NREL/TP-214-4588 • UC Category: 270 • DE92001194

The Photovoltaic Manufacturing Technology Project: A Government/Industry Partnership

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Prepared for the 1992 ASME International Solar Energy Conference, Maui, Hawaii 4-8 April 1992

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Task No. PV250101

December 1991

On September 16, 1991, the Solar Energy Research Institute was designated a national laboratory, and its name was changed to the National Renewable Energy Laboratory.

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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

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THE PHOTOVOLTAIC MANUFACTURING TECHNOLOGY PROJECT: A GOVERNMENT/INDUSTRY PARTNERSHIP

1992 ASME International Solar Energy Conference, April 4-8, 1992

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ABSTRACT

The Photovoltaic Manufacturing Technology (PVMaT) project is a government/industry photovoltaic manufacturing research and development (R&D) project composed of partnerships between the federal government (through the U.S. Department of Energy) and members of the U.S. photovoltaic (PV) industry. It is designed to assist the U.S. PV industry in improving manufacturing processes, accelerating manufacturing cost reductions for PV modules, increasing commercial product performance, and generally laying the groundwork for a substantial scale-up of U.S.-based PV manufacturing plant capabilities.

The project is being carried out in three separate phases, each focused on a specific approach to solving the problems identified by the industrial participants. These participants are selected through competitive procurements. Furthermore, the PVMaT project has been specifically structured to ensure that these PV manufacturing R&D subcontract awards are selected with no intention of either directing funding toward specific PV technologies (e.g., amorphous silicon, polycrystalline thin films, etc.), or spreading the awards among a number of technologies (e.g., one subcontract in each area). Each associated subcontract under any phase of this project is, and will continue to be, selected for funding on its own technical and cost merits.

Phase 1 of this project, the problem identification phase, was completed early in 1991. Phase 1 competitive bidding was open to any U.S. firm with existing manufacturing capabilities, regardless of material or module design. Twenty-two subcontracts of up to $50,000 each were awarded. Phase 2 is now under way. This is the solution phase of the project and addresses problems of specific manufacturers. Subcontracts under the first Phase 2 solicitation, called Phase 2A, will be awarded in early Fiscal Year (FY) 1992. This Phase 2A solicitation was only open to participants in the Phase 1 effort. The envisioned subcontracts under Phase 2 may be up to three years in duration and will be highly cost-shared between the U.S. government and U.S. industrial participants. A second, overlapping, and similar process-specific solicitation (Phase 2B) is planned to follow soon and will be open to all U.S. PV manufacturing companies. A third portion of the PVMaT project, called Phase 3, is also under way, although it is slightly behind Phase 2. A Phase 3A solicitation was released in October of 1991 for subcontracted team research on module related R&D problems common to several PV manufacturers. In Phase 3, because of the general interest to industry, some general issues related to PV module development will be studied through various teaming arrangements. The PVMaT project's ultimate goal is to ensure that U.S. industry retains and extends its world leadership role in the manufacture and commercial development of PV components and systems. Activities to date under PVMaT have received outstanding support, and the level of interest in participation is exceptional.

THE PVMaT PROJECT

A decade ago, U.S. companies had captured 60% of the international market for PV modules. Today that share has dwindled to less than 35%, as shown in Figure 1. To help reverse this declining trend in U.S. competitiveness, DOE has initiated the Photovoltaic Manufacturing Technology (PVMaT) project, a five-year, three-phase, $55-million technology transfer project that is expected to reduce PV manufacturing costs and expand U.S. production capacity [Witt et al., 1991].

This paper will focus mainly on the description of the PVMaT project in general and a description of the work carried out under Phase 1.

PHASE 1

The Phase 1 portion of the PVMaT project, the problem identification phase, was completed early in 1991. This effort involved competitive bidding open to any U.S. firm with existing manufacturing capabilities, regardless of material or module design. Early in 1991, the competitive selection process for this phase was completed with the award of twenty-two subcontracts. Each of

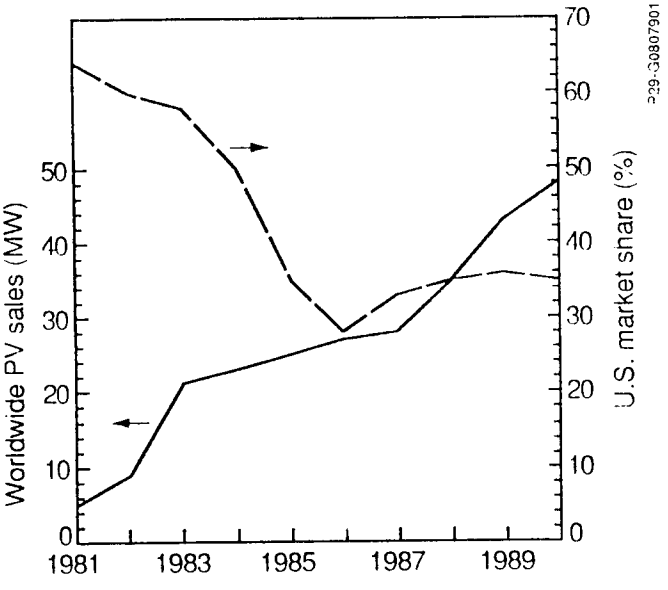


Figure 1. U.S. photovoltaic market share competitiveness.

these subcontracted efforts was funded at a level of up to $50,000 and involved a duration of three months (see Table 1). The problems identified by the research in this phase of the project were process-specific in nature and represented opportunities for individual industrial participants to improve their manufacturing processes, reduce manufacturing costs, increase product performance, and/or support a scale-up of U.S.-based manufacturing plant capabilities. These opportunities have since been detailed in the approaches suggested by these organizations for Phase 2 research. It is not anticipated that another solicitation like Phase 1 will occur. The procurement under this phase was only meant to precede and support the Phase 2A solicitation.

Phase 1 subcontracted research included five subcontractors working on flat-plate crystalline silicon technology, ten working on flat-plate thin-film modules (one on thin-film crystalline silicon, five on amorphous silicon, and four on polycrystalline thin-films), six working on concentrator systems, and two working on general equipment/production options.

Table 1. PVMaT Phase 1 Subcontractors

Subcontractor	Location Funding	Subcontract # Prin. Invest.
Spire Corporation	Bedford, MA $49,843	XC-1-10057-1 S.J. Hogan
Astropower Inc.	Newark, DE $50,000	XC-1-10057-2 W.R. Bottenberg
Solarex Corporation	Rockville, MD $49,974	XC-1-10057-3 J.H. Wohlgemath
Siemens Solar Indust.	Camarillo, CA $46,181	XC-1-10057-4 C. Eberspacher
Westinghouse Electric	Pittsburgh, PA $49,992	XC-1-10057-5 R. Rosey
Silicon Energy Corp.	Chatsworth, CA $49,602	XC-1-10057-6 M.J. Stern
Glasstech Solar Inc.	Golden, CO $49,913	XC-1-10057-7 S. Brown
Global PV Specialists	Canoga Park, CA $47,800	XC-1-10057-8 H. Somberg
Alpha Solarco Inc.	Cincinnati, OH $48,380	XC-1-10057-9 E.C. Schmidt
Photon Energy, Inc.	El Paso, TX $49,500	XC-1-10057-10 S.P. Albright
Energy Conversion	Troy, MI $50,000	XC-1-10057-11 M. Izu
Mobil Solar	Billerica, MA $50,000	XC-1-10057-12 A. Kalejs
ENTECH Inc.	Dallas, Texas $49,940	XC-1-10057-13 M.J. O'Neill
Boeing Aerospace	Seattle, WA $49,862	XC-1-10057-14 W.J. Stanbery
Solar Kinetics, Inc.	Dallas, TX $48,290	XC-1-10057-15 S.T. Saifee
Chronar Corporation	Lawrenceville,NJ $49,080	XC-1-10057-16 J. Macneil
Crystal Systems Inc.	Salem, MA $50,000	XC-1-10057-17 F. Schmid
Iowa Thin Films Tech.	Ames, IA $47,827	XC-1-10057-18 D.P. Grimmer
Solar Cells Inc.	Toledo, OH $38,034	XC-1-10057-19 J.L. Brown
Kopin Corporation	Taunton, MA $50,000	XC-1-10057-20 R.P. Gale
Solar Engineering Appl	San Jose, CA $50,000	XC-1-10057-21 N. Kaminar
Spectrolab Inc.	Sylmar, CA $35,169	XC-1-10057-22 D.R. Lillington

Flat-Plate Crystalline Silicon Modules

Crystalline silicon (c-Si) is the most common semiconductor material in PV devices. With Phase 1 PVMaT support, five companies have detailed their problems in this technology. This group of crystalline silicon research organizations consists of Mobil Solar Energy Corporation of Billerica, Massachusetts; Crystal Systems Inc. of Salem, Massachusetts; Westinghouse Electric Corporation of Pittsburgh, Pennsylvania; Solarex Corporation of Rockville, Maryland; and Siemens Solar Industries of Camarillo, California.

Mobil Solar is a major manufacturer of c-Si modules using the Edge-Defined Film-Fed Growth (EFG) method. Mobil is presently supplying a 180 kW-ac array to Photovoltaics for Utility-Scale Applications (PVUSA), a major demonstration project in California. Mobil Solar research efforts under Phase 1 of the PVMaT project have identified several problem areas that can be addressed to improve its process and reduce its silicon material usage by 50% [Kalejs, 1991]. Among these are (1) reducing material usage by decreasing wafer thickness to an 8-mil (200-μm) thickness, (2) increasing laser-cutting throughput, and (3) improving the wafer mechanical quality (cell testing shown in Figure 2).

Crystal Systems is a manufacturer of crystalline-silicon ingots, bars, and wafers. Crystal Systems research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Schmid, 1991]. Among these areas are the optimization of the Fixed Abrasive Slicing Technique (FAST) technology. This technology will allow for a reduction in slicing costs and an improvement in Crystal Systems' material utilization, thus reducing wafer cost.

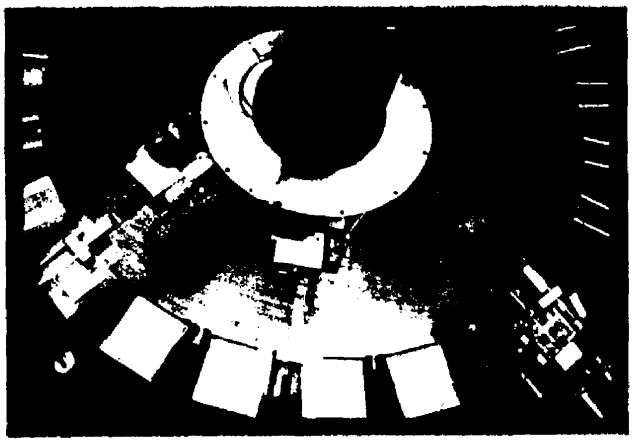


Figure 2. Cell testing of Mobil Solar Energy Corporation EFG-grown crystalline silicon-wafer devices.

Westinghouse is a manufacturer of dendritic web solar cells. Westinghouse researchers are working on reducing material and process costs through their dendritic web process. Westinghouse research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Easoz and Herlocher, 1991]. Among these are (1) increasing the growth rates, average crystal area, and productive furnace time; (2) using stacked diffusion; (3) manufacturing larger cells and modules; (4) increasing module efficiency by 1.4% absolute using surface passivation, improved antireflective coatings, and cell texturization; and (5) optimizing module design using the bifacial conversion characteristics of dendritic web solar cells.

Solarex presently manufactures both polycrystalline silicon cells and thin-film, single junction, amorphous silicon modules (see Figure 3). Solarex research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Wohlgemath et al., 1991]. Among these are (1) cell efficiency improvements (from the present 12.5%-16.5%) by introducing multijunction devices into the module assembly line, (2) more efficient use of materials via increased process yield, (3) reduction in labor content via automation, and (4) reduction in materials costs, particularly framing.

The fifth company in this group is Siemens Solar. They are presently the world's largest producer of PV with products including single crystal-silicon and thin-film copper-indium-diselenide ($CuInSe_2$) modules (see Figure 4). Siemens Solar research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Jester and Eberspacher, 1991]. Among these are (1) improvements in Cz c-Si growth, (2) improvements in existing wafer-sawing technology, and (3) improvements in cell processing and module fabrication.

Flat-Plate, Thin-Film Modules

Modules made of thin-film materials have inherent cost advantages, including the use of less semiconductor material and integrated manufacturing for cells and modules. Prices (per watt) for a-Si modules are comparable to those for crystalline silicon. Other promising thin-film technologies—such as $CuInSe_2$, cadmium

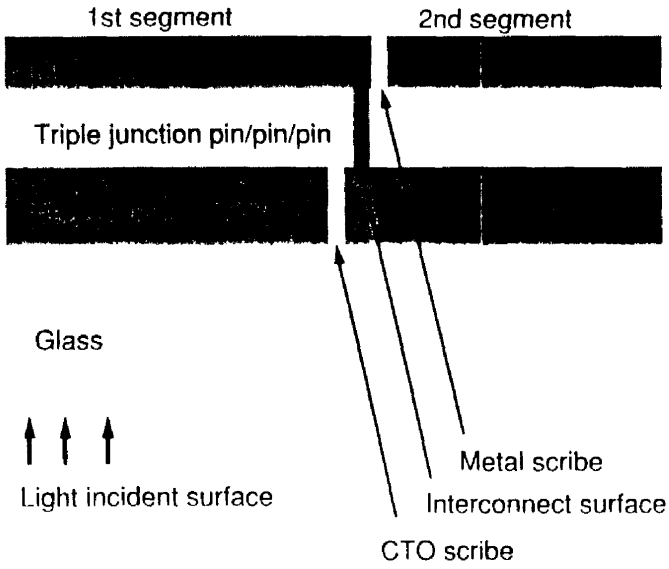


Figure 3. Solarex thin-film, single-junction, amorphous silicon module with individual laser scribes.

telluride (CdTe), thin-film silicon, and gallium arsenide are rapidly approaching commercialization.

Ten U.S. companies have received Phase 1 support to identify potential cost reductions for thin-film module manufacturing; one is working in thin-film crystalline silicon, five are concentrating on a-Si, and four have focused on polycrystalline thin-films.

AstroPower, Inc. is a manufacturer of, and the single organization that is focusing on, thin-film crystalline silicon solar cells (shown in figure 5). AstroPower research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Bottenberg, 1991]. Among these are

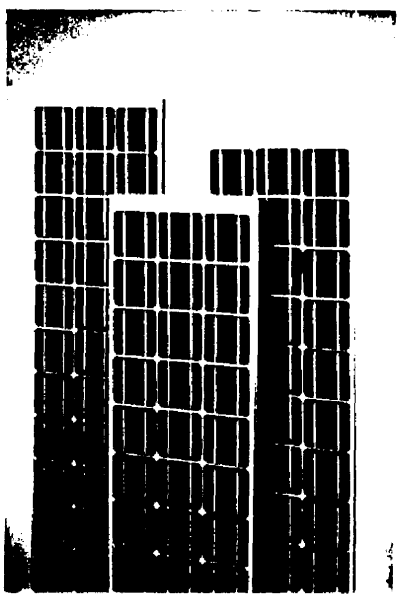


Figure 4. Siemens Solar Industries single crystal-silicon module.

(1) improving the production rate and quality of AstroPower's proprietary silicon film, (2) improving cell efficiency, (3) reducing material cost, (4) reducing labor cost through automation, and (5) increasing production capacity.

The five amorphous silicon (a-Si) research organizations are: Glasstech Solar Inc. of Golden, Colorado; Iowa Thin Films Technologies Inc. (ITF) of Ames, Iowa; Energy Conversion Devices (ECD) of Troy, Michigan; Silicon Energy Corporation of Chatsworth, California; and Chronar Corporation of Lawrenceville, New Jersey.

Glasstech is a manufacturer of single junction a-Si PV modules. Glasstech is presently using a proprietary glass-in/panel-out concept for the in-line processing of 40 cm x 120 cm a-Si modules. Glasstech research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Brown et al., 1991]. Among these are (1) incorporation of a vertical, double-sided reactor; (2) enhanced electrode and gas flow designs; (3) improved back contacts and tin-oxide layers; and (4) improved module designs.

ITF is a producer of monolithic a-Si modules on a continuous polymer substrate using automated processing. ITF research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Grimmer, 1991]. Among these are (1) developing roll-to-roll deposition capability for the a-Si layer and ZnO layer, (2) developing screen-printable etching steps for the top conducting contact layer, and (3) reducing the cost of the substrate material.

ECD is presently the manufacturer of continuous, roll-to-roll, tandem-junction, a-Si alloy devices. The roll-to-roll process produces a complete solar cell structure on flexible stainless steel webs 1,000 feet long and 14 inches wide. ECD research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Izu, 1991]. Among these are (1) incorporating narrow band gap material to improve conversion efficiencies and stability, (2) incorporating proprietary microwave plasma Chemical Vapor Deposition (CVD) manufacturing technology for high production throughput and higher gas utilization, and (3) reducing the cost of materials and assembly labor through new product design and automation.

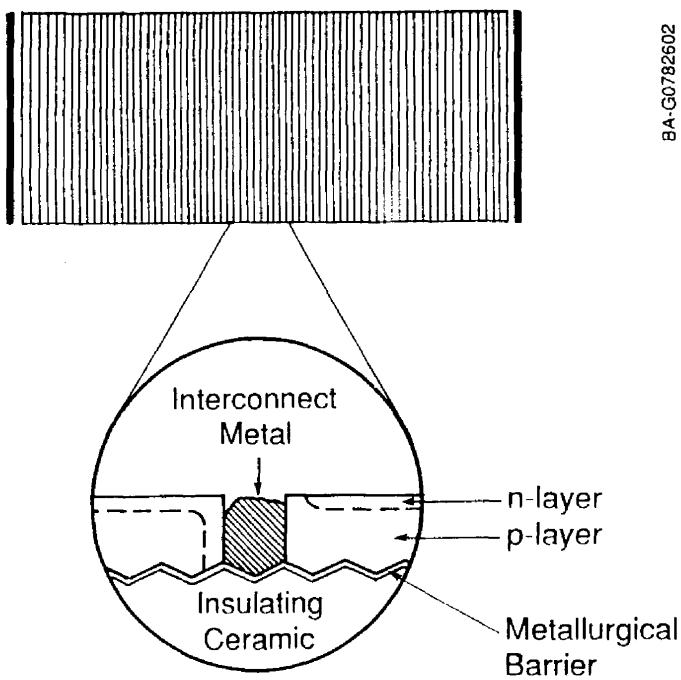


Figure 5. AstroPower thin-film crystalline silicon solar cell.

Silicon Energy is a manufacturer of multiple-junction, thin-film a-Si PV and is doing business as the Utility Power Group (UPG). They are presently a 300 kW/year production facility dedicated to internal R&D activities and various DOE PV programs. UPG research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Stern, 1991]. Among these are (1) optimization of the automation of its manufacturing line (shown in Figure 6), (2) improving and reducing the material required for encapsulation, and (3) introducing real-time monitoring for processing and quality control of its production line.

The fifth company in this group is Chronar, a manufacturer of thin-film a-Si PV. Chronar's research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Macneil, 1991]. Among these are the implementation of automated cost reductions.

Additionally, four organizations have focused on polycrystalline thin films. This group of research organizations consists of Siemens Solar Industries of Camarillo, California; Boeing Aerospace and Electronics of Seattle, Washington; Photon Energy, Inc. of El Paso, Texas; and Solar Cells Inc. of Toledo, Ohio.

Siemens Solar, as previously stated, is presently the world's largest producer of PV crystalline silicon and a-Si and products. Siemens Solar also has a major research effort in thin-film $CuInSe_2$ modules, for which they have a planned production of 20 kW in deliverable modules under the PVUSA project. Siemens research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Jester and Eberspacher, 1991]. Among these are (1) improving materials use efficiency, and (2) increasing yield and $CuInSe_2$ module efficiency through automation.

Boeing is a supplier of thin-film solar cell manufacturing systems and is a research organization working on the development and

Figure 6. Utility Power Group multiple-junction, thin-film a-Si production line.

scale-up of processing for $CuInGaSe_2$ modules. Boeing research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Stanbery, 1991]. Among these are (1) uniform large-scale evaporation sources for the constituent elements Cu, In, Ga, and Se; (2) a high-yield process for depositing ultrathin cadmium-zinc sulfide (CdZnS) conformal coatings onto $CuInGaSe_2$ films for high-quality heterojunctions; and (3) scaling up current aqueous deposition processes and novel low-temperature organometallic-chemical-vapor-deposition (MOCVD) techniques.

Two companies are investigating improvements to CdTe technology. The first, Photon Energy, is a manufacturer of CdTe/CdS cells and modules using low-cost, high-throughput, production-line scalable spray processes. They are presently scaling up for production of 20 Kw of 4-ft^2 CdTe module deliverables under the PVUSA project. Photon Energy research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Albright, 1991]. Among these are (1) reducing the labor cost through process automation, (2) improving module efficiency, and (3) reducing material usage through improved equipment design.

The fourth company in the thin-film group and the second CdTe company is Solar Cells Inc. (SCI), which is a development/manufacturing company producing large-area, thin-film PV modules for utility generating systems. Solar Cells is developing the technology for a high-throughput manufacturing line to produce 60 cm x 120 cm thin-film CdTe PV modules deposited by close-spaced sublimation (CSS). SCI research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Brown, 1991]. Among these are (1) investigating problems associated with uniform deposition of large-area modules, (2) developing equipment for very high-throughput deposition, (3) developing patterning techniques for large area modules, and (4) developing cost-effective encapsulation techniques.

Concentrators

Concentrator modules use lenses to intensify the sunlight falling on banks of small, highly efficient cells, which reduces material costs. R&D issues include optimum cell packaging and assembly, concentrator optics, and low-cost tracking arrays and support structures. Manufacturing cost reductions would occur primarily through automated assembly.

The six concentrator companies working in this area are Alpha Solarco Inc. of Cincinnati, Ohio; Solar Engineering Applications Corporation (SEAC) of San Jose, California; Kopin Corporation of Taunton, Massachusetts; ENTECH Inc. of Dallas, Texas; Spectrolab Inc. of Sylmar, California; and Solar Kinetics, Inc. of Dallas, Texas.

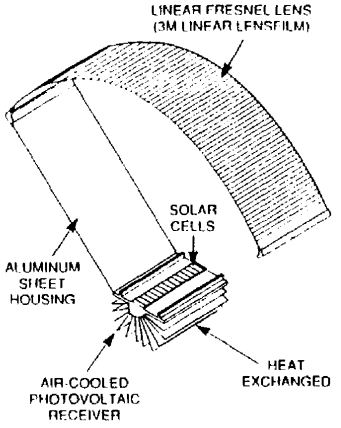
Alpha Solarco is a manufacturer of high-concentration PV modules. They are presently installing a second generation system on the world's largest automated two-axis solar tracking structure to produce low-cost electric power for utilities. Alpha Solarco research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Schmidt, 1991]. Among these are (1) developing and testing new manufacturing designs, methods, and materials for cell assembly and PV modules; (2) designing a prototype automated PV cell assembly line; and (3) developing production controls and training procedures for a prototype line.

SEAC is a manufacturer of 10X concentrator systems using one-sun cells with a 14 MW/year extruded lens manufacturing facility in place. SEAC research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Kaminar et al., 1991]. Among these are (1) investigating the problems associated with, and the potential of, adding module housing sides to lens extrusions and (2) significantly reducing labor cost through automation of the process.

Kopin is a manufacturer of high-efficiency, thin-film GaAs concentrator cells with a 22 MW/year prototype production capability presently in place. Kopin research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Gale, 1991]. Among these are (1) studying the existing pilot line to identify problems, (2) the design of a tandem cell structure for 1000X concentrators, (3) improving thin-film cell processing manufacturing, and (4) integrating either a chemical removal process called chemical epitaxial liftoff or the cleavage of lateral epitaxy for transfer (CLEFT) process into Kopin's cell fabrication process.

ENTECH is a manufacturer of concentrator modules. ENTECH researchers are presently producing 3 ft x 10 ft modules using large-area one-sun cells with line-focus Fresnel lenses, shown in Figure 7. ENTECH's research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [O'Neill et al., 1991]. Among these are (1) working with key vendors to improve the products they supply to ENTECH and (2) dramatically reducing labor cost and increasing yield by automation of the process.

Spectrolab is a leading supplier of GaAs and Si solar cells and modules to the PV industry. Spectrolab research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Lillington, 1991]. Among these are (1) optimizing two specific multijunction concentrator designs based on discrete GaAs and Ge cells,



First of two key advances, a curved Fresnel lens cover concentrates sunlight on a narrow strip of silicon cells.

Figure 7. ENTECH concentrator module using large-area one-sun cells with a line-focus fresnel lens.

(2) improving manufacturing yields, and (3) developing larger, more efficient MOCVD growth systems.

The sixth company in this research group, Solar Kinetics Inc. (SKI), is a manufacturer of several crystalline silicon concentrator systems with a 200-600 Kw/year capacity. SKI research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Saifee and Konnerth, 1991]. Among these are (1) designing and developing a prototype tooling for demonstration of low-cost injection molding of point focus Fresnel lenses, (2) detailed design of a 1 MW plant, and (3) detailed plant design for 5 MW capacity for automated manufacturing of 100-W concentrating PV modules.

Other Phase 1 Activities

Two Phase 1 participants are targeting improvements to their commercial lines of manufacturing equipment; these participants are Global Photovoltaic Specialists Inc. (GPS) of Canoga Park, California; and Spire Corporation of Bedford, Massachusetts.

GPS is a PV technology company that provides the equipment and know-how for integrated turnkey factories. They are presently investigating the installation of a fully-automated, computer-integrated production line in the United States. GPS research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Somberg, 1991]. Among these are (1) improving the characteristics of the semicrystalline cast wafers, (2) introducing processes such as spray-on diffusion, dual antireflection coatings, and ink-jet metallization printing, and (3) developing and integrating all of the requirements for full automation using computer integrated manufacturing.

The second company in this group, Spire Corporation, is a major manufacturer of PV test and module production equipment. They presently have small-scale production activities for high-efficiency silicon modules, and material research in compound semiconductors and a-Si. Spire research efforts under Phase 1 of the PVMaT project have identified several problem areas for the improvement of its process [Hogan, 1991]. Among these are (1) developing module processing equipment that will handle thin (< 200 μm) c-Si wafers, (2) increasing automation, (3) increasing processing rates, and (4) increasing processing yields.

PHASE 2

Phase 2 of the PVMaT project is now under way, with an expected duration of five years. This phase will consist of multiple competitive procurements over five years, and subcontracts awarded under any of these solicitations may be up to three years in duration. The first solicitation under this phase, 2A, was only open to those organizations that received awards in the Phase 1 solicitation. The award selection process has been completed for this solicitation and subcontract negotiations are currently under way with the top ranked offerors.

Phase 2 is considered the solution phase of the PVMaT project and will primarily address the process-specific problems of the specific manufacturer that were identified under Phase 1 efforts. The subcontracts envisioned under this phase are expected to be highly cost-shared by the U.S. government and U.S. industrial participants.

A second, overlapping, and similar process-specific Phase 2 solicitation is planned to follow the Phase 2A effort in about a year. Future solicitations under Phase 2 of PVMaT will be open to all organizations. Therefore, organizations that were not ready for the Phase 2A procurement cycle will have another chance to "ramp up" and participate in Phase 2B, the solution phase of this project.

PHASE 3

There are "general" R&D problems in the PV industry that are relatively common problems to the industry as a whole, a number of companies, or to the design and deployment of PV systems. The PVMaT project will address these generic problem areas through a team research approach. A Request for Proposals on this generic manufacturing technology was released in October of 1991 (RR-2-11219: Teamed Research and Development on Photovoltaic Manufacturing Technology, Phase 3A - Shared Process Issues), with proposals due in January of 1992. Participants for these generic research activities may come from a consortia of industrial companies, individual companies, a university or group of universities, combinations of company and university groups, or other groups with special capabilities for solving a particular problem. These proposed research organizations will focus on module-related R&D problems found to be common to several industrial PV manufacturers. They will also work in tandem with material and component manufacturers to help strengthen the PV industry.

CONCLUSIONS

In summary, the long-term goals of the PVMaT project are to assist U.S. industry in retaining and extending its world leadership role in the manufacture and commercial development of PV equipment, components, and systems and to encourage the investment of U.S. capital in U.S. PV manufacturing R&D and large-scale domestic manufacturing facilities. Phase 1 activities under this project have been completed, with each company identifying and developing a specific set of R&D areas that address their specific process problems. In FY 1991, a competitive solicitation was directed to these Phase 1 participants to identify R&D efforts appropriate under Phase 2 of this project. Under Phase 2, selected companies will develop and implement solutions to their manufacturing problems. The final selection of successful bidders under this phase has been completed, negotiations are under way at this time, and the award of research subcontracts is expected to begin soon. It is anticipated that as many as six subcontracts will be awarded under this phase, in which successful bidders will be supported for as long as three years as they realize improvements to their manufacturing processes. As with most PVMaT projects, these companies will be expected to cost-share their work.

Future efforts in the PVMaT project are expected to include an additional Phase 2B solicitation focusing on company-specific problems (open to all U.S. firms, including those who weren't yet ready for the Phase 1 call for proposals). Additionally, a Phase 3A solicitation was released in October of 1991 for subcontracted team research on module-related R&D problems common to several PV manufacturers. The activities under PVMaT to date have received outstanding support, and the level of interest in participation is exceptional.

ACKNOWLEDGMENT

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

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