SERI/TP-211-3272
UC Category: 63

SERI's Photovoltaic R&D Project: Recent Progress and Future Directions

T. Surek

November 1987

Presented at a Special Meeting of the
Kansai Section of the
Japan Solar Energy Society and the
Japan Applied Physics Society
November 10, 1987
Osaka, Japan

Prepared under Task No. PV740101
Program No. 3

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications, which are generally available in most libraries: *Energy Research Abstracts, (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

SERI's PHOTOVOLTAIC R&D PROJECT: RECENT PROGRESS AND FUTURE DIRECTIONS

Thomas Surek

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401, U.S.A.

ABSTRACT

Photovoltaic (PV) research efforts at the Solar Energy Research Institute (SERI) focus on developing improved generations of photovoltaic technologies having the potential for low cost, high performance, and long-term reliability. The new PV technology generations are thin-film single-junction and multijunction devices suitable for either flat-plate or concentrator systems, and advanced crystalline silicon sheet materials. Improvements in materials and processing, solar cell design, and cell fabrication techniques have led to remarkable progress for these new generations of photovoltaic devices leading to record cell efficiencies in nearly all material areas. Current research identified the criticality of source material purity and the device processing conditions for a number of different PV materials. Furthermore, attention to total device design and processing helped to realize greater understanding of metallic contacts, transparent conductors, and interlayers. The development of sophisticated models enabled quick assessment of device concepts. Another characteristic of current research directions is increased collaboration among PV experts. Enhanced measurement and characterization techniques, along with interaction among PV scientists, are adding to a strong scientific foundation for the photovoltaic future.

INTRODUCTION

Photovoltaics is an attractive technology for utility-scale electricity generation. PV provides diversification of the mix of electricity supply options; large-scale PV systems are modular and require short and well-defined lead times for deployment--recent experience by U.S. utilities showed systems come on-line, on-schedule and within budget; and PV provides another high technology product to help increase U.S. industrial competitiveness.

Providing industry with the PV knowledge base for further development has been the cornerstone of the U.S. Department of Energy's (DOE) "National Photovoltaics Program: Five Year Research Plan, 1987-1991" (1). The plan is predicated upon partnerships, among the federal government, private industries, universities and electric utilities, pursuing the most pertinent R&D and effectively transferring the results to the community. The target of the plan is not based on serendipity, but on dedicated efforts directed towards an ambitious, yet attainable goal. The goal is to improve the conversion efficiency and reliability of photovoltaic systems while reducing their cost to the point where they provide electrical energy at a levelized cost of 6¢/kWh (constant 1986 dollars). This goal places photovoltaic electricity in a competitive position with electricity generated by other sources. To achieve this 6 ¢/kWh goal, the research activities of the Five Year Research Plan are directed toward the long-term technology goals shown in Table 1. The technical goals are a range of a set of module efficiency and cost targets which will meet the 6¢/kWh electricity cost goal.

There exist several opportunities for attainment of performance improvements in, and cost reduction for, photovoltaics. Thin-film single-junction and multijunction devices

Table 1: Federal/Industry Long-Term (Year 2000) Technical Goals (1986 dollars).
Based on a levelized constant dollar electricity cost-target of 6¢/kWh.

	Flat-Plate Systems	Concentrator Systems
Module Efficiency at 25°C	15%-20%	25%-30%
Module Cost	$45-$80/m^2	$60-$100/m^2
Balance-of-System Costs		
-- area-related	$50-$100/m^2*	$125/m^2
-- power-related	$150/kW	$150/kW
System Life Expectancy	30 years	30 years

*Balance-of-system costs vary depending upon the type of flat-plate system (fixed, 1-axis, or 2-axis tracking).

are practical approaches to the ambitious goals, as are advanced crystalline silicon sheet materials which are produced at a high throughput and yield high solar cell efficiencies. For these new generation technologies to achieve the performance/cost goals, significant resources and research talent are required, along with the coordination of multidisciplinary research teams. The federal government assigned SERI to conduct the Advanced Research and Development (AR&D) Project in photovoltaics for DOE's Photovoltaic Energy Technology Division. The project's primary research emphasis is on establishing and developing promising new approaches to photovoltaic cells, such as thin-film single-junction and multijunction concepts. SERI's PV activities involve management of subcontracted R&D, development of state-of-the-art measurement and device fabrication capabilities, basic and applied research within its in-house laboratories, and transfer of R&D results to industry. Research activities are undertaken with promising photovoltaic materials, including thin films of hydrogenated amorphous silicon alloys (a-Si:H), polycrystalline thin films of copper indium diselenide ($CuInSe_2$) and cadmium telluride (CdTe), thin films of gallium arsenide (GaAs) and III-V alloys, and crystalline silicon sheet materials. The research includes studies of single-junction and multijunction devices made from these materials and other alloys. Approximately 80 highly qualified scientists, engineers, technicians, managers, analysts and other professionals at SERI conduct this research (see Figure 1) along with over 60 subcontracted research groups in universities, industry and non-profit laboratories.

Table 2 shows the budget distribution for SERI's PV AR&D Project for fiscal year (FY) 1987 and prior years. The table shows the budget distribution by material area for the subcontracted programs, and the in-house research costs. The relative emphasis on material areas in the in-house programs is similar to that in the subcontracted areas. It can be seen from the table that over 60% of the funds available for research were subcontracted to industry and university laboratories. It should be noted that the SERI research in crystalline silicon materials is part of the Crystalline Silicon Research Project, managed for DOE by Sandia National Laboratories. In the subcontracted area, two important supporting research programs are the New Ideas for Photovoltaic

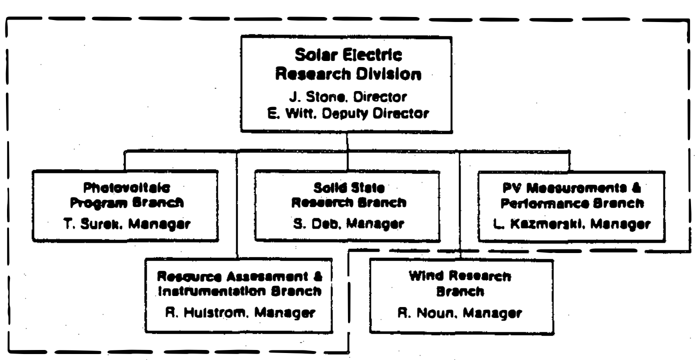

Figure 1: Organization of SERI's Photovoltaic Advanced R&D Project (dashed area).

Table 2: SERI Photovoltaic Advanced R&D Project Budget History

SERI In-House	FY1978-FY1985 ($M)	FY1986 ($M)	FY1987 ($M)
Research	42.5	8.7	9.1
Capital Equipment	12.2	0.9	0.8
Subcontracts[a]			
Amorphous Silicon Thin Films	36.1	7.2	9.2
Polycrystalline Thin Films	29.1	2.9	2.9
High Efficiency Concepts (III-V)	22.2	2.4	3.0
Crystalline Silicon	20.7	0.4	0.4
New Ideas	16.0[b]	1.0	0.5
University Program	1.0	1.2	1.3
Total Subcontracts	125.1	15.1	17.3
TOTAL PROGRAM	179.8	24.7	27.2

(a) Amounts under subcontract areas include approximately 15% for program management, fees, etc.
(b) Includes $9.0M for Photoelectrochemical Cell research.

Conversion Program and the University Participation Program. The objective of New Ideas research is to identify new materials and device configurations, and to conduct preliminary R&D in the most promising of these new areas. The University Participation Program provides a mechanism for establishing and maintaining the infrastructure of dedicated personnel and facilities needed for conducting fundamental research at universities. The intention is to pursue promising ideas, unencumbered by milestone restrictions and excessive reporting requirements.

This paper describes the current research directions by reporting recent accomplishments by SERI subcontractors and in-house researchers. The accomplishments are grouped by the materials research areas of Table 2; the New Ideas and University Programs, as well as in-house R&D activities which cut across the material areas, are described under the section on "Support Activities".

TECHNICAL ACCOMPLISHMENTS

Amorphous Silicon Thin Films

As DOE's management center for the entire federally-funded amorphous silicon program, the Amorphous Silicon Research Project (ASRP) Office was established within SERI's PV Program Branch in 1983. The ASRP is responsible for implementing national energy policy in amorphous silicon by coordinating all federally-funded R&D in this area. The objectives of the research are to improve and understand the optoelectronic properties of amorphous-silicon-based alloy materials and to improve the conversion efficiency and stability of single-junction and multijunction solar cells and submodules. The research is directed toward the achievement of the National PV Program's FY1990 goals, which are 10% efficiency for single-junction and 13% efficiency for multijunction submodules of at least 1000 cm^2 area.

The ASRP plan involves two principal activities -- multidisciplinary activities and fundamental research activities. Multidisciplinary activities involve government/ industry cost-shared programs made up of broad-based research teams located at the individual company's facilities performing directed research ranging from preparation and evaluation of starting materials to the demonstration of proof-of-concept cells and submodules. Fundamental research activities involving basic, higher risk, and supporting research are done by universities and research laboratories, including in-house research at SERI. These fundamental research activities include studies on light-induced effects; materials deposition rate; alternative deposition methods; amorphous-silicon-based alloy materials; material and plasma characterization; and modeling, testing, and reliability. Thin-film module testing and reliability research for the ASRP is carried out in SERI's PV Measurements and Performance Branch.

The first government/industry cost-shared program started in 1984 and ended in early 1987. The four subcontract awards, totalling approximately $18.6M, were cost-shared about 30% by industry. A major accomplishment of the first initiative was Solarex Corporation's achievement of the program's primary technical goal: an 8% conversion efficiency for a submodule with a total area greater than 1000 cm^2. Other significant technological advances included Chronar Corporation's single-junction, monolithic, amorphous silicon submodule with a 5% total-area conversion efficiency over an area of 2790 cm^2; 3M Company's amorphous silicon submodules on a highly flexible, plastic roll substrate; and Spire Corporation's innovative method for fabricating high-quality, low-bandgap, hydrogenated amorphous-silicon-based alloy materials for use in multijunction cells.

Laboratory cell efficiencies have also improved significantly as a result of the first initiative. SERI has recently measured a cell from Solarex Corporation with an 11.7% conversion efficiency for an area of 0.25 cm^2. State-of-the-art 1 cm^2 area solar cells have reached 11.5% efficiency (Figure 2). Three specific technical advancements can be cited for the increased efficiencies: (i) the development of high quality, textured SnO_2:F having low electrical sheet resistance and high optical transmission; (ii) the development of a multilayer back-reflecting contact consisting of ITO/Ag layers; and (iii) the development of graded p/i interface structures using superlattice p-Si,C:H layers and transitional doped or intrinsic interface layers using compositional grading in amorphous Si,C:H films. Use of improved textured SnO_2:F front contacts and multilayer reflecting back contacts has resulted in increased values of J_{sc} (18 to 19 mA/cm^2), especially through an enhancement in the red spectral response of cells (e.g., 62% at 700 nm). Use of graded p/i interface structures has resulted in enhanced values of V_{oc} through reduced interface recombination and improvements in the fill-factor as well. Even further improvements can be expected by the extrapolation of present work, and efficiencies of 14% for amorphous silicon single-junction cells appear possible.

Based on the success of the first government/industry program, SERI initiated a second three-year program in January 1986 directed toward single-junction and multijunction amorphous silicon cell and submodule research. Based upon a public solicitation, four companies were awarded contracts in 1987: ARCO Solar, Solarex, Chronar, and Energy Conversion Devices (ECD). ARCO Solar will be developing a four-terminal submodule using amorphous silicon and copper indium diselenide. Solarex, using dc glow discharge, will develop multijunction submodules using amorphous silicon-germanium as the bottom cell. Chronar, using a vertical rf glow

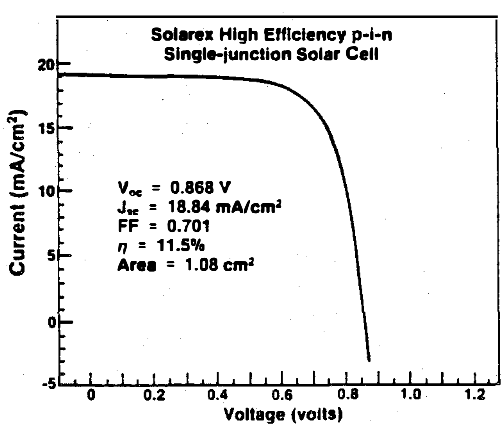

Figure 2: I-V characteristics of Solarex's state-of-the-art 11.5% amorphous silicon solar cell.

Government/Industry Program (1987-1990)

$40 Million, Cost Shared 50% by Industry

ARCO Solar

Multiple gap, multijunction submodules (1 ft^2)
Four terminals
Top, a-Si:H
Bottom, $CuInSe_2$
Glass substrate

ECD

2-3 stacked cells
Amorphous silicon-based alloys
RF glow discharge
Roll-to-roll process
Metal substrate

Chronar

Single junction submodules (1 ft^2)
Multijunction submodules, same bandgap (1 ft^2)
RF glow discharge
Glass substrate

Solarex

Multiple gap, multijunction submodules (1 ft^2)
Two terminals
Amorphous silicon-based materials
DC glow discharge
Glass substrate

Figure 3: Technical approaches of participants in second amorphous silicon government/industry program.

discharge system, will perform studies on increasing the efficiency of the single-junction submodule efficiencies and multijunction submodule efficiencies using same bandgap a-Si:H materials. ECD will concentrate on research to determine the limit of a-Si based alloy materials with the overall goal of demonstrating 18% efficiencies in tandem or triple all-amorphous-silicon based multijunction, laboratory-size solar cells. The approach selected by each company is summarized in Figure 3. The primary goals of this research program, cost-shared 50% by the government and industry, are to achieve the FY 1990 efficiency goals for submodules stated earlier.

Significant advances were also made in the fundamental research activities of the ASRP. At the International Conference on Stability of Amorphous Silicon Alloy Materials and Devices (2), several new models were proposed to qualitatively and quantitatively explain the observed behavior of amorphous silicon thin films under illumination. The two basic models can still be grouped into bond-breaking or defect-conversion models. The bond-breaking model, supported by Xerox researchers and generally accepted by others, proposes microscopic origins of the observations which rely on intrinsic, weak silicon-silicon bonds in the amorphous network and highly mobile hydrogen atoms. The activation energy required to break a weak silicon-silicon bond to create dangling bonds is less than 1.0 eV and depends on the local configurations and nearby impurities or hydrogen atoms. Recombination of electrons and holes before external collection is generally accepted as the initiator in the subsequent creation of defects.

In the area of alternate deposition techniques for a-Si, several research groups are investigating chemical vapor deposition (CVD) methods, such as photochemical vapor deposition (photo-CVD), thermal CVD, and laser-induced CVD, to either improve the photostability or device performance, or to potentially reduce manufacturing costs. At present, the photo-CVD method using mercury-sensitized gases has shown the most promise; recently, a solar cell fabricated by researchers at the Institute of Energy Conversion was measured by SERI to be 9.6% efficient. In-house researchers at SERI have developed an innovative technique for maintaining window transparency during photo-CVD. The technique also provides a convenient method for fluorine incorporation into the a-Si film.

The main thrust of SERI in-house research in a-Si is to acquire a better understanding of the physics and chemistry of amorphous-silicon-based alloy materials and devices for improving their photovoltaic performance characteristics. Studies of the microstructure of amorphous silicon alloy films are leading to an understanding of the role of microvoids in determining the electronic properties and stability behavior of the films. It was concluded that lowering the microvoid density and better passivation

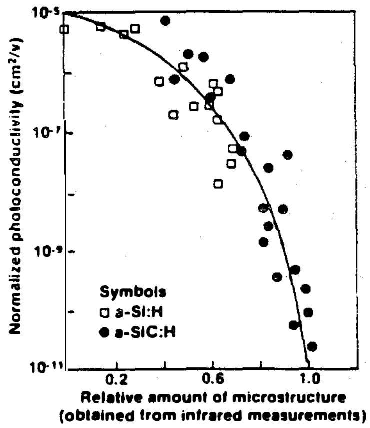

Figure 4: Effect of microstructure (microvoids) on photoconductivity of two amorphous silicon alloy materials. Data for other amorphous silicon alloy materials follow the same universal curve.

will produce good PV quality films. Using this understanding of microvoids, a universal parameter was developed for describing the photoconductivity of amorphous silicon alloys (Figure 4). Recently, researchers developed two original approaches for minimization or elimination of microvoids: (i) periodic etching with XeF_2 during CVD; and (ii) hydrogen implantation of heat-treated a-Si films. In the important area of the light-induced effect in a-Si, SERI researchers have determined that there is no correlation between film stress and the light-induced effect. This discovery is contrary to what some other researchers have reported previously.

In the area of transparent conducting oxide films, new starting materials were found which are less costly, less toxic, and safer to handle than tetramethyltin. Harvard University showed that dimethyldichlorotin (a solid at room temperature with a low vapor pressure) is a promising starting material. Solarex Corporation demonstrated that tin tetrachloride (a liquid at room temperature) can also be used as a starting material. Using these substitute tin sources has produced transparent conducting films on glass substrates with similar electrical and optical properties, and should lower the cost of thin-film devices.

The prospects for amorphous silicon photovoltaics appear promising: the goals of the government/industry program should be met with continued commitment of the partners, and there should be continuing advances in the fundamental research areas. At the same time, industry's attention is turning to increasing production volumes and module sizes in efforts to further lower manufacturing costs. End-user interest in technology is also increasing. Several joint demonstration projects between U.S. manufacturers and utility companies have started during the past 1 1/2 years, the largest being a grid-connected electric power generating system installed by Alabama Power Company, using modules fabricated by Chronar Corporation, which is operating at a peak power of about 75 kW.

Polycrystalline Thin Films

The objective of this research is to develop cells and submodules that meet DOE's long-term goals by achieving high efficiencies (15%–20%), low cost (under $\$45/m^2$), and reliability (30 years).

The approach relies on developing solar cells based on highly light-absorbing compound semiconductors such as $CuInSe_2$ and CdTe and their alloys. These semiconductors are fabricated as thin-film cells (1-3 microns thick), lowering material and processing costs. Polycrystalline thin-film $CuInSe_2$ and CdTe cells have each achieved over 10% efficiency (confirmed at SERI). Reported active-area efficiencies of small $CuInSe_2$ cells are in the 11%-13% range at four laboratories (SERI, ARCO Solar, Boeing, and the Institute of Energy Conversion). A 9.6% efficiency for a 91-cm^2 $CuInSe_2$ device (Boeing), consisting of four interconnected solar cells, has been verified at SERI (Figure 5), as has a 10.5%, 1.22 cm^2 area CdTe solar cell fabricated by Southern

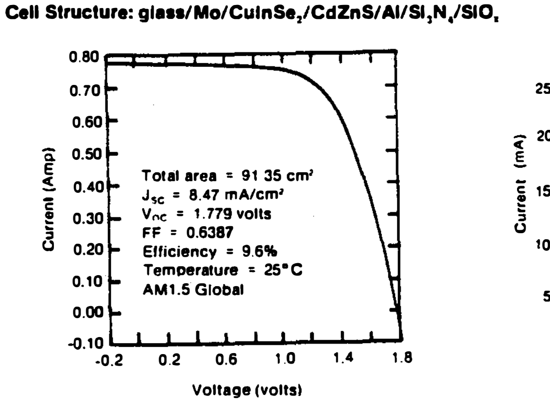

Figure 5: I-V characteristics of Boeing's 9.6% efficient submodule consisting of four solar cells.

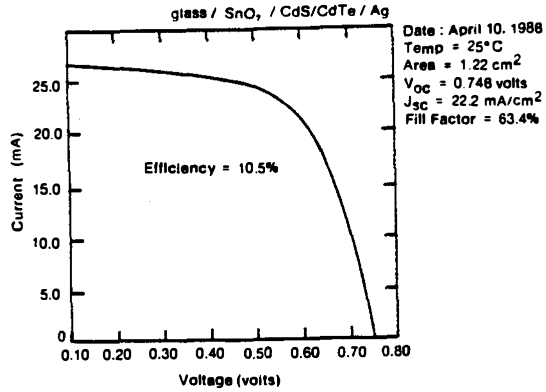

Figure 6: I-V characteristics of 10.5% efficient CdTe solar cell fabricated by Southern Methodist University.

Methodist University (Figure 6). $CuInSe_2$ shows good proven stability under controlled conditions (9000 hours of illumination). Innovative cell designs are now addressing past difficulties in contacting CdTe.

Polycrystalline cells still require development to achieve 15%-20% conversion efficiencies. Two strategies are being used: continued development of single-junction cells and innovative research on two-junction cascade cells. Improvement of the single-junction technologies has been steady and reliable. In attempts to increase the bandgap, and thereby increase the solar cell efficiency, Boeing has investigated $CuGaInSe_2$ solar cells. With a Ga content of about 25%, a bandgap of 1.14 eV and an efficiency of 10.2% (1.07 cm^2 area) have been achieved. Developing two-junction $CuInSe_2$-based cascade cells allows for even more ambitious long-term efficiency goals. Combining two well-matched single-junction cells should lead to better than 20% efficiency. The materials being investigated for the top cells include CdTe and ZnTe alloyed with Mn, Mg, Zn, and Hg. Researchers at the Institute of Energy Conversion achieved an ohmic transparent back contact for a CdTe solar cell. This is the first practical step to using CdTe or alloy as the top cell in a four-terminal cascade structure.

An approach being pursued by ARCO Solar involves the combination of an a-Si top cell and a $CuInSe_2$ bottom cell in a four-terminal device structure (see previous section). An efficiency of 13.7% has been reported for laboratory-size devices, and over 10% was reported for submodule prototypes.

Developing scalable, low-cost fabrication methods is important in providing industry with a foundation for future large-area, high-throughput commercial processes. Research on alternative methods for fabricating polycrystalline cells includes: for $CuInSe_2$, an electrochemical/selenization method, a reactive sputtering method, evaporation, a hybrid sputtering/evaporation method, and a one-step electrodeposition method; for CdTe, close-spaced sublimation, evaporation, electrodeposition and metal-organic chemical vapor deposition (MOCVD). The one-step electrodeposition process was recently innovated by SERI researchers. Work is continuing on optimizing the parameters for achieving high quality films for device fabrication.

The primary emphasis of SERI's in-house research in polycrystalline thin films involves fabrication of promising ternary thin-film solar cell materials and devices to: (i) understand the defect chemistry and charge transport in these materials that control their photovoltaic properties; (ii) understand the role of the oxidation process in thin films of $CuInSe_2$ and $CdS/CuInSe_2$; (iii) modify these materials to optimize device performance; and (iv) investigate related, but hitherto unexplored, novel photovoltaic ternary materials. As a result of fundamental studies on $CuInSe_2$ films, SERI scientists fabricated $CdS/CuInSe_2$ devices performing at 10.3% efficiency. Through surface modification of the $CuInSe_2$, an open-circuit voltage of 640 mV has been demonstrated for a $CdS/CuInSe_2$ device.

Other studies at SERI have resulted in the correlation of optical properties of $CuInSe_2$ and $CuGaSe_2$ thin films with composition; the determination of electrical properties versus composition at low temperatures (40-300K); development of a model for the interaction of oxygen with $CuInSe_2$ films; and identification of the effects of ion and electron beams on the analysis of the devices. The Crystal Growth Research Group in SERI's Solid State Research Branch has produced crystals of the new semiconductors LiZnAs and LiZnP, and conducted extensive attempts to produce CuZnAs, LiCdP, $MgGeAs_2$ and $MgSnP_2$ (these latter may not be physically stable compounds). The growth of these new, theoretically predicted PV compounds allows for initial investigations of basic properties such as bandgap, absorption coefficient, and lattice constant -- the promising materials may be investigated later in thin-film form.

A major program development in FY1987 has been the recompetition of the subcontracted research in polycrystalline thin films. The recompetition attracted new industrial participants in the CdTe solar cell area and resulted in cost-shared research programs. One of the new groups, Ametek Applied Materials Laboratory, has made a significant contribution to the advancement of thin-film CdTe technology. Ametek takes advantage of its unique "n-i-p" cell structure (see Figure 7) to address the CdTe/contact degradation problem which has been a major unresolved issue facing the technology. The n-CdS is deposited by spray pyrolysis, the i-CdTe by electrodeposition, and the p-ZnTe by evaporation. Active area efficiencies of 9.3% have been reported for a monolithically, series-interconnected 10-cell submodule of 51 cm^2 area, with the total area efficiency reported as 6.1%. Further improvements in the module design are expected to reduce area losses to less than 15%. Initial stability tests have been very promising, with no degradation reported after 800 hours of testing at 100 mW/cm^2 illumination. SERI has verified greater than 10%, 4 cm^2 area heterojunction devices (CdTe/CdS) fabricated by Ametek.

Another new subcontractor is Photon Energy which produces large-area CdTe/CdS submodules by a low-cost, wet-chemical method. SERI has measured an output of 4.3 W (outdoor measurement) on a nearly one-square-foot monolithically interconnected submodule consisting of 27 cells in series. Small-area cells of 9.7% efficiency with high open-circuit voltage (0.788 V) and fill-factor (0.68) have been reported by the subcontractor.

Increasing investments in the private sector in polycrystalline thin films, as demonstrated through the recent interest in the SERI procurements and the resulting cost-shared subcontracts, indicate a bright future for these technologies. Continuing efforts at scaling up the deposition processes, and increased efforts in the fundamental understanding of $CuInSe_2$ and CdTe materials and devices, are likely to result in the emergence of these materials as commercial PV products in the near future.

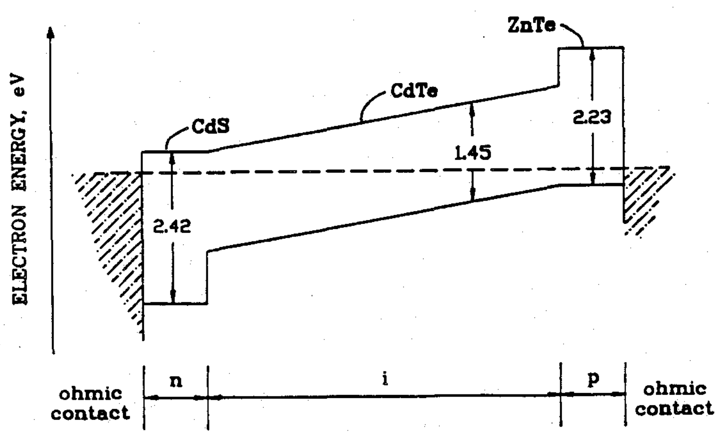

Figure 7: Idealized band diagram of Ametek's n-i-p solar cell structure for CdTe.

SERI

High Efficiency Concepts (III-V)

The research efforts in this area cover two main approaches: thin-film GaAs, and multijunction concentrator cells. The principal objective of thin-film GaAs research is to understand techniques for single-crystal, thin-film growth for industrial development of 20% efficient, flat-plate modules. This research also directly contributes to the goals for multijunction concentrator cells through its emphasis on controlling deposition mechanisms.

Concentrator cell research objectives are to understand and control the complex crystal growth processes needed for deposition of high-quality ternary and quaternary alloys of III-V compound semiconductors. These alloys are currently the best candidates for achieving greater than 30% efficient concentrator cells. The research also offers the high payoff potential of exceeding 35% efficiencies in the longer term. Research on concentrator cells synergistically supports the flat-plate interests, and it is essential in reaching the longer-term goal of realizing very high efficiency, thin-film, multijunction cells applicable for flat-plate modules.

Several important accomplishments by SERI subcontractors and in-house researchers in FY1987 are noteworthy. The Kopin Corporation, a spin-off company from SERI-supported research at MIT Lincoln Laboratory, formed a single-crystal, thin-film GaAs CLEFT (cleavage of lateral epitaxy films for transfer) layer separated from an entire 5 cm diameter wafer. This is roughly an order of magnitude larger area than was achieved at Lincoln Laboratory where reactor size limited growth areas to several square centimeters, and demonstrates the promise of scale-up for this deposition process. Recently, SERI measured a CLEFT-grown, double heterostructure AlGaAs/GaAs solar cell fabricated by Kopin. The efficiency of the 1 cm^2 device was 20.2% with V_{OC} = .996V, J_{SC} = 25.96 mA/cm^2 and FF = 78.18%. This particular cell had not been separated from its substrate; the low fill-factor may actually be improved in separated cells due to the improvement of the back contact to the cell.

Spire Corporation achieved a record efficiency of 23.7% for a 0.25 cm^2 area single-junction GaAs solar cell operating at one sun (AM 1.5) (Figure 8). This one-sun efficiency is the highest measured to date by SERI. Spire has also produced a 4-cm^2 device with nearly comparable characteristics (23.6% efficiency; see Figure 8). Researchers attribute this success to improvements in crystal growth control and device processing.

Varian Associates, which has been developing a monolithic cascade cell of AlGaAs/GaInAs, has achieved successful results, as verified recently by SERI measurements. Five key results are: (i) a 9.99% efficient, 3 cm^2 area cascade-configured GaInAs (1.15 eV) single-junction cell under graded layers and 1.75 eV AlGaAs; (ii) a 16.81% efficient, 4 cm^2 area AlGaAs (1.75 eV) solar cell; (iii) a 14.89% efficient, 4 cm^2 area AlGaAs (1.93 eV) solar cell; (iv) a 22.73%, 4 cm^2 area GaAs single-junction heteroface cell ; and (v) a metal-interconnected cascade cell of 1.93 eV AlGaAs on GaAs of 22.1% efficiency, 0.5 cm^2 area. This is the first SERI-verified

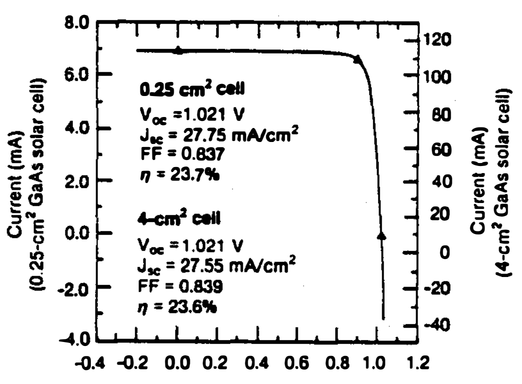

Figure 8: I-V characteristics of Spire's record efficiency (one sun) GaAs solar cells.

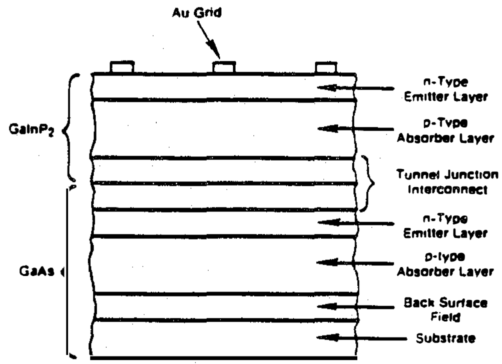

Figure 9: Schematic of new lattice-matched tandem cell invented by SERI researchers.

measurement of a high-efficiency monolithic cascade cell. Under an AM0 spectrum (for which this device was tuned), an efficiency of 22.46% was measured -- a record efficiency for an AM0 solar cell.

SERI in-house research progressed on the innovative, lattice-matched $GaInP_2$/GaAs tandem structure (Figure 9). Recent studies have centered on measurements of absorption and reflection coefficients of $Ga_{0.5}In_{0.5}P$, and the bandgap as a function of growth parameters. The reflection coefficient was found to be somewhat higher in the blue and the absorption coefficient lower than for similar III-V compounds. The effect of growth parameters is on the degree of ordering of the Ga and In atoms through its effects on adatom surface mobility. Shallow homojunctions of $GaInP_2$ have been fabricated with efficiencies of about 9% (no anti-reflection coating). With AR coating, the efficiency of these devices should exceed 13%. In another development by SERI researchers, GaP layers with far lower defect densities than reported in the literature have been grown on Si substrates. Control of the interfacial contamination, leading to better nucleation and coalescence of the first-deposited GaP, has led to these results. This research is aimed at the development of GaAsP/Si cascade cells.

In a cooperative effort between SERI researchers and Spire Corporation, the highest efficiency GaAsP solar cell was fabricated (grown on a GaAs substrate): 17.7% efficiency, 0.25 cm^2 area. SERI's characterization and analysis of defects in the Spire-grown GaAsP layers, and subsequent recommendations for an improved crystal structure to reduce dislocation densities in the lattice-mismatched structure, have led to the record high efficiency device.

In another collaborative effort between Spire and SERI researchers, the effects of hydrogen passivation of Spire's GaAs-on-Si solar cells are being studied using the Kaufman ion beam system at SERI. The SERI results exceed previous attempts to passivate these devices; increases in V_{oc} of nearly 60 mV have been observed using a low energy (approximately 300 eV) beam for 10 minutes. The study is continuing to evaluate the effects of various parameters in the hydrogen treatment on the device characteristics.

A new research initiative in FY1988 is aimed at clarifying the issues related to large-scale III-V epitaxy by examining the fundamental mechanisms (e.g., fluid flows, mass transport, thermal gradients, chemical kinetics). The research is expected to lead to development of design criteria for advanced reactors.

Crystalline Silicon

The long-term objective of research on crystalline silicon materials is to identify new technologies for growth of high-quality silicon sheet at high growth rates. This research is also expected to provide near-term knowledge to the existing crystalline silicon industry for application to processing improvements.

The subcontracted research currently supports seven university groups: three projects, with Cornell University, Arizona State University and the State University of New York-Albany, are supported to investigate the initial and post-cell-processing properties of various types of silicon materials. Particular emphasis is placed on understanding the roles of oxygen, carbon, hydrogen and fast-diffusing elements. A second area is the investigation of cell processing steps which can maintain or enhance the minority carrier lifetime of the silicon in completed cell structures. The development of traditional heat treatment and transient processing steps which form shallow doping profiles and denuded zones is under investigation at North Carolina State University. Research at the University of Kentucky and Massachusetts Institute of Technology is aimed at identifying crystal growth regimes which can simultaneously provide high-area production rates for silicon sheet and low (zero) dislocation densities. The approach involves modelling the crystal growth and thermal stresses in existing and advanced ribbon configurations. The project also supports characterization of the physical parameters of silicon near its melting point and measurements of residual stress in the ribbons (at the University of Illinois, Chicago), data which are needed for iterative improvements in the models.

In-house research at SERI centers on the growth of high-purity silicon crystals by float-zoning. Recently, the minority carrier lifetime of 52-mm-diameter, dislocation-free silicon crystals was increased to 21 ms for 200 ohm-cm material. A number of high-purity, gallium-doped crystals have been grown with resistivities ranging from 200 to 0.2 ohm-cm. The observed minority lifetimes were 21 ms at 200 ohm-cm, 16 ms at 13 ohm-cm, 7 ms at 2 ohm-cm, and 0.4 ms at 0.5 ohm-cm. The 0.2 ohm-cm crystal could not be measured because of its high conductivity. The crystals are now being readied for commercial wafering and polishing prior to distribution to Si cell researchers for cooperative device work (e.g., Georgia Institute of Technology, Spire, Stanford University, and University of New South Wales).

Researchers in SERI's PV Measurements and Performance Branch have recently accomplished the first atomic-level imaging of grain boundaries in polycrystalline silicon providing the first verification of silicon-hydrogen bonding during the passivation process and silicon-shallow-acceptor bonding during or after electronic neutralization.

Follow-up activities to the university subcontracts in FY1988 will involve a joint initiative with Sandia Laboratories aimed at cooperative programs between industry and universities.

Support Activities

Several of the SERI PV AR&D Project activities cut across the material areas described in the previous sections.

Subcontracted research in this area includes the New Ideas and University Participation Programs. Current participants in these programs and the subject of their research efforts are identified in Table 3. Both programs, although innovative and fundamental in nature, have consistently contributed to the goal-oriented materials research efforts in other areas of the SERI PV Project.

SERI's efforts in theoretical solid state physics are in basic and applied research on the theory of semiconductors to achieve a better understanding of the electronic and structural properties underlying the interaction of semiconductor systems with sunlight. This has led to innovative concepts and selection of novel materials and configurations for further R&D. Accomplishments included development of the theory of electronic structure of new $A^{I}B^{II}C^{V}$ compounds (e.g., LiZnP, LiZnN) suggesting new potentially PV-applicable semiconductors, some of which were grown at SERI, as described above. Other theoretical work predicted hitherto unknown ordered phases of III-V alloys with potentially very attractive PV properties; this work is also leading to a better understanding of $Ga_xIn_{1-x}P$ solar cells being developed by SERI researchers.

Table 3: Participants and Research Topics in SERI's New Ideas and University Participation Programs

University Program (FY1985-86 Awards)	Research Topic
North Carolina State University	New Approaches for High-Efficiency Solar Cells by MOCVD
University of Utah	Electronic Processes in Thin-Film PV Materials
University of Southern California	Low-Temperature MOCVD Growth Processes for High Efficiency Solar Cells
Stanford University	Ion-Beam Doping of II-VI Compounds During Physical Vapor Deposition
Brown University	Rapid Liquid Phase Epitaxy of Ternary III-V Semiconductors for Tandem Solar Cell Applications
University of Illinois	Surface Reactions During the Growth of Copper Indium Diselenide Films from Cu, In, and Se Vapors
Syracuse University	Research on Defects and Photocarrier Processes in Amorphous Hydrogenated Silicon Alloys
Carnegie-Mellon University	Improvement of Bulk and Epitaxial III-V Semiconductors for Solar Cells by Creation of Denuded Recombination Zones
New Ideas Program (FY1987 Awards)	
Georgia Tech Research Inst.	New Concepts for High Efficiency Energy Conversion: The Avalanche Heterostructure and Superlattice Solar Cell
International Solar Electric Tech.	Low Cost Techniques for Producing CdZnTe Devices For Cascade Cell Application
Rensselaer Polytechnic Institute	Hydrogen Radical-Enhanced Growth of Solar Cells
Stanford University	High Efficiency Flat Plate Silicon Solar Cells
Vactronics Laboratory Equip., Inc.	Novel Precursor Compound for High Rate Photodeposition

During FY1987, SERI's PV Measurements and Performance Branch has expanded to combine the extensive diagnostic and characterization facilities with the SERI outdoor test facility in order to facilitate diagnostic and preventative chacterization of cells and modules. The new branch activities are divided into five cooperative units: Advanced Module Testing and Performance; Cell Performance and Electro-Optical Measurements; Device Modeling and Fabrication; Materials Characterization; and Surface and Interface Analysis.

During the past year, more than 4000 materials and devices were evaluated and tested in the branch's laboratories. These activities, which encompass the range of characterization from fundamental chemical/compositional determinations of cell interfaces to long-term outdoor module testing and evaluation, are the results of cooperative interactions with subcontractors, internal SERI researchers and the photovoltaic industry. During the past year, this SERI program has worked with over 130 organizations worldwide, representing universities, industry and government laboratories. The group provides measurement, testing, characterization and device fabrication/modeling support to research and development groups involved in solar cell technologies.

Cell efficiency measurements, and verification of the efficiency records described earlier, are a specific program responsibility. SERI researchers are at the forefront of efforts to establish standard cell and module measurement techniques for determining efficiency and other critical component parameters for photovoltaic cells. All the SERI-measured parameters reported in this paper conform to the strict characterization procedures implemented by this SERI-led effort. The accepted standard conditions for reporting efficiencies are: for one-sun (flat plate) applications, 1000 W/m^2 irradiance, 25^oC temperature and AM1.5 global (ASTM E-892); and for concentrator applications, 28^oC temperature and AM1.5 direct (ASTM E-891). Current efforts involve collaborations with the PV community to resolve the complex issues related to the measurement of efficiencies of multijunction solar cells.

SERI's Resource Assessment and Instrumentation Branch provides data, instrumentation, and measurement and analyses techniques to characterize variations in solar radiation resources. Analyses of selected PV device performance are performed jointly with researchers from SERI, industry, universities, and other groups. The result is a better understanding of the sensitivity of current and proposed PV devices to variations in solar radiation resources caused by different climates. Two recent accomplishments include: (i) development of a much improved (15% uncertainty versus 35% uncertainty) direct-beam insolation model which is currently being implemented by Sandia Laboratories for better design of PV systems; and (ii) cooperative efforts with the PV research community that combines SERI's spectral irradiance models with the researchers' device models to examine the sensitivity of the devices to spectral irradiance variations.

CONCLUSIONS

Improvements in materials and processing, solar cell design, and cell fabrication techniques for the new generation of PV technologies continue to result in efficiency gains, a bottom-line parameter for the conversion of sunlight into electricity. Steady and dramatic advances are expected to continue during this decade. As the physics, chemistry, and device engineering of thin-film single junction and multijunction solar cells and advanced silicon sheet materials become better understood and controlled, industry's ability to fabricate low-cost, high performance and long-term reliable photovoltaic electricity devices will emerge. The continued federal/industry partnership should accelerate the attainment of the long-term goals in Table 1. The end result will be the opportunity for the U.S. to utilize photovoltaics as a secure, inexhaustible energy supply.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Energy under Contract No. DE-AC02-83CH10093.

REFERENCES

This review paper has drawn liberally, and without reference, from the research results of SERI subcontractors and in-house researchers. Many of these research efforts, except for some recent results and updates reported here, are described in the Proceedings of the Nineteenth IEEE Photovoltaic Specialists Conference held in New Orleans, Louisiana in May 1987. Further information is also available in the annual Branch Reports which can be obtained by contacting the Managers identified in Figure 1. Specific references cited are listed below.

(1) U.S. Department of Energy, "National Photovoltaics Program: Five Year Research Plan, 1987-1991", DOE/CH10093-7, May 1987. (Available from National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161).

(2) "Stability of Amorphous Silicon Alloy Materials and Devices", B.L. Stafford and E. Sabisky, eds., AIP Conf. Proc. No. 157 (American Institute of Physics, New York, 1987).