestion event.

The commercial building valuation study builds upon a completed "business as usual" valuation by incorporating tangible and intangible externalities in the valuation metric. As before, this metric is the breakeven turnkey system cost, i.e., the cost below which a system would be profitable to its owner benchmarked against a selected return on investment. The tangible externalities include replacement value for either roofing or glazing material, as well as an application of load control techniques discussed below. Still intangible externalities include emergency value and environmental value that can be indirectly quantified through insurance premium discount proposals and projected emission cleanup costs.

The solar load controller, developed under cofunding from NYSERDA, is control methodology acting on a building or appliances end-use setting to maximize the peak shaving capability of a customer sited PV array. The SLC can be embodied as a control device in an energy/control appliance (e.g., a smart thermostat) or as an algorithm coded in an Energy Management System (EMS). Two prototypes are developed and tested under real conditions, one at the University at Albany's CESTM building, implemented as a modification to the buildings' EMS, and the other at the University at Albany's East Campus, implemented as a smart thermostat driving an individual air conditioning unit.

Status/Accomplishments
Six UPVG ground-truth test sites have been selected, including: (1) a fixed-tilt 81 kW-ac PV plant operated by the New York Power Authority in Yonkers; (2) a fixed-tilt 14.9 kW-ac PV array in LaGrange, GA (operated by Interface Flooring); (3) a fixed-tilt 2.5 kW-ac array in Davis, CA (SMUD); (4) a one-axis tracking 117 kW-ac PV array at Sacramento Airport (SMUD); (5) a fixed-tilt 1.8 kW-ac residential PV array in Rosemount, MN (Northern State Power); and (6) a one-axis tracking 70 kW-ac PV array in Tempe, AZ (APS). Evaluation results will be the object of two articles to be presented at the 2000 ASES conference and the 16th European PV conference.

Several inquiries for load matching evaluation have received (notably LIPA and the Platte River Power Authority) but none has materialized yet, as those who ask need to assemble load data. We have however been able to look at grid-stressing peak load situations in the and New York City and Chicago area, pointing to a substantial solar resource availability [see publication list].

The commercial PV valuation with externalities led to two publications listed below. The bottom line is that the tangible externalities can bring the value of a fixed PV system (either vertical PV glazing or PV roofing) to the level of an ideal two axis tracking PV array. If all of the externalities are considered, then 85% of the US markets would have a Breakeven turnkey Cost in excess of $4000/kW-ac.

The solar load controller was successfully tested and a focus group composed of potential industrial partners and SLC users was assembled for a limited presentation of the results. The following consensus emerged.

- The SLC successfully accomplishes its task with simple HVAC installations and has demonstrated solid potential for more complex HVAC systems
- The SLC is a good thing for grid-connected commercial PV-integrators, helping systems economics, thereby enhancing the sales potential
- As a device the SLC should reside on the HVAC, rather than the PV power conditioning side, except for SLC-enhancing components such as micro storage capability that could reside on the inverter side
- Several beta-test sites should be operated and analyzed before final product definition and dissemination.

This material will be further discussed in a brief report under preparation.

Planned FY 2000 Milestones: Test market solar load controller and expand commercial niche market analysis. Publish paper and brochure on value of distributed resource reliability value to utility grid.

Major Reports Published in FY 1999:
*NREL Photovoltaic Program FY 1997 Annual Report***,** NREL/BK-210-23607, (June 1998).

Major Articles Published in FY 1999:

Perez, R. C. Herig, H. Wenger, J. Schlemmer, K. Elsholz and B. Bailey, (1999): Maximizing the Value of customer-sited commercial PV system, Proc. UPEX 99, Tucson, AZ (Utility Photovoltaic Group, Washington, DC)
Perez, R., M. Kmiecik, C. Herig and H. Wenger, (1999): Mapping the Value of Commercial PV Applications in the US Accounting for Externalities. Proc. ASES Annual Meeting, Portland ME.
Perez R., H. Wenger, C. Herig and M. Kmiecik, (1999): Photovoltaic Market Valuation and Load Matching, NCPV FY-1998 Annual report, NREL/BK-210-25626 pp.437-440
Perez R., (1999), Jul 6th, 1999 Heat Wave, Peak Demand Records & Outages in New York City...PV Would Have Worked! Custom study posted at: http://lunch.asrc.cestm.albany.edu/~perez/
Perez R., and H. Wenger, (1999) Final Report on Photovoltaic Valuation, submitted to NREL (contracts No. XAD-8-17671-01 and XAX-6-16817-01), 41 pp., NREL, Golden, CO

PV for Utility Applications

User-Scale Applications - Photovoltaics (USAPV)

Agreement #: DE-FG36-93CH10587	**Project Period:** 9/27/93–6/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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<tr><td>Organization Type: IN</td><td>Congressional District: 11</td></tr>
<tr><td>Directing Organization:
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Robert Martin
Phone: 303-275-4763
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User-Scale Applications – Photovoltaics</td></tr>
<tr><td>DOE Funding Allocation:
1994: $352,740
1995: $303,864</td><td>Cost Share Funding:
1994: $352,740
1995: $658,030</td></tr>
</table>

Project Objective: The prime objectives of the USAPV program is three fold as follows: 1) develop the necessary marketing business plans and regulatory framework to integrate photovoltaic technology into the portfolio of products and services offered by the utility, 2) develop the necessary standards for and understanding of PV technology such that PV becomes one of several solutions employed by utilities to solve operational problems and meet distribution system peak demands, and 3) introduce at least 10 MW of new PV demand within the northeastern United States.

Approach/Background: USAPV was originally proposed and sponsored by Congressman Dean Gallo (R-NJ) as a program that would encourage greater visibility and opportunity for the integration of PV technology in New Jersey and the northeastern United States. The New Jersey Board of Regulatory Commissioners (NJBRC) has been in the forefront of regulatory reform in the promotion of demand side management programs and is an advocate of PV applications in New Jersey. Both the NJBRC and NJDEPE strongly support and endorse the project. Furthermore, regulatory support may promote a broader acceptance and visibility for this PV initiative in the utility industry. User Scale Applications - Photovoltaics (USAPV) will implement cost shared demonstrations of utility-owned, end-user and distributed applications of photovoltaic technology. USAPV's objective is to leverage federal funds with private funding from utilities customers, PV industry, state regulatory agencies, and other participating organizations. USAPV will monitor and evaluate projects, each cost-shared on a minimum of a 50/50 basis. USAPV will establish priorities for demonstration projects and will be responsible for their management, data collection and reporting. USAPV will be managed by a Steering Committee with representation from the participating utilities, New Jersey Department of Environmental Protection and Energy (NJDEPE), and U.S. DOE with advisement from a Technical Review Committee representing PV experts from National Laboratories and utilities, industry, and research organizations.

Status/Accomplishments: Jersey Central Power & Light and Atlanta Electric initially sponsored projects on a 50/50 cost share basis for the implementation of projects in the areas of fluorescent and outdoor lighting, and isolated load applications. Nine projects have been completed through those two utilities. Three additional utilities, Metropolitan Edison Company, Potomac Electric Power Company, and New York Power Authority have completed projects under USAPV grants. Two additional projects, Taunton Municipal Lighting Plant and Tampa Electric Company have been completed.

Planned FY 2000 Milestones: Complete the 19 grid-integrated PV systems being installed through a grant to Don Bradley of Solar Strategies Development Corporation. Submit final report.

Major Reports Published in FY 1999: none

Major Articles Published in FY 1999: none

Technology Experience to Accelerated Markets in Utility Photovoltaics (TEAM-UP)

Agreement #: DE-FC36-93CH10560	**Project Period:** 10/1/92–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Dan Ton **Phone:** 202-586-1693 / **Phone:** 202-586-4618 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail:** Dan.Ton@ee.doe.gov	Utility Photovoltaic Group (UPVG) 1800 M Street, NW, Suite 300 Washington, DC 20036-5802	
	Organization Type: IN	**Congressional District:** NA
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Jeffrey Serfass **Phone:** 202-857-0898 **Fax:** 202-223-5537	
Project Manager: Robert Martin **Phone:** 303-275-4763 **Fax:** 303-275-4753 **E:mail**: robert_martin@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** Utility Photovoltaic Group (UPVG)
	DOE Funding Allocation: 1994: $1,000,000 1997: $300,000 1995: $8,891,000 1998: $2,00,000 1996: $5,400,054 1999: $3,800,000	**Cost Share Funding:** 1994: $209,000 1997: $7,942,410 1995: $9,337,727 1998: $4,458,000 1996: $5,400,054 1999: $11,861,254

Project Objective: The Utility PhotoVoltaic Group's (UPVG's) objectives is the establishment of an accelerated market for suppliers of photovoltaic systems that allows investments in larger manufacturing facilities, thus reducing photovoltaic unit costs through economies of scale, creating even broader market potential. TEAM-UP, a multi-year, 50 MW hardware initiative, provides for small-scale applications and grid-connected programs, as well as, focusing on commercialization strategies for photovoltaic systems in the utility industry. The prime objective of TEAM-UP is achieving sustained, domestic PV commercialization by the year 2000.

Approach/Background: Created in September 1992, the Utility PhotoVoltaic Group's original Program Development Plan addressed the large potential for applications of photovoltaic systems for electric utilities and their customers. The first activity focused on technology transfer and promotion to accelerate today's potential economic applications of photovoltaic systems for the benefit of electric utilities and their customers, while the other parallel program was the formulation and exploitation of strategies that would result in high-volume purchases of photovoltaic systems for emerging applications. Phases 1 and 2 of the agreement focused on these two parallel activities, whereas Phase 3 includes the implementation of utility market acceleration strategies.

Implementation of UPVG's hardware initiative, TEAM-UP, began during Phase 3 with funding for grid-connected projects and support of market/buyer teams for grid-independent applications. During Phase 3, twelve (12) grid-connected projects were initiated. Of the awards, nine are active projects, which represent 1.9 MW of photovoltaic installations valued at $21 million. Additionally, UPVG was instrumental in securing funding either through TEAM-UP or other sources for more than 80% (21 projects) of the 26 proposals received in response to the grid-connected applications (GCA) Request for Proposals issued in December 1994. Five teams were formed which will serve as market development and/or buyer teams for six (6) off-grid applications of photovoltaics, including remote residential service, water pumping applications, and lighting applications. The 1994 and 1995 TEAM-UP RFP's (Round One and Round Two) led to 22 agreements for efforts with a total value exceeding $44 million and will result in more than 1,300 PV systems being installed in 35 utility service areas around the United States. Over 4.5 MW of new PV system capacity will result from these efforts.

The 1997 TEAM-UP Request for Proposals (RFP) for cost-shared, grid-connected and grid-independent ventures was issued on October 3, 1997. A total 13 ventures were awarded FY98 funding under Round 3 of the TEAM-UP program. The Phase 5 program focused on four task areas: 1) expanding PV technology experience base; 2) increasing PV business opportunities and markets; 3) supporting the community/city buildings initiative; and 4) education, communication, and promotion. TEAM-UP has funded 36 ventures since 1995.

Status/Accomplishments: October 1999 marked the completion of installations under Round Two (Round One installations were completed by October 1998), as well as a significant percentage of Round Three installations – a total of 5.9 MW of PV.

Planned FY 2000 Milestones: By October 2000, a total of 2,300 PV systems will be installed, totaling 7.4 MW of PV capacity.

Agreement #: DE-FC36-93CH10560

Major Reports Published in FY 1999: Technical and Business Experiences of TEAM-UP Program Partnerships "4.5 Megawatts of PV and Counting," Annual Technical Report

Major Articles Published in FY 1999: none

Coordination and Development of the Washington 5,000 Solar Rooftops by 2005 Collaborative

Contract #: AAX-8-18640-01	**Contract Period:** 6/98–6/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Managers: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** richard.king@ee.doe.gov	Washington State University Energy Program 925 Plum Street, SE, Building 4 P. O. Box 43165 Olympia, WA 98504-3165	
	Organization Type: IN	**Congressional District**: 3
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator (s)** Mike Nelsen **Phone**(360) 956-2148 **Fax:** (360) 956-2030	
Technical Monitor: Christy Herig **Phone**: 303-384-6546 **Fax**: 303-384-6491 **E:mail**: christy_herig@nrel.gov	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1998: $25,000	**Cost Share Funding:**

Project Objective: This subcontract is directed towards community partnership development activities for the Million Solar Roofs Initiative (MSRI) implementation. The MSRI plans to install one million solar thermal and photovoltaic installations on US buildings by 2010. The plan is to accomplish this through community partnership teams, which may involve the utility/energy service provider, industry (building/solar), state and local governments and other potential stakeholders. The MSRI community teams will coordinate planning education, business alliances, value analysis and infrastructure development to identify the participation approach which best fits the community needs. This flexible approach to implementation of the MSRI should allow the community teams to create a solar technology commercialization plan of highest value and therefore highest potential for sustainability beyond the initiative.

Approach/Background: The Washington States 5,000 Solar rooftops By 2005 has already undertaken aggressive steps towards deploying solar electric systems as outlined in the Background section. They will therefore take the lead in this partnership development project through the following activities.

- Organize a meeting between Washington utilities and the Washington solar industry. This meeting will identify the community partnership team and provide the foundation for the collaborative to obtain the 5,000 solar rooftop goal as committed to the Million Solar Roofs Initiative.

- Utilizing the output from the meeting, develop a consensus document which identifies the collaborative partnership team, the short term commitments to build the infrastructure for solar technology deployment (local and state) and develop the long term plan for the collaborative's participation in the MSR initiative through the year 2010.

Status/Accomplishments: All activities has been completed. Additionally, a solar energy coop has been formed. The meeting originally funded by this subcontract was repeated as the Northwest Solar Summit, with funding from Bonneville Power Authority.

Planned FY 2000 Milestones: None

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

Mexico Support

Contract #: BB-5930	**Contract Period:** 2/27/98–10/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Arizona Public Service Co. 400 N. 5th St. Phoenix, AZ 85004-3902	
	Organization Type: IN	**Congressional District:** 2
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** C. V. Mathai **Phone:** 602-250-3569 **Fax:** 602-250-3872	
Technical Monitor: Charles J. Hanley **Phone:** 505-844-4435 **Fax:** 505-844-7786 **E:mail:** cjhanle@sandia.gov	**B&R Code:** EB22	**Cost Share Information:** DOE/Wind DOE/Storage USAID/Mexico
	DOE Funding Allocation: 1998: $150,000 1999: $0	**Cost Share Funding:** 1998: $100,000 (USAID) 1999: $0

Project Objective: Implementation of renewable energy hybrid mini-grid in Baja California Sur, Mexico, to increase the use of renewable energy technologies in Mexico. This program is supported by both DOE and USAID/Mexico. (Total contract is $250,000, with $50,000 applicable to photovoltaics.)

Approach/Background: Support implementation of a centralized hybrid wind-PV-diesel mini-grid system in the village of San Juanico. This pilot project will provide valuable knowledge and expertise regarding the use of hybrid renewable energy systems, which expertise will be applicable to future projects in Mexico.

Status/Accomplishments: Completed installation of project.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PV for International Applications

Renewable Energy Business Development in China

Contract#: AAX-8-17679-01	**Contract Period:** 2/26/98–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Center for Renewable Energy Development Zhansimen Road, Shahe, Changping County Beijing 102206, P.R.C.	
	Organization Type: ZZ	**Congressional District:**
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** J. Li **Phone:** 011 8610 6973-7074 **Fax:** 011 8610 6973-3110	
Technical Monitor: Debra Lew **Phone:** 303/384-7522 **Fax:** 303/384-7419 **E:mail:** Debra_Lew@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1997: $94,933 1998: $39,870 1999: $70,157	**Cost Share Funding:**

Project Objective: To establish a framework for specific collaboration in order to promote renewable energy business development between the U.S. and China. To hold workshops and study tours, leveraging other events, which will bring US and Chinese businesses together for future partnerships and cooperation. To support information dissemination through websites and newsletters business related data from the US and China for mutual exchange with companies in both countries. To proactively support the development of renewable energy projects in China and project participation by U.S. and Chinese companies.

Approach/Background: Joint cooperation with the Center for Renewable Energy Development in Beijing is conducted to generate a number of information products to exchange between China and the U.S. for the purpose of promoting business cooperation and the development of opportunities. Joint efforts are also conducted to support market-conditioning efforts in financing and policy. Whenever possible, CRED and NREL will leverage other events in order to bring US and Chinese businesses together at least cost. Exchange visits, workshops and study tours are used to reach these goals.

In order to bring relevant market information to US businesses, CRED has assisted in development of market and technology assessments, which are published as reports and distributed widely through the US business community. Websites and newsletters are also used to disseminate information.

Status/Accomplishments: Market and technology assessments made during 1998 were published in 1999, including the *PV Business Application and Evaluation* Report and *Renewable Energy Markets In China: An Analysis of Renewable Energy Markets in Guangdong, Jiangxi, Jilin and Yunnan, with Updated Information from Beijing* Report. CRED conducted a solar thermal business study tour to the US in 4/99, bringing Chinese companies and government representatives to meet with US companies and government representatives and to visit US solar thermal installations. A US/China Renewable Energy Business workshop and study tour was held in 11/99 to bring 13 US companies to China for the purpose of increasing US markets for renewable energy products and services in China. This workshop and study tour resulted in several potential deals, partnerships and distributorships for US wind and PV suppliers.

Planned FY 2000 Milestones: The solar thermal business study tour was successfully completed in 4/99. The Renewable Energy Business workshop and study tour were successfully completed in 11/99. A Chinese language website to provide information on business opportunities and policies will be prepared and linked to an NREL English-language website. A China PV market study will be published in both Chinese and English in 2000.

Major Reports Published in FY 1999:
"Comparison of Renewable Energy Policies of China and the United States," Zhang Zhengmin and Li Jingjing of CRED and Yih-huei Wan of NREL, 1999.

PV for International Applications

Rural Electrification Using Photovoltaics in Northwestern China

Contract#: AAX-8-17680-01	**Contract Period:** 12/5/97–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
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E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Chinese Ministry of Agriculture
No. 11 Nongzhanguan Nanli
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<tr><td>Organization Type: ZZ</td><td>Congressional District:</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
J. Li
Phone: 011 86 10 6419-2610 Fax: 011 86 10 6500-2448</td></tr>
<tr><td rowspan="2">Technical Monitor:
Debra Lew
Phone: 303/384-7522
Fax: 303/384-7419
E:mail: Debra_Lew@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
Chinese Ministry of Agriculture</td></tr>
<tr><td>DOE Funding Allocation:
1996: $100,000
1998: $50,000
1999: $45,000</td><td>Cost Share Funding:
1996: $80,000</td></tr>
</table>

Project Objective: In general, there are several objectives. To expand the use of PV renewable energy systems throughout western and northwestern China for solar home lighting, educational school systems, etc. by expanding the knowledge base for solar applications in rural China, especially through the Gansu Project. To perform technical and economic analysis for rural electrification options to identify the most cost effective way on a life cycle basis for supplying rural electrification needs in China. To characterize the market for solar rural electrification systems in Qinghai and Xinjiang provinces in western China. To provide technical assistance for the Asia-Pacific Solar Energy Training Center being supported by the Ministry of Agriculture in Lanzhou in Gansu.

Approach/Background: Rural electrification options analyses will be conducted on data which has been collected in surveys for Xinjiang and Qinghai provinces in northwestern China. The analyses will characterize the best options for supplying rural electrification needs in this remote region of China and will provide a characterization of the existing market for solar PV systems. Technical assistance will be supplied to the regional testing and training facility in Lanzhou to support the resources of the Chinese Ministry of Agriculture in extending the training services available to several provinces in western China.

Status/Accomplishments: Surveys at the county level in ten counties in Xinjiang and Qinghai and the required provincial and national data has been collected and analyzed and the final report will be published in early 2000. Two-week training session held for 30 technicians and local government officials from northwest China at the Asia-Pacific Solar Energy Training Center in Lanzhou in 11/99. Installation of demonstration systems at a village near the Great Wall in Beijing, showing the PV technology and its applications at a school and household in 10/99.

Planned FY 2000 Milestones: Publish analysis results of the project by early 2000. Training session held for 30 solar technicians and government officials in 11/99.

Major Reports Published in FY 1999: None.

PV for International Applications

Mexico Support

Contract #: AV-1215	**Contract Period:** 12/6/96–12/31/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
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E:mail: Richard.King@ee.doe.gov</td><td colspan="2">Ecoturismo y NT
Zaragosa, Mexico</td></tr>
<tr><td>Organization Type: ZZ</td><td>Congressional District:</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
Arturo Romero
Phone: 011-525-824-1358 Fax: 011-525-825-1734</td></tr>
<tr><td rowspan="2">Technical Monitor:
Charles J. Hanley
Phone: 505-844-4435
Fax: 505-844-7786
E:mail: cjhanle@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1996: $95,000
1997: $
1998: $
1999: $60,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Provide technical and strategic support to the Mexico Renewable Energy Program, specifically activities in Quintana Roo, Baja California Sur, and in protected areas.

Approach/Background: Provides technical support for pilot renewable energy projects with partner organizations in Mexico.

Status/Accomplishments: Established a local committee in Quintana Roo to oversee implementation of renewable energy projects.

FY 2000 Milestones: None. Contract will be ending**.**

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999:

Romero Parades Rubio, A., et al. *Aplicacion de las Energias Renovables en las Reservas Ecologicas*, ANES Proceedings, October 1998, p. 3.

Romero Parades Rubio, A., et al. *Lecciones Aprendidas de 30 Sistemas Fotovoltaicos para Bombeo de Agua Instalados en Quintana Roo*, ANES Proceedings, October 1998, p. 9

China Program Website Development and Communications

Contract#: TDH-9-29120-01	**Contract Period:** 9/20/99-9/20/00

Sponsoring Office Code: EE-13	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Julie Cardinal 5225 White Willow Drive, M210 Fort Collins, CO 80528	
	Organization Type: IN	**Congressional District:** 4
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Julie Cardinal **Phone:** 970-206-1296	
Technical Monitor: Debra Lew **Phone:** 303/384-7522 **Fax:** 303/384-7419 **E:mail:** Debra_Lew@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None
	DOE Funding Allocation: 1999: $24,500	**Cost Share Funding:**

Project Objective: This project was designed to support the U.S. renewable energy industry in developing business opportunities in China. The main objective is to develop an English-language website, which will contain information from and be linked to a Chinese-language website, that will provide information on Protocol activities, new business opportunities, new policies, and market and industry reports that have been developed by NREL. This project will also support business development through developing a database of US and Chinese company contacts for distribution of timely business-related information and through supporting communications outreach to US companies.

Approach/Background: The website is being prepared to disseminate information widely to US businesses by posting DOE/NREL China activities, pilot projects and reports on the internet. A database is also being established which contains US companies that are interested in China markets. The business newsletters which are prepared by the Chinese Center for Renewable Energy Development will also be posted on the website and routed to the US companies in the database.

Status/Accomplishments: The website is currently being developed.

Planned FY 2000 Milestones: The website is anticipated to be completed by the end of 1999.

Major Reports Published in FY 1999: None.

PV Power Systems International Conference Support

Contract #: BE-8906	**Contract Period:** 1/12/99-12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Morse Associates, Inc. Washington, DC	
	Organization Type: IN	**Congressional District:** NA
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** Fred Morse **Phone:** 202-483-2393 **Fax:** 202-265-2248	
Technical Monitor: W.ard I. Bower **Phone**: 505-844-5206 **Fax**: 505-844-6541 **E:mail:** wibower@sandia.gov	**B&R Code**: EB22	**Cost Share Information**:
	DOE Funding Allocation: 1999: $55,000	**Cost Share Funding:**

Project Objective: Support, through Organizing Committee and U.S. industry, the Third International Executive Conference on PV Power Systems in Competitive Electricity Markets.

Approach/Background: Serve on international organizing committee and contact appropriate U.S. industry and utility personnel to participate, speak, and lead conference proceedings.

Status/Accomplishments: The organizing committee meetings resulted in conference agenda, speakers, and directions. Contact with U.S. industry resulted in participation by 45 top executives, decision-makers, and managers. A committee of government participation has been organized to provide input for a Government Perspectives report on "Policy Options to Encourage PV Markets" report.

FY 2000 Milestones:

- Government Perspectives report entitled "Policy Options to Encourage PV Markets"
- Industry policy report
- Meeting participation
- Minutes of the Executive Meeting

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PV for International Applications

PV International Market and Applications Development

Contract #: DE-AC36-98-GO10337	**Contract Period:** 10/1/98–9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
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E:mail: Richard.King@ee.doe.gov</td><td colspan="2">National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td></tr>
<tr><td>Organization Type: FF</td><td>Congressional District: 6</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator (s)
C. Hanley , D. Lew , P. Lilienthal , L. Roybal, B. Stafford, J. Stone**, R. Taylor , W. Wallace
Phone: **303-384-6470 Fax: **303-384-6481 E:mail: **jack_stone@nrel.gov</td></tr>
<tr><td rowspan="2">Technical Monitor:
Jack Stone
Phone: 303-384-6470
Fax: 303-384-6481
E:mail: Jack_Stone@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1997: $1,447,000
1998: $1,721,000
1999: $1,750,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The activities of the NREL and Sandia PV International activities will support the four EE/RE strategic goals for its international activities: 1) Address emerging global environmental and energy issues; 2) Promote trade and market development; 3) Promote energy and environmental security; and 4) Conduct cooperative research and development. The overarching strategic objective for the NREL and Sandia international activities will be to accelerate the establishment of self-sustaining EE/RE markets and businesses in developing and transition countries. Existing bilateral agreements and memorandums of understanding (MOUs) will continue to be supported. Activities will be broadly classified into policy, technology, and markets.

Approach/Background: International activities funded by the DOE PV Program will be aligned with the primary functions of the DOE PV Program to partner with industry and academia to foster an environment leading to profitable and sustainable markets. The NREL and Sandia activities will be carried out in countries in the developing world chosen for their government's commitment to renewable energy and the potential of a large market for U.S. industry. Activities will include, but not be limited to, providing technical assistance, demonstrating technical feasibility of new technologies, providing education and training to government and NGO personnel, developing test protocols which place American products on a leveled playing field with foreign companies, and business development including facilitating joint venture agreements between foreign and U.S. companies. Technical assistance will be used to leverage in-country program activities by providing support for the development and implementation of international projects. The credibility of the U.S. government, through MOUs developed at the highest levels of the governments, will be utilized to maintain a presence for the United States in these countries which can effectively counter the activities of the foreign competition which place U.S. companies at a disadvantage. High level policy benefits will be utilized to assist developing countries with clean development to encourage their cooperation with international environmental goals (climate change, emission trading) and other foreign policy initiatives that benefit from international support. Also, the U.S. is providing development assistance in numerous countries through AID, UNDP, World Bank and other funding agencies for which our technical assistance and training activities can make the efforts of those other agencies more effective.

Status/Accomplishments: Working with DOE and the U.S. State Department, justifications were presented to waive the sanctions imposed by the United States on India on the grounds that the Ramakrishna Mission Initiative was a humanitarian activity. The waiver was granted and NREL was instructed to restart the project in West Bengal.

Working with the U.S. based non-profit Project C.U.R.E., NREL approached a number of international funding sources to discuss installing PV energy systems to provide electricity for medical equipment at rural health clinics in communities where grid extension will not be feasible in the near future. NREL has been invited by the UNDP and the World Bank to make proposals for two programs to implement this approach in collaboration with indigenous NGOs in Uganda.

Through dialogue, demonstrations, and training with renewable energy companies, international organizations, and government officials from different countries, NREL is gaining valuable feedback on its village power models. NREL is discussing potential partnerships with a number of U.S. energy companies (consultants and project developers) to develop new uses and means of distributing the modeling program HOMER. NREL staff coordinated a meeting between Global Solar, a US PV manufacturer and R&D firm in Wheat Ridge, CO, and representatives of China's Ministry of Agriculture to discuss potential private sector joint ventures in China. The two parties agreed to continue their dialogue.

The China program had the following accomplishments during FY99:

- Inner Mongolia Hybrid Household Project – By the end of 1999, 125 US/Chinese household PV/wind systems will be installed in this pilot project between DOE/NREL and the Inner Mongolia New Energy Office. An additional 120 US/Chinese systems will be installed during 2000. As a result of this activity, local officials in Dongwu County have completed a feasibility study and plan for 4,000 hybrid systems to be installed over the next 5 years.
- Rural Electrification Survey and Analysis – In China, rural electrification surveys at the county level in ten counties in Xinjiang and Qinghai and the required provincial and national data has been collected and analyzed and the final report will be published in early 2000.
- Business Development Reports – Three renewable energy market and technology assessments have been prepared in partnership between the Center for Renewable Energy Development (CRED) and DOE/NREL for publishing in 1999/2000: *PV Business Application and Evaluation; Renewable Energy Markets In China: An Analysis of Renewable Energy Markets in Guangdong, Jiangxi, Jilin and Yunnan, with Updated Information from Beijing;* and *Commercialization of Solar PV Systems in China*.
- Business Development Workshops and study tours – CRED conducted a solar thermal business study tour to the US in 4/99, bringing Chinese companies and government representatives to meet with US companies and government representatives and to visit US solar thermal installations. A three-day workshop on Wind Energy Business Development and Policy Analysis was held in April 1999 to train Chinese officials and companies in business development for grid-connected wind power. As a follow-up to the 9/98 US/China Rural Electrification Workshop, a second US/China Renewable Energy Business Workshop and study tour was conducted by DOE/NREL with 13 US companies in China during early November 1999. This workshop and study tour was fruitful in assisting US companies with potential new customers, distributorships, and partnerships.

Planned FY 2000 Milestones: 1. Publish summary reports and fact sheets on different applications, 2. Semi-annual status report that includes a description of the latest version of the models and updated documentation and user list, 3. Issue report on operational status of PV systems in the Sundarbans region of India, 4. PV technology, status, applications training materials, 5. Linked Chinese-language and English-language websites which describe updated information on renewable energy news, markets, business opportunities, policies, and projects in China, 6. End-of-year report on status of Mexico financing of and training programs, 7. Implementation report on nationwide replication of FIRCO program in Mexico

Major Reports Published in FY 1999:

NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).

"Comparison of Renewable Energy Policies of China and the United States," Zhang Zhengmin, Li Jingjing, and Yih-huei Wan, 1999.

"Initial Results of Socio-Economic Assessment Surveys in IMAR: Qinghai and Xinjiang," University of Delaware , May 1999.

"Market Assessment Survey Instrument for Rural Renewable Energy Market Development in Western China," University of Delaware, January 1999.

"Rural Renewable Energy Analysis and Design Tool (RREAD): Details for the Windows Version," University of Delaware, July 1999.

Major Articles Published in FY 1999:

Stone, J., et al., "The Ramakrishna Mission Economic PV Development Initiative," *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion Proceedings; July 6-10, 1998, Vienna, Austria,* pp. 2962-2965 (1998).

Wallace, W., et al., "The Use of Photovoltaics for Rural Electrification in Northwestern China," *2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion Proceedings; July 6-10, 1998, Vienna, Austria,* pp. 2916-2920 (1998).

Ullal, H., "NRI Electrifies Rural West Bengal with Solar Power," The Himalayan News (Ed: Mohan Ashtakala), Denver, CO; October, 1999.

Stone, J., et al., "PV Electrification in India and China: The NREL's Experience in International Cooperation," Progress in Photovoltaics: Research and Applications, September-October (1998), pp. 341-356.

PV for International Applications

Mexico Support

Contract #: BB-4655	**Contract Period:** 12/5/97–12/4/98

<table>
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<tr><td>Organization Type: IN</td><td>Congressional District: 4</td></tr>
<tr><td>Directing Organization:
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Charles J. Hanley
Phone: 505-844-4435
Fax: 505-844-7786
E:mail: cjhanle@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None</td></tr>
<tr><td>DOE Funding Allocation:
1998: $10,000
1999: $0</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: Provide technical and strategic support to the Mexico Renewable Energy Program.

Approach/Background: Provides technical support for pilot renewable energy projects with partner organizations in Mexico.

Status/Accomplishments: Distributor training was concluded and contract was closed out with approval of contractor's final report.

FY 2000 Milestones: None. Contract ended.

Major Reports Published in FY 1999: None.

Major Articles Published in FY 1999: None.

PV for International Applications

Mexico Support

Contract #: DE-AC04-94AL85000	**Contract Period:** 10/1/98 – 9/30/99

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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<tr><td>Organization Type: FF</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
Sandia National Laboratories, Albuquerque
P.O. Box 5800, MS0753
Albuquerque, NM 87185-0753</td><td colspan="2">Principal Investigator(s)
Charles Hanley
Phone: 505-844-4435 Fax: 505-844-7786</td></tr>
<tr><td rowspan="2">Technical Monitor:
Christopher P. Cameron
Phone: (505) 845-8161
Fax: (505) 844-6541
E:mail: cpcamer@sandia.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:</td></tr>
<tr><td>DOE Funding Allocation:
1999: $210,000</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The objective is to accelerate the acceptance of commercially viable renewable energy technologies for off-grid productive use applications in Mexico. This work is done in partnership with U.S. and Mexican industry, and the goal is the establishment of sustainable and growing new markets for renewable energy technologies.

Approach/Background: The program is implemented through the development of partnerships with in-country institutions who have ongoing and funded activities wherein renewable technologies can help them to achieve their goals. Examples include rural development and conservation organizations. Through the provision of technical assistance, training, and the implementation of pilot projects, the Sandia team works with these partners—and suppliers of systems—to help them build the institutional capacity to implement renewable energy projects.

Status/Accomplishments: The program is in its "replication and institutionalization' phase, wherein technical assistance is being provided to assure the widespread application of renewable technologies. This is being achieved through the development of innovative programs with the World Bank and the Global Environment Facility, and through helping partner organizations to include the appropriate use of renewable energy technologies in their strategic plans. It is projected that in the next five years, direct investment of $20 - $40 million will be made in renewable energy systems as a direct result of this program.

FY 2000 Milestones:

- End-of-year report on status of Mexico financing and training programs
- Implementation report on nationwide replication of FIRCO program in Mexico

Major Reports Published in FY 1999:

- Hanley, Charles. "The Renewable Energy Program in Mexico," Quarterly Highlights of Sandia's Photovoltaics Program, Volume 4, 1998.

Major Articles Published in FY 1999:

- Richards, Elizabeth, Charles Hanley, et al. "Photovoltaics in Mexico: A Model for Increasing the Use of Renewable Energy Systems," Advances in Solar Energy, American Solar Energy Society, 1999.

PV for International Applications

SWRES Mexico Support

Contract #: AT-7335	**Contract Period:** 6/4/96–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Southwest Technology Development Institute (SWTDI) Las Cruces, NM 88003-0001	
	Organization Type: CU	**Congressional District:** 2
Directing Organization: Sandia National Laboratories, Albuquerque P.O. Box 5800, MS0753 Albuquerque, NM 87185-0753	**Principal Investigator(s)** R. Foster **Phone:** 505-646-3948 **Fax:** 505-646-3841	
Technical Monitor: Charles J. Hanley **Phone:** 505-844-4435 **Fax:** 505-844-7786 **E:mail:** cjhanle@sandia.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1998: $250,000 1999: $250,000	**Cost Share Funding:**

Project Objective: Provide technical and strategic support to the Mexico Renewable Energy Program.

Approach/Background: Provides technical support for pilot renewable energy projects with partner organizations in Mexico.

Status/Accomplishments: Supported program milestones: pilot installations in 12 Mexican states (50% increase in states); reported on programmatic impacts; continued maintenance of database and web page.

FY 2000 Milestones:
- Support to nationwide replication with FIRCO
- Production of CD ROM training guide

Major Reports Published in FY 1999:
- Foster, R. E., G. Cisneros, C. Hanley, "Mexican Renewable Energy Development: Creating New Markets," Proceeding of Sustainable Applications for Tropical Island States (SATIS) '99, Caribbean Solar Energy Society, San Juan, Puerto Rico, August 25-27, 1999, p. 221-227.

- Foster, R. E., R. C. Orozco, A. Romero, "Lessons Learned from the Xcalak Village Hybrid System: A Seven Year Retrospective," ISES 1999 Solar World Conference Proceedings, International Solar Energy Society, Israel Ministry of Science, Jerusalem, Israel, July 4-9, 1999.

Major Articles Published in FY 1999:
- Foster, R. E., G. Cisneros, "Final Project Report: Energy Conservation to Complement the Village Hybrid System of Xcalak, Quintana Roo, Mexico," North American Fund for Environmental Cooperation, Montreal, Canada, July, 1999.

- Foster, R. E., G. Cisneros, A. Cota, "FIRCO Morelos Workshop: Photovoltaic Water Pumping Systems," Development Associates, Inc., USAID, Washington, D. C., July, 1999.

- Cisneros, G., R. E. Foster, A. Cota, "Train the FIRCO Trainers: Applications and Program Development of PV Systems," Development Associates, Inc., USAID, Washington, D. C., June, 1999.

- Romero, A., R. Foster, A. Sánchez, Bombeo de Agua con Sistemas Fotovoltaicos [PV Water Pumping Systems], XXIII Semana Nacional de Energía Solar, ANES, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoachan, Mexico, October 4-8, 1999.

- Guía para el Desarrollo de Proyectos de Bombeo de Agua con Energía Renovable [Renewable Energy Water Pumping Guide], Sandia National Laboratories, New Mexico State University, Las Cruces, New Mexico, February, 1999.

Evaluation of Intermediate Applications for Photovoltaics in the United States and Developing Countries

Contract#: XCU-7-16806-01	**Contract Period:** 6/1/97–9/30/00

<table>
<tr><td>Sponsoring Office Code: EE-13</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King
Phone: 202-586-1693
Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov</td><td colspan="2">University of Delaware
Center for Energy and Environmental Policy
Newark, DE 19716</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401</td><td colspan="2">Principal Investigator(s)
J. Byrne
Phone: 301-831-8405 Fax: 302-831-3098</td></tr>
<tr><td rowspan="2">Technical Monitor:
Debra Lew
Phone: 303/384-7522
Fax: 303/384-7419
E:mail: Debra_Lew@nrel.gov</td><td>B&R Code: EB22</td><td>Cost Share Information:
None.</td></tr>
<tr><td>DOE Funding Allocation:
1996: $125,000
1998: $ 22,575
1999: $ 47,908</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: The project focus is to complete the rural electrification survey and analysis project in China.

Approach/Background: In FY 1999, the subcontractor collaborated with the Chinese Ministry of Agriculture (MOA) and the Chinese Ministry of Sciences to collect data and perform analyses from a technical and socio-economic survey of several counties in Inner Mongolia, Xinjiang, and Qinghai provinces in China. Analyses consisted of evaluating rural electrification options and performing market characterizations for the northwestern region of China. MOA also visited the University of Delaware for training in analysis techniques and conducted some analysis of the survey data during this visit.

Status/Accomplishments: Data templates were prepared by the University of Delaware for data collection in 20 counties in three provinces in northwestern China under the supervision of the Ministry of Agriculture and the Chinese Academy of Sciences in China. The information was transmitted in Excel spreadsheet format to University of Delaware for analysis. A stage two data collection process to fill gaps in the first data set was conducted; analysis will be complete at the end of 1999 with a report in January 2000.

Planned FY 2000 Milestones: The results of the rural electrification survey and analysis will be published in early 2000.

Major Reports Published in FY 1999:
"Initial Results of Socio-Economic Assessment Surveys in IMAR," Qinghai and Xinjiang, May 1999.

"Market Assessment Survey Instrument for Rural Renewable Energy Market Development in Western China," January 1999.

"Rural Renewable Energy Analysis and Design Tool (RREAD): Details for the Windows Version," July 1999.

Major Articles Published in FY 1999:
"Renewable Energy Options for Addressing Rural needs: The Case of Western China," John Byrne and Bo Shen, draft, 1999.

"Opportunities and Challenges for China's Power Sector," John Byrne, Bo Shen and Jihong Zhao, draft, 1999.

Outreach and Program Management

Solar Energy Information Materials - Million Solar Roofs Initiative

Contract #: DE-FG01-99EE10705	**Contract Period:** 9/29/99–9/28/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King / Lynne Gillette
Phone: 202-586-1693 / Phone: 202-586-1495
Fax: 202-586-8148 / Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Lynne.Gillette@ee.hq.gov</td><td colspan="2">American Solar Energy Society (ASES)
2400 Central Avenue, Suite G-1
Boulder, CO 80301</td></tr>
<tr><td>Organization Type: NP</td><td>Congressional District: 2</td></tr>
<tr><td>Directing Organization:
DOE Office of Solar Energy Technology
1000 Independence Ave., SW
Washington, DC 20585</td><td colspan="2">Principal Investigator
Larry Sherwood
Phone: 303-443-3130 Fax: 303-443-3212 Email: LSherwood@ases.org</td></tr>
<tr><td rowspan="2">Technical Monitor:
Lynne Gillette
Phone: 202-586-1495
Fax: 202-586-8148
Email: Lynne.Gillette@ee.hq.gov</td><td>B&R Code: EB2202</td><td>Cost Share Information: None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $ 96,305</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This project was initiated as part of the Million Solar Roofs Initiative and aimed at providing Million Solar Roofs Partnerships and others with high quality, consistent solar energy information materials.

Approach/Background: The American Solar Energy Society (ASES) and the North Carolina Solar Center (NCSC) will jointly research and report on existing solar information materials and then develop a series of print and web-based brochures for different solar technology applications.

Status/Accomplishments: Project is just getting underway. (11/99)

Planned FY 2000 Milestones:

Report on existing Solar public information	3/00
Seven print brochures	9/00
Seven Web interactive brochures	9/00

Major Reports Published in FY 1999:
None

Major Articles Published in FY 1999:
None

Photovoltaics for You (PV4You)

Contract #: DE-FG01-99EE35084	Contract Period: 7/09/99–7/08/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Lynne Gillette — **Phone:** 202-586-1495 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Lynne.Gillette@ee.hq.gov	Interstate Renewable Energy Council P.O. Box 1156 Latham, NY 12110	
	Organization Type: NP	**Congressional District:** 21
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** J. Weissman **Phone:** 617-323-7377 **Fax:** 617-325-6738 **Email:** WeissmanPV@aol.com	
Technical Monitor: Lynne Gillette **Phone**: 202-586-1495 **Fax**: 202-586-8148 **Email**: Lynne.Gillette@ee.hq.gov	**B&R Code**: EB22	**Cost Share Information**: None
	DOE Funding Allocation: 1999: $600,000	**Cost Share Funding:**

Project Objective: To develop and distribute information on PV and to educate key stakeholder groups including state government agencies, local government offices, consumer representative agencies, school officials and students. PV4You brings stakeholders together to build awareness and understanding; identifies barriers to the deployment of photovoltaics and strategies to overcome them; and provides assistance leading to accelerated adoption of off-grid and grid-connected PV.

Approach/Background: This project consists of six core actions. 1) Ongoing support and assistance for the PV4You State working groups and network. 2) PV4You Outreach to Cities Project encourages incorporation of PV into city programs for affordable housing, job training, and the environment. 3) The PV4You National Consumer Project provides assistance and information to on PV to consumer agencies. 4) The PV4You Solar Schools Project is to educate teachers, students, and school officials about solar energy. 5) The PV4You National Public Education Project is aimed at keeping PV4You stakeholder network well informed give them the tools to increase awareness of PV among public and private decision makers. 6) The PV4You Project on PV Interconnection to the Grid provides general and technical information on interconnection issues to key stakeholders.

Status/Accomplishments: Fourteen states, twelve cities, and sixteen state consumer representative offices are actively involved in PV4You Projects. Many other agencies, cities, and states have a connection to the PV4You projects and other IREC programs.

Planned FY 2000 Milestones:
- Going Solar Model Public Education Kit (a collection of brochures, fact sheets, etc. to serve as models for community education as well as a number of new & updated visual and audio tools - release date is December 99)
- B-Roll Tape (Video) on Community Installations (this will be part of the Going Solar Kit)
- Annual meeting (June 2000)
- Two workshops on interconnection issues (1 was held in Virginia; the next one is planned for June in Madison, WI)
- Two workshops on community PV projects (Spring 2000 in Columbus, Ohio and in New Jersey)
- Presentations at major solar, teacher, city, state and other conferences Video on Community Installations

Major Reports Published in FY 1999:
PV4U Connections Newsletter (biannually).
Web-based PV4U Connections Clearinghouse and Bibliography Services (annually).
Connecting PV to the Utility Grid. 2nd Edition
Three monthly electronic newsletters on state/local information, interconnection issues, and schools
Consumer Letter - 6/year

Major Articles Published in FY 1999: None.

Outreach

Photovoltaics for Utilities (PV4U)

Contract #: FG41-94R110638	**Contract Period:** 4/20/94–4/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Interstate Renewable Energy Council P.O. Box 1156 Latham, NY 12110	
	Organization Type: NP	**Congressional District**: 21
Directing Organization: Department of Energy, Boston Support Office One Congress Street Boston, MA 02144	**Principal Investigator (s)** J. Weissman **Phone:** 617-323-7377 **Fax:** 617-325-6738	
Technical Monitor: R. Michaud **Phone**: 617-565-9713 **Fax**: 617-565-9723	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1994: \$400,000 1997: \$600,000 1995: \$400,000 1998: \$600,000 1996: \$600,000	**Cost Share Funding:**

Project Objective: Organize and support state level associations to promote utility connected photovoltaic applications, and to supply those state associations with information in order to accelerate the commercialization of photovoltaics through the utility sector.

Approach/Background: The Interstate Renewable Energy Council (IREC) works to accelerate the sustainable utilization of renewable energy sources and technologies in and through state and local government activities. The Photovoltaics for Utilities Program represents an alliance of states that have established collaborative forums to accelerate the commercialization of photovoltaics. PV4U State Working Groups identify regulatory, policy, and institutional barriers to PV deployment and develop strategies to overcome these hurdles.

Status/Accomplishments: Fourteen states have active PV4U Working Groups where representatives from regulatory commissions, utility companies, the solar industry state and federal government agencies, consumer groups, and advocacy organizations, meet to work on policy and market barriers. Three states are part of the PV4U Alliance but have been less active due to the closing of an energy office and changes in leadership.

Planned FY 2000 Milestones: None, project has ended.

Major Reports Published in FY 1999:
PV4U Connections Newsletter (biannually).
PV4U Connections Clearinghouse and Bibliography Services (1 edition)
Connecting PV to the Utility Grid - 2nd edition.
PV4U Consumer Letter (about every other month).
Going Solar Public Education - Updated Kit
Communities Going Solar Workshops (Hawaii, Boston, Long Island)
Interconnection Workshops (Colorado, Portland, North Carolina, etc.)
Going Solar Background Reading Document (companion piece for workshops)
Presentations at major state and national conferences

Major Articles Published in FY 1999:
Numerous papers published in the Solar 99 Conference Proceedings.

Photovoltaics Program Technical Support

Contract#: AXE-9-29605-01	**Contract Period:** 4/12/99 to 1/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Jeffrey Mazer **Phone:** 202-586-2455 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Jeffrey.Mazer@ee.doe.gov	McNeil Technologies, Inc. 6564 Loisdale Ct., S-800 Springfield, VA 22150	
	Organization Type: IN	**Congressional District:** 8
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** K. DeGroat **Phone:** 703-921-1632 **Fax:** 703-921-1610 **E:mail**: kdegroat@mcneiltech.com	
Technical Monitor: Robert McConnell **Phone:** 303-384-6419 **Fax:** 303-384-6481 **E:mail:** robert_mcconnell@nrel.gov	**B&R Code:** EB22	**Cost Share Information:** None.
	DOE Funding Allocation: 1999: $139,851	**Cost Share Funding:**

Project Objective: Task 1: Gather information from the U.S. Department of Energy (DOE) Office of Science (OS) to compile a list of PV-related projects in fundamental and exploratory research that are supported by OS at NREL, other national laboratories, and universities. The compilation shall contain abstracts of each project, principal investigator contact information, contract duration, and funding amounts.

Task 2: Compare development and manufacturing issues for concentrator and flat-plate technologies. Manufacturing analyses shall include processes, plant and equipment investment issues developed from experience in the PVMaT program.

Task 3: Work with NREL and DOE staff to support the PV technology road map and five-year program plan activities, including preparation of schedules, outlines, and drafts, including arrangements for workshops and other means for obtaining various stakeholder inputs and reviews.

Task 4: Subcontractor shall survey the United States PV industry to identify how much of their product in 1998 was sold for grid-connected applications in the US, remote systems in the US, consumer products, and overseas remote systems. Estimate the cumulative totals from the 1970s to today for each of these markets. Then evaluate and compare contrasting projections of future PV installed capacity completed recently by the Energy Information Administration, Royal Shell, and others. Recommend an analytical framework for estimates of future installed MWs, kWhrs produced, tons of carbon avoided, BTUs avoided, market sizes, etc., to more accurately quantify the value of photovoltaics in future energy scenarios that include other energy sources.

Background: These four tasks address program planning, data and analysis needs for the PV program. The first task is designed to characterize related basic research outside the program that may help improve sharing of scientific information and collaboration in key areas. Task 2 will update information on concentrator manufacturing and development issues which are of increased interest because of continuing advances in high-efficiency PV technology. The third task involved McNeil in assisting NREL in developing the PV 5 Year Plan and inputs to the industry road map, which had to be completed in time for a 1/1/2000 publication date. The fourth task expands on current collection of industry data and projections to try and resolve some of the lingering inconsistencies between data sets and explore the methods and assumptions behind different sources of information needed for program planning.

Accomplishments: McNeil Technologies completed a report and database on Office of Science research projects relevant to the PV program. It is available to NREL personnel and other researchers interested in finding out about research projects funded by the Office of Science. Over 80 projects representing over $20 million in research projects with some relevance to PV development were found, categorized by the type of research: basic, directed basic, specific basic, materials/processes, applied, technology applications, or education testing. The data is easily sorted by performing organization and principal investigator to highlight centers of research activity and key contacts.

Contract#: AXE-9-29605-01

For the 5-Year Plan McNeil gathered photos from industry sources, obtained release forms to allow their use in the final publication, and explanations of the content. Sources included the HBCUs, individual manufacturers and installers, and university partners. Photos not used in the 5-Year Plan may be used for future publication projects, with proper releases. McNeil worked with James Rannels to develop his Director's message, and reviewed late versions of the final plan. For the roadmapping exercise McNeil Technologies reviewed different growth projections developed by NREL with industry input, critiqued the assumptions used to develop them, and compared the projections to other sources. The inputs eventually became part of the industry roadmap projections through NREL.

For Task 4 McNeil submitted a first-draft review of data sources and projections to NREL, which will be updated and melded with survey data to produce a final report. An internet data form and companion mailings were developed to gather industry input on key markets domestically and overseas. McNeil reviewed EIA data and assumptions for their Annual Energy Outlook projections of solar energy use, forwarding the results to NREL and PV program staff for use in their discussions with EIA on improving their forecasting model for PV.

Planned FY2000 Milestones: In FY2000 McNeil will complete its analysis of concentrator manufacturing issues and submit a report on key issues to NREL. McNeil's gathering of industry data and analysis of key metrics and forecasts will also be completed and submitted to NREL. No further work is anticipated on the Office of Science Task. For Task 3 McNeil will be returning original photos and materials as appropriate to companies and organizations that offered them for use in the five year plan.

Major Reports Published in FY 1999:
None.

PV Program Information Dissemination to Enhance PV's Commercial Potential

Contract #: DE-FG01-99EE35083	**Contract Period:** 5/12/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King — **Phone:** 202-586-1693 — **Fax:** 202-586-8148 Lynne Gillette — **Phone:** 202-586-1495 — **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Lynne.Gillette@ee.hq.gov	National Association of Regulatory Utility Commissioners 1100 Pennsylvania Ave. NW STE 603 Washington, DC 20004	
	Organization Type: NP	**Congressional District**: NA
Directing Organization: Department of Energy, Boston Support Office One Congress Street Boston, MA 02144	**Principal Investigator (s)** John Emmitte **Phone:** 202-898-2217 **Fax:** 202-898-2213 **Email:** jemmitte@naruc.org	
Technical Monitor: R. Michaud **Phone**: 617-565-9713 **Fax**: 617-565-9723	**B&R Code**: EB2202	**Cost Share Information**: None.
	DOE Funding Allocation: 1999: $ 50,000	**Cost Share Funding:**

Project Objective: To develop and distribute information that will enhance PV's commercial potential.

Approach/Background: This project includes several activities that will assist state public utility regulators as they work with other stakeholders in a photovoltaics collaborative. It will facilitate participation of state regulators in PV Compact meetings, facilitate work on interconnection regulation issues, and enable dissemination of information from PV compact and interconnection work to state regulators nationwide.

Status/Accomplishments: Three commissioners participated in the October 1999 PV Compact Coordination Council meeting.

Planned FY 2000 Milestones:
- Report to NARUC Committee on Energy Resources and Environment.
- Annual Report for Regulators with summary of PV compact activities and recommendations for regulatory actions to enhance the development of PV resources.

Major Reports Published in FY 1999:
None

Major Articles Published in FY 1999:
None.

NREL PV Program Management

Contract#: DE-AC36-99GO10337	**Contract Period:** 10/01/98 - 09/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	National Renewable Energy Laboratory 1617 Cole Boulevard Golden, CO 80401	
	Organization Type: FF	**Congressional District:** 6
Directing Organization: National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Lawrence L. Kazmerski , Thomas Surek **Phone:** 303-384-6600, 303-384- 6471 **Fax:** 303-384-6481 **E-mail:** kaz@nrel.gov, tom_surek@nrel.gov	
Technical Monitor: N/A	**B&R Code:** EB22	**Cost Share Information:**
	DOE Funding Allocation: 1998: $1,761,000 1999: $2,215,000	**Cost Share Funding:**

Project Objective: The objectives are to provide the program management, analysis, coordination, integration, and reporting necessary to conduct an efficient and effective DOE PV Program. The objectives include management support to coordinate and integrate the activities of NREL in-house and subcontracted research activities. This project also ensures that in-house PV facilities are maintained as resources for, and open to, the U.S. PV research and development community. The objective of the National Center for Photovoltaics (NCPV), headquartered at NREL, is to serve as a focal point for the Program, to strengthen communications, and further unify national PV interests.

Approach/Background: The NCPV provides overall coordination of the DOE PV Program's Annual Operating Plan at the request of DOE. NREL and Sandia National Laboratories (SNL), partners in the NCPV, provide the management oversight for the respective projects in their laboratories, as well as management support for the NCPV. This project consists of program management, analysis, administration, budget control, reporting, and integration, as well as staff, equipment and facilities oversight to provide the foundation for consistent program progress. The management and operation of the NCPV are also supported by this project. Staff members respond to new research developments, changing resource requirements and availability, and to overall PV program needs, including environmental safety and health (ES&H). The project also supports communications activities such as developing and maintaining the DOE/NCPV/ NREL/SNL web sites, periodic news releases, and various program overviews and brochures. Major activities in FY 1999 included facilitating development of a PV Technology Roadmap by industry and developing the next 5-year plan for the DOE PV Program for publication in FY 2000.

Status/Accomplishments:
- Led the development of a new 5-year plan for the DOE PV Program for the period FY 2000 - FY 2004.
- Facilitated a U.S. Photovoltaics Industry PV Technology Roadmapping Workshop.
- Participated in an audit by the General Accounting Office of peer review processes used by the program.
- Published four issues of *NREL PV Working with Industry*, a quarterly report distributed to more than 1200 members in the PV community.

Planned FY 2000 Milestones:
- Publish new 5-year plan for DOE PV Program (January 1, 2000).
- Facilitate completion of a PV Technology Roadmap by the U. S. PV industry.

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).
Photovoltaic Energy Program Contract Summary, Fiscal Year 1998, DOE/GO-10099-721 (January 1999).
Photovoltaic Energy Program Overview, Fiscal Year 1998, DOE/GO-10099-737 (March 1999).

Major Articles Published in FY 1999: None.

Removing CC&R Barriers to Residential and Commercial Solar Energy

Contract #: DE-FG01-99EE10704	**Contract Period:** 9/15/99–9/14/00

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
<tr><td rowspan="2">DOE HQ Program Manager:
Richard King Lynne Gillette
Phone: 202-586-1693 Phone: 202-586-1495
Fax: 202-586-8148 Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
E:mail: Lynne.Gillette@ee.hq.gov</td><td colspan="2">Pace University School of Law
78 North Broadway
White Plains, NY 10603</td></tr>
<tr><td>Organization Type: CU</td><td>Congressional District: 19</td></tr>
<tr><td>Directing Organization:
DOE Office of Solar Energy Technology
1000 Independence Ave., SW
Washington, DC 20585</td><td colspan="2">Principal Investigator (s)
Fred Zalcman
Phone: 914-422-4082 Email: fzalcman@law.pace.edu</td></tr>
<tr><td rowspan="2">Technical Monitor:
Lynne Gillette
Phone: 202-586-1495
Fax: 202-586-8148
Email: Lynne.Gillette@ee.hq.gov</td><td>B&R Code: EB2202</td><td>Cost Share Information:
Pace University School of Law</td></tr>
<tr><td>DOE Funding Allocation:
1999: $ 88,470</td><td>Cost Share Funding:
1999: $ 14,280</td></tr>
</table>

Project Objective: This project was initiated as part of the Million Solar Roofs Initiative and aimed at removing barriers to building-related solar energy use. The specific objective are to:

- Improve understanding of codes covenants and restriction and how they may adversely impact solar installations.
- Provide a legal and conceptual framework for recognizing legitimate local aesthetic and economic interests without unduly restricting solar installations.
- Offer practical advice to homeowners and businesses on navigating the design approval process.
- Assess the effectiveness of existing laws intended to restrict the preclusive effect of codes covenants and restrictions.

Approach/Background: The Pace University project team's goal is to educate and influence the many parties interested in or affected by local codes covenants and restriction. They will develop a handbook and a model workshop. They will demonstrate these resources at a series of at least four workshops in communities that have strong barriers to solar energy.

Status/Accomplishments: Project is just getting underway. (10/99)

Planned FY 2000 Milestones:
Handbook completed.
Model workshop completed.
Four workshops presented.

Major Reports Published in FY 1999:
None

Major Articles Published in FY 1999:
None

Outreach

Renewable Energy Technology Analysis (RETA)

Contract #: FG4194R110639	**Contract Period:** 5/1/94–12/31/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov	Pace University Law School 78 North Broadway White Plains, NY 10603-3710	
	Organization Type: CU	**Congressional District**: 19
Directing Organization: Department of Energy, Boston Support Office One Congress Street Boston, MA 02144	**Principal Investigator (s)** Sam Swanson **Phone:** 802/ 652-0056 **Fax:** 802/ 658-0563	
Technical Monitor: R. Michaud **Phone**: 617-565-9713 **Fax**: 617-565-9723	**B&R Code**: EB22	**Cost Share Information**: None.
	DOE Funding Allocation: 1994: $180,000 1995: $200,000 1998: $200,000	**Cost Share Funding:**

Project Objective: Support consideration of advancing utility investments in Photovoltaics by providing information, education, and training to public interest groups, including environmental and community-based consumer proponents.

Approach/Background: Coordinate with the Photovoltaics Compact Coordination Council in order to encourage and support public interest group participation in State Working Group Collaboratives and utility PV installation projects such as TEAM-UP. It also involves coordination with the PVEP Project that is being conducted out of NARUC. This was an unsolicited proposal, DOE No. P9400002C. The proposal was paneled in Boston, recommended for funding, and the Justification for Acceptance of an Unsolicited Proposal was originated and signed by the Program Officer in Boston, Counsel and a Contract Officer in Boston, and forwarded and signed in Washington by the DOE Assistant Secretary, EE, during March and April, 1994.

Status/Accomplishments: Provided information, education, and training to public interest groups in several key states identified by PV Compact Coordination Council, including environmental and community-based consumer proponents, regarding the cost effectiveness of utility investments in photovoltaics. Contributions included assistance to environmental groups in Arizona on the implementation of the solar portfolio standard proposed by the state utility regulatory commission, assistance in Florida with developing criteria for effective “green pricing programs” to finance utility investments in PV, assistance to public interest groups in New York State on implementing effective environmental disclosure programs, net metering policies mandated by the state legislature, and assistance to PV stakeholders on organizing PV stakeholder education. The project also initiated efforts to develop the Power *Scorecard* electricity product rating program by partnering with six large environmental organizations. The Power Scorecard program will be carried on by the Pace Renewable Energy Technology Analysis Project grant awarded in June 1999. During the life of the grant the project partnered with the PV4You and UPVG initiatives to sustain collaborative efforts to overcome PV market barriers.

Planned FY 2000 Milestones: None. Contract is completed.

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None.

Outreach

Renewable Energy Technology Analysis (RETA)

Contract #: DE-FG01-99EE35085	**Contract Period:** 6/09/99–6/08/03

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Lynne.Gillette@ee.hq.gov	Pace University Law School 78 North Broadway White Plains, NY 10603-3710	
	Organization Type: CU	**Congressional District**: 19
Directing Organization: Department of Energy, Boston Support Office One Congress Street Boston, MA 02144	**Principal Investigator (s)** S. Swanson **Phone:** 518-266-1245 **Fax:** 518-283-5008 **Email:** Samswanson@aol.com	
Technical Monitor: Lynne Gillette **Phone**: 202-586-1495 **Fax**: 202-586-8148 **Email**: Lynne.Gillette@ee.hq.gov	**B&R Code**: EB22	**Cost Share Information**: Pace Univ. School of Law
	DOE Funding Allocation: 1999: $199,970	**Cost Share Funding:** 1999: $117,372

Project Objective: In coordination with other groups working on PV outreach, Pace University will provide objective information aimed at converting consumer preferences for "green" electricity into actual purchases of PV.

Approach/Background: Pace University will develop the web-based analysis tool "Power Scorecard." The scores for power providers will give consumers information about the environmental impacts of their choice of power producers. They will also continue to provide technical support to a variety of stakeholders through the PV Clearinghouse. The information from both these components will be a cornerstone of a consumer information campaign to advance investments in Solar and other clean renewable power sources.

Status/Accomplishments: Provided information, education, and training to public interest groups, including environmental and community-based consumer proponents, regarding the cost effectiveness of utility investments in photovoltaics

Planned FY 2000 Milestones: The power scorecard will be completed for Pennsylvania and California.

Major Reports Published in FY 1999:

Major Articles Published in FY 1999:

Outreach

Solar Energy Finance - Million Solar Roofs Initiative

Contract #: DE-FG01-99EE10707	**Contract Period:** 10/01/99–1/31/01

<table>
<tr><td>Sponsoring Office Code: EE-11</td><td colspan="2">Performing Organization(s)</td></tr>
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Fax: 202-586-8148 Fax: 202-586-8148
E:mail: Richard.King@ee.doe.gov
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Willitis, CA 95490</td></tr>
<tr><td>Organization Type: NP</td><td>Congressional District: 1</td></tr>
<tr><td>Directing Organization:
DOE Office of Solar Energy Technology
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Email: Lynne.Gillette@ee.hq.gov</td><td>B&R Code: EB2202</td><td>Cost Share Information:
Renewable Energy Development Institute</td></tr>
<tr><td>DOE Funding Allocation:
1999: $ 48,000</td><td>Cost Share Funding:
1999: $ 15,000</td></tr>
</table>

Project Objective: This project was initiated as part of the Million Solar Roofs (MSR) Initiative and aimed at providing MSR Partnerships and with the necessary tools for education on financing solar energy projects.

Approach/Background: The Renewable Energy Development Institute (REDI) will produce a Solar Energy Finance handbook that will include information on existing programs, case studies of various financing approaches for a diverse audience. They will also produce a "how-to-finance" booklet specifically for residential consumers. They will be developing model solar financing workshops and conducting four of these workshops in MSR partnership areas across the country.

Status/Accomplishments: Project is just getting underway. (11/99)

Planned FY 2000 Milestones:
Solar energy finance handbook published (hardcopy and electronic)
Model workshop developed

Major Reports Published in FY 1999:
None

Major Articles Published in FY 1999:
None

Sandia PV Program Management

Contract #: DE-AC04-94AL85000	Contract Period: 10/01/98 - 09/30/99

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 **E-mail**: Richard.King@ee.doe.gov	Sandia National Laboratories P. O. Box 5800 Albuquerque, NM 87185-0753	
	Organization Type: FF	**Congressional District:** 1
Directing Organization: Sandia National Laboratories P. O. Box 5800 Albuquerque, NM 87185	**Principal Investigator(s)** Chris Cameron, James Gee **Phone:** 505-844-8161, 505-844-7812 **Fax:** 505-844-6541 **E-mail:**cpcamer@sandia.gov, jmgee@sandia.gov	
Technical Monitor: N/A	**B&R Code:** EB22	**Cost Share Information:**
	DOE Funding Allocation: 1998: $400,000 1999: $440,000	**Cost Share Funding:**

Project Objective: The objectives are to provide the program management, analysis, coordination, integration, and reporting necessary to conduct an efficient and effective DOE PV Program. The objectives include management support to coordinate and integrate the activities of Sandia in-house and subcontracted research activities. This project also ensures that in-house PV facilities are maintained as resources for, and open to, the U.S. PV research and development community. The objective of the National Center for Photovoltaics (NCPV), in which Sandia is a partner, is to serve as a focal point for the Program, to strengthen communications, and further unify national PV interests.

Approach/Background: Sandia participates in the NCPV, which provides overall coordination of the DOE PV Program's Annual Operating Plan at the request of DOE. Sandia and NREL (NCPV partners) provide the management oversight for the respective projects in their laboratories, as well as management support for the NCPV. This project consists of program management, analysis, administration, budget control, reporting, and integration, as well as staff, equipment and facilities oversight to provide the foundation for consistent program progress. The management and operation of the NCPV are also supported by this project. Staff members respond to new research developments, changing resource requirements and availability, and to overall PV program needs, including environmental safety and health (ES&H). The project also supports communications activities such as developing and maintaining the Sandia PV web site, periodic releases of interest to the PV industry, publication of technical and general interest documents about the program, and developing various program overviews and brochures. A major activity in FY 1999 included facilitating development of a PV Technology Roadmap by industry.

Status/Accomplishments:
- Led the development of a U.S. PV Industry Technology Roadmapping Workshop
- Participated in development of the FY98 DOE Annual Program Review
- Participated in the development of a new 5-year plan for the DOE PV Program for the period FY 2000 - FY 2004.
- Performed a DOE-mandated programmatic self-assessment
- Maintained a Sandia photovoltaics website that averages about 100,000 hits per month
- Published four issues of *Sandia's Quarterly PV Program Highlights*, distributed to approximately 2500 members of the PV community.

Planned FY 2000 Milestones:
- Participate in development of a new 5-year plan for DOE PV Program (January 1, 2000).
- Facilitate completion of a PV Technology Roadmap by the U. S. PV industry.

Major Reports Published in FY 1999:
NCPV FY 1998 Annual Report, NREL/BK-210-25626, (June 1999).
Photovoltaic Energy Program Contract Summary, Fiscal Year 1998, DOE/GO-10099-721 (January 1999).
Photovoltaic Energy Program Overview, Fiscal Year 1998, DOE/GO-10099-737 (March 1999).

Major Articles Published in FY 1999: None

PV Program Management

Photovoltaics Program Technical Support

Contract #: AXE-9-29605-02	**Contract Period:** 5/4/99–11/30/99

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<tr><td>Directing Organization:
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None.</td></tr>
<tr><td>DOE Funding Allocation:
1999: $73,415</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: (Sentech) The purpose of this study was to examine current battery and heat engine applications to assess the market potential for photovoltaics to supplant the existing power source or to provide complementary power. This study was intended to be a broad look at applications, although in-depth market analysis on each of the applications was not in the scope of the project. (PERI) The study was designed to begin to advance the DOE/EPRI *Renewable Energy Technology Characterizations* to a regional level where specific technology characteristics and market circumstances can be analyzed more fully. This study provides additional perspective on the progress required to enhance the future market prospects of flat plate and concentrator PV technology.

Approach/Background: (Sentech) The teams approach included:
- Gathering performance and market data on battery and engine powered applications from trade associations, web sites, literature, manufacturers, private data collection firms, and personal contacts.
- Assembling an analytical grid containing the power needs and physical properties of each application.
- Defining figures of merit that could be used to evaluate the suitability for photovoltaics.
- Selecting the most promising and conducting further analysis.
- Summarizing the resultant opportunities for subsequent review by DOE and the PV industry.

(PERI) The approach taken was:
- *Regional Resource Characterization:* Site-specific insolation data was obtained from the NREL Solar Radiation Manual. Regional population distribution data was used to develop average regional resource adjustment factors.
- *Regional Demand and Wholesale Prices:* Energy Information Administration data was used to project electricity demand growth for each of the thirteen regions examined for the study. Wholesale competitive market prices for electricity were developed for each region from several sources.
- *Regional Technology Characterizations:* Regional capacity factor adjustments were applied to the *Renewable Technology Characterizations* projections to obtain the regional cost of electricity figures over time.

Market Penetration: A logit function-based market allocation model was used to estimate relative market shares of flat plate and concentrator technology for each region of the analysis. The same model was then used to compare COE projections for the two photovoltaic technologies to the regional wholesale electricity price and to allocate the electricity demand growth for each region. This analysis produced an estimate for market penetration for the two photovoltaic technologies.

Status/Accomplishments: (Sentech) A draft of the document Exploratory Studies of Opportunities for Photovoltaics Market Growth was prepared and submitted to NREL for review and comment.
(PERI) A draft of the document Comparative Analysis of Concentrating and Flat-Plate Technology was prepared and submitted to NREL and DOE for review and comment.

Planned FY 2000 Milestones: Complete final reports.

Major Reports Published in FY 1999: None

Photovoltaic Systems Monitoring Program

Contract#: DE-FG01-99EE35087	**Contract Period:** 6/1/99–9/30/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King / Dan Ton **Phone:** 202-586-1693 / **Phone:** 202-586-4618 **Fax:** 202-586-8148 / **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Dan.Ton@ee.doe.gov	State of California, California Energy Commission (CEC) 1516 Ninth Street, MS-1 Sacramento, CA 95814	
	Organization Type: ST	**Congressional District:** 5
Directing Organization: Golden Field Office 1617 Cole Blvd. Golden, CO 80401	**Principal Investigator(s)** Sanford Miller **Phone:** (916) 653-2834 **Fax:** (916) 653-2543 **E:mail**: smiller@energy.state.ca.us	
Technical Monitor: Robert Martin Phone:303-275-4763 Fax:303-275-4753 **E:mail**:Robert_Martin@nrel.gov	**B&R Code**: EB2202	**Cost Share Information**: CEC
	DOE Funding Allocation: 1999: $135,249	**Cost Share Funding:** 1999: $135,250

Project Objective: The objective of the project is to collect and analyze data on PV and other emerging renewables (ER) capacity additions and performance, so that policy makers and industry stakeholders can have consistent, comparative information on the trends in sizes, capacity factors and electricity production over the crucial transition period. This data forms the fundamental and primary measure of assessing technology development. When analyzed in conjunction with other information (such as financial incentives, electric industry restructuring), this information can provide insights for program and policy development. This information and analyses will assist stakeholders (financiers, developers, energy service companies) directly involved with emerging renewable power project development and marketing. It can also be used to provide end-users with more information on PV technologies.

Approach/Background: The analysis will be primary based on the empirical data on system types, capacity additions and electricity production resulting from California's $54 million Emerging Renewables Buydown Program. Recipients of Buydown Program will be asked to participate in the monitoring program. Monitoring equipment will be installed at the premises to record daily operating information including generation and customer demand. Customers will also be requested to complete questionnaires on customer satisfaction. The survey and operating data will become part of a baseline for evaluation of market acceptance, dependability and reliability analyses.

The monitoring program results will eventually become a part of the baseline information that can:

. Enable assessment of seasonal and weather-based variations in production by geographic region;
. Enable assessing future production when PV and other ER systems are operated in response to competitive market conditions;
. Permit analysis of capability of various system sizes to meet customer demands;
. Offer insights into cost-effective requirements necessary for systems to gain market acceptance; and,
. Provide better understanding how expanded development of small, distributed generation systems will affect the electricity marketplace

Status/Accomplishments: The data and analyses will be documented in an annual report for years 1999 and 2000. It will also be posted on the Internet on the Commission's web site. The Commission staff will also present the data at national solar industry conferences and PV/fuel cell/small wind meetings.

Planned FY 2000 Milestones: Produce quarterly and annual reports to state coordinators and stakeholders.

Major Reports Published in FY 1999: None

Major Articles Published in FY 1999: None

Building a Market for Photovoltaics Through Electric Service Providers

Contract #: DE-FG01-99EE35086	**Contract Period:** 08/06/99–07/31/00

Sponsoring Office Code: EE-11	**Performing Organization(s)**	
DOE HQ Program Manager: Richard King **Phone:** 202-586-1693 **Fax:** 202-586-8148 Lynne Gillette **Phone:** 202-586-1495 **Fax:** 202-586-8148 **E:mail:** Richard.King@ee.doe.gov **E:mail**: Lynne.Gillette@ee.hq.gov	Utility PhotoVoltaic Group 1800 M Street, NW, Suite 300 Washington, DC 20036-5802	
	Organization Type: IN	**Congressional District**: NA
Directing Organization: DOE Office of Solar Energy Technology 1000 Independence Ave., SW Washington, DC 20585	**Principal Investigator (s)** Bob Gibson **Phone:** 202-857-0898 **Fax**: 202-223-5537 **Email**: bgibson@ttcorp.com	
Technical Monitor: Lynne Gillette **Phone**: 202-586-1495 **Fax**: 202-586-8148 **Email**: Lynne.Gillette@ee.hq.gov	**B&R Code**: EB2202	**Cost Share Information**: UPVG
	DOE Funding Allocation: 1999: $298,682	**Cost Share Funding:** 1999: $60,015

Project Objective: This education and outreach project "Building a Market for Photovoltaics Through Electric Service Providers" will develop an integrated flow of information between electric utilities and other energy service providers, their customers, and key stakeholders in the solar industry, financial community and the architect/builder community. The information will help break down existing market barriers and create a marked acceleration of the use of PV electricity.

Approach/Background: UPVG will rely heavily on the experiences and lessons learned as a result of their involvement with the TEAM-UP (Technology Experience to Accelerate Markets in Utility Photovoltaics) demonstrations. The main purpose for this project will be to widely disseminate the results of TEAM-UP.

Status/Accomplishments: The major accomplishments on this contract to date include: published "Schools Going Solar" brochure; presented information on connecting with the customer issues, green pricing, PV markets and building integrated PV at the UPEx meeting in October 1999; published UPVG Record, Fall 1999 (report on TEAM-UP projects and market development); published "Bringing Photovoltaic Power into the Mainstream" brochure (how utilities can enter PV market-partially funded through E&O grant); published first of five issues of the Solar Sheet, media tip sheet on utilities and PV; with sidebars on TEAM-UP, in July/August 1999 issue; updated and added information to web site, created more links to web versions of Schools Going Solar, the Record and TEAM-UP data and information.

Planned FY 2000 Milestones:
Interactive exchange and other updates on Web site
Report on PV Market Opportunities for Electric Service Providers
Report on green pricing and customer preference
Report on building-integrated PV
Report on cost-effective PV
Report on lessons learned installing PV
More issues of the Solar Sheet, the UPVG Record and topical information sheets

Major Reports Published in FY 1999:
Schools Going Solar Brochure
UPVG Record
Bringing Photovoltaic Power into the Mainstream
Solar Sheet

Major Articles Published in FY 1999:
"Letting the Sun Shine In: The Promise and Reality of Photovoltaic Technology" *SourceBook*, November 1999
"What's New in Building Integrated Photovoltaics" *Environmental Design and Construction*, July/August

Interconnection Barriers – Solution for the Million Solar Roofs Initiative

Contract #: DE-FG01-99EE10706	**Contract Period:** 9/24/99–11/30/00

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<tr><td>Organization Type: IN</td><td>Congressional District: NA</td></tr>
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None</td></tr>
<tr><td>DOE Funding Allocation:
1999: $117,180</td><td>Cost Share Funding:</td></tr>
</table>

Project Objective: This project was initiated as part of the Million Solar Roofs Initiative and aimed at removing barriers to interconnecting building-related PV systems with the utility grid. The effort covers both technical and non-technical barriers and will identify solutions to remove these barriers. It is a combined effort of UPVG and PVUSA. The specific objective is to help resolve technical and non-technical issues relating to PV interconnection to the utility grid.

Approach/Background: The UPVG/PVUSA project team's goal is to develop materials that will offer potential solutions for both the technical and non-technical barriers to interconnection. They will develop a handbook and a model workshop. They will demonstrate these resources at a series of at least four workshops in Million Solar Roof communities that have identified interconnection issues.

Status/Accomplishments: Project is just getting underway (11/99). The project team, under other UPVG federal funding, has conducted a preliminary interconnection workshop as part of the UPVG's UPEx 1999 conference held in Tucson, AZ on 6 and 7 October 1999. Results and lessons learned from this development workshop will be utilized to establish the structure for the pending Million Solar Roofs interconnection workshops.

Planned FY 2000 Milestones:

PV Interconnection Guidelines Handbook	9/00
Model Workshop Plan	9/00
Four workshops conducted	11/00

Major Reports Published in FY 1999:
None

Major Articles Published in FY 1999:
None

Appendices

PERFORMING ORGANIZATIONS BY NAME

[ ] DENOTES THE ORGANIZATION TYPE

ORGANIZATION CODES

CU College, University, or Trade School (Non-HBCU)
HB Historically Black College or University
FF Federally funded (R&D Lab Operated for Profit)
IN Private Industry
NP Foundation or Lab (Non-Profit)
ST Regional State, or Local Government Facility
TA Trade or Professional Organization
US Federal Agency
ZZ Foreign

PERFORMING ORGANIZATIONS BY STATE

PERFORMING ORGANIZATIONS BY TECHNOLOGY AREA

<u>Applications and Market Development, Outreach, and Program Management</u>

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Program Planning, Analysis, Outreach, and Management

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13. ABSTRACT *(Maximum 200 words)*
This report summarizes the in-house and subcontracted research and development (R&D) activities under the National Center for Photovoltaics (NCPV) and U.S. Department of Energy (DOE) National Photovoltaics Program from October 1, 1998, through September 30, 1999 (FY 1999). The mission of the DOE National Photovoltaics Program is to make PV a significant part of the domestic economy—as an industry and an energy resource. The two primary goals of the national program are to (1) maintain the U.S. industry's world leadership in research and technology development and (2) help the U.S. industry remain a major, profitable force in the world market. The NCPV is part of the National PV Program and provides leadership and support to the national program toward achieving its mission and goals.

14. SUBJECT TERMS
photovoltaics ; National Center for Photovoltaics ; NCPV ; crystalline silicon ; high-efficiency materials and devices ; amorphous silicon ; cadmium telluride ; copper indium diselenide ; gallium arsenide ; III-V materials ; balance of systems ; measurements and characterization ; exploratory materials and devices ; Historically Black Colleges and Universities ; HBCU ; thin films ; Photovoltaic Manufacturing Technology ; PVMaT ; modules ; systems ; applications ; market development

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NCPV: *www.nrel.gov/ncpv*
Sandia: *www.sandia.gov/pv*

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