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MANUFACTURING IMPROVEMENTS IN THE PHOTOVOLTAIC MANUFACTURING TECHNOLOGY (PVMAT) PROJECT

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ABSTRACT: The Photovoltaic Manufacturing Technology Project (PVMaT) 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. The goals of PVMaT are to 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; and enhance the investment opportunities for substantial scale-ups of U.S.-based PV manufacturing plant capacities. The approach for PVMaT has been to cost-share risk taking by industry as it explores new manufacturing options and ideas for improved PV modules and other components, advances system and product integration, and develops new system designs, all of which will lead to overall reduced system life-cycle costs for reliable PV end products.

The PVMaT Phase 4A module manufacturing R&D projects are just being completed, and initial results for the work directed primarily to module manufacture are reported in this paper. Fourteen new Phase 5A subcontracts have also just been awarded, and planned R&D areas for the ten focussed on module manufacture are described. Finally, government funding, subcontractor cost-sharing, and a comparison of the relative efforts by PV technology throughout the PVMaT project are presented.

Keywords: Manufacturing and Processing - 1: Module Manufacturing - 2: PV Module -3

1. INTRODUCTION

The Photovoltaic Manufacturing Technology Project (PVMaT) 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. Its goals are to 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; and enhance the investment opportunities for substantial scale-ups of U.S.-based PV manufacturing plant capacities.

PVMaT was initiated in 1990. Its concept, general management, and procurement approaches were developed by a team consisting of representatives from industry, government, and national laboratories. Multi-year projects are being carried out through cost-shared awards resulting from competitive solicitations. Each proposal is evaluated by a panel of experts selected from technology, manufacturing, business planning, and applications (including utility) areas. To date, there have been five phases: Phase 1, identifying the industry's problems on a company-by-company basis; Phase 2 (in two parts, A and B), supporting research and development (R&D) to resolve module manufacturing problems and reduce manufacturing costs; Phase 3, supporting R&D to resolve generic issues in module manufacturing; Phase 4A, supporting R&D to facilitate product-driven manufacturing advances involving balance-of-systems components as well as modules; and Phase 5A, continuing efforts similar to those addressed Phase 4.

This paper describes activities primarily related to module manufacture and includes Phase 4A2 R&D results and newly awarded Phase 5A subcontract plans. Phase 4A1 and 5A1 subcontracts, addressing systems and system components other than modules, are described in a separate paper in these proceedings. The paper is by H. P. Thomas et al., from the National Renewable Energy Laboratory. Phases 1, 2, and 3 of PVMaT have been described in detail in earlier papers [1-3]. Finally, in this paper, we present some summary information on government funding, subcontractor cost-sharing, and a comparison of the relative efforts by PV technology throughout the PVMaT project.

2. PHASE 4A2

R&D results from the five PVMaT 4A2 projects are presented below.

ASE Americas, Inc. is advancing its technology through manufacturing line improvements that consist of (1) a further decrease in the edge-defined film-fed growth (EFG) wafer thickness to 250 micrometers in mass production and an increase in the number of wafers produced from one crucible,

(2) an increase in the electronic quality of as-grown EFG material to meet the demands for higher-efficiency solar cells, (3) an improved solar-cell fabrication technology, (4) developing a diffusion glass removal process that is environmentally safe and reduced in cost, and (5) developing an integrated interconnect, lamination, and fabrication method. Recent accomplishments include construction and demonstration of prototype equipment for removing phosphorous glass from diffused wafers that can reduce acid consumption and fluoride emissions by 95%, implementation of the first phase of a Statistical Process Control program and the development of a new module diode housing.

AstroPower, Inc. has completed its 4A subcontract that addressed the development of a low-cost manufacturing capability for Silicon-Film^{TM} solar cells and panels by using the continuous-processing capability of the Silicon-Film^{TM} technology. Their efforts have been to (1) eliminate wafer-sawing steps, (2) develop a high-yield, continuous manufacturing technology, and (3) increase solar-cell size. The AP225 Silicon-Film^{TM} cell is in production, and efficiencies exceeding 12% have been measured on this 240-cm^2 cell. Small-scale devices have demonstrated efficiencies of 16.6%. Processing advances include the development of a continuous diffusion process and a continuous antireflection-coating process.

Iowa Thin Film Technologies Inc. is increasing the throughput of their metallization, a-Si deposition, laser-scribing, and welding processes, with the goal of reducing the overall module manufacturing costs on the ITF production line by 68%. They have improved laser registration and substrate throughput by 30% through the development of a new position detector and alignment system and the installation of a new laser scriber, increased throughput in the printer by 70% with an active screen alignment that allows a 10-micron reproducibility, identified a water-based ink that withstands the subsequent processing temperatures, and improved the throughput of the ZnO deposition process step by 50%.

Photovoltaics International, LLC is establishing a low-cost manufacturing capability for linear concentrator modules by using their continuous-processing capability. Under this manufacturing effort, they will take advantage of the continuous-processing capability of their lens and side-panel extrusion technology. They have completed the tooling and testing of the new 20-inch lens extrusion process equipment, completed the design and initial fabrication of the receiver assembly station, completed design and prototyping of the roll-formed frame process, and completed development of the self-jigging, low $V_{oc,}$ linear concentrator module.

Siemens Solar Industries is addressing improvements in their Czochralski (Cz) silicon module manufacturing technology to reduce module cost per watt by 18%. These goals are being addressed by identifying alternative Cz module designs, material sources, and processes that lower module component costs, and by improving manufacturing process yields, reducing labor costs in Cz module manufacturing, and increasing productivity. They have implemented production of the 150-mm cell and module product line, which leverages the use of silicon by over 30% in the production of Cz solar cells; continued to improve manufacturing productivity and yield by over 10%; implemented Statistical Process Control in their diffusion and cell printing lines to improve capability and electrical yields; and implemented polysilicon preparation techniques to mitigate silicon supply variation on yields.

3. PHASE 5A

Eleven subcontracts have been awarded in the PVMaT 5A competition and three more are in the final stages of negotiations. The 14 subcontracts are expected to total about $60 million over a 3-year period with a 48% subcontractor cost-sharing. (Thirty-one offerors responded to the PVMaT 5A Request for Proposals. They proposed activities totaling more than $97 million. Of that amount, about 49% was offered as subcontractors' cost-share.)

Table 1 presents the 5A winners and their respective areas of manufacturing R&D. Subcontractors addressing primarily their own process-specific module manufacturing problems are designated 5A2. Subcontractors addressing primarily generic R&D of interest to broad portions of the industry or system and other non-module component manufacturing problems are designated 5A1.

TABLE 1. PVMaT PHASE 5A MANUFACTURING AREAS

Type	Company	Manufacturing R&D Area
5A1	Ascension Technology, Inc.	Manufacture of the Advanced SunSine^{TM} 325 AC Module
5A2	ASE Americas Inc.	The EFG High Volume PV Manufacturing Line
5A2	AstroPower	Silicon-Film^{TM} Solar Cells by a Flexible Manufacturing System
5A1	Crystal Systems, Inc.	Production of Solar Grade Silicon by Refining of Liquid Metallurgical Grade Silicon
5A2	Energy Conversion Devices, Inc.	Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy PV Manufacturing Technology
5A2	Evergreen Solar, Inc.	Continuous, Automated Manufacturing of String Ribbon Si PV Modules
5A2	Global Solar Energy, L.L.C.	Throughput Improvements for Thin-Film Based CIGS Modules
5A1	Omnion Power Engineering Corporation	Manufacturing and System Improvements for One and Two kW Inverters
5A1	PowerLight Corporation	Advanced Powerguard^{R} Manufacturing

5A2	Siemens Solar, Inc.	R&D on Siemens Cz Silicon Product Manufacturing
5A2	Solar Cells, Inc.	R&D on CdTe Product Manufacturing
5A2	Solarex	Improvements in Polycrystalline Silicon PV Module Manufacturing
5A2	Spire	Post-Lamination Manufacturing Process Automation for Photovoltaic Modules
5A1	Utility Power Group	Development of a Fully-Integrated PV System for Residential Applications

As mentioned above, Phase 5A subcontracts, addressing systems and system components other than modules, are described in a separate paper by H. P. Thomas et al., from the National Renewable Energy Laboratory. The other 5A awards are described below.

ASE Americas Inc. will work on improvements in process integration, Statistical Process Control implementation, data systems implementation, and ISO9000 and ISO14000 implementation. The improvements will be directed at reducing yield losses in areas of electrical and mechanical performance and reducing chemical waste. ASE will also develop processes that can be scaled to high volumes in the growth of thin EFG cylinders with improved productivity, as well as the production of solar cells from much thinner wafers. This effort includes work in laser-cutting technology to increase speed for cutting wafers and R&D to ensure a stronger EFG wafer and improve cell processing to achieve 15% solar cell efficiencies.

AstroPower, Inc. is improving their flexible manufacturing system for their Silicon-Film™ solar cells. Their research during this three-year effort will address several areas of the Silicon-Film™ production line, including the development of a continuous, in-line processing technology for large-area (30-cm wide by 1.2-m long) planks with higher throughputs, reduced material cost, and increased safety. As part of this subcontract, AstroPower will develop a continuous, high-speed, large-area contact metallization process for large-area Silicon-Film™. This will significantly increase their throughput, improve front-contact line width and contact resistance, and reduce cost. Achieving the expected improvements in the Silicon-Film™ sheet-growth processes would result in large-area (900-cm^2), 12%-efficient (10.8-W) solar cells.

Crystal Systems, Inc. is working on the production of solar-grade silicon by refining liquid metallugical-grade (MG) silicon at low cost, in abundant supply to meet the PV industry's rapidly expanding needs. The approach proposed is based on thermo-chemical refining techniques and the Heat Exchanger Method $(HEM)^{TM}$. The goal of this work will be equipment and processes adequate for use in an MG-silicon production plant using 500-kg charges, as well as demonstrating the removal of impurities, including boron and phosphorous, to less than 1 ppma after refinement at the 500-kg charge level. The development and implementation of this upgraded solar-grade silicon feedstock is expected to result in significant labor cost savings and increased throughput, with the production cost goal of solar-grade silicon to be less than $20/kg.

Energy Conversion Devices, Inc. (ECD) is performing manufacturing R&D to: develop 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; develop a set of in-line, real-time, material-quality monitoring systems for production machines; demonstrate the feasibility of using Zn metal targets in the DC sputtering process to prepare ZnO layers for high-performance back-reflectors; and redesign the internal hardware for a-Si intrinsic layer (i-layer) deposition chambers.

Evergreen Solar, Inc. is improving their string ribbon crystal-growth process through reductions in labor and material costs, and capital costs of additional furnaces, through increased automation and increased efficiency. They will also develop high-throughput automated cell and module manufacturing line processes such as: a continuous glass etch; high-speed drying and application of decals; automation in diffusion, glass etch, high-speed drying, printing and application of contact decals; and molecular hydrogen passivation. Additionally, Evergreen will increase their manufacturing automation and throughput and decrease their labor costs by deploying a patterned backskin, an in-line tester, and an automated stringing operation.

Global Solar Energy, L.L.C. will perform R&D as follows: refining an all-laser, multiple-beam, high-speed scribing method for all copper indium gallium diselenide (CIGS) PV layers; developing a process for ink-jet printing as a replacement to screen printing for insulating scribed areas, and integration of this process, along with the laser-scribing methods, into the manufacturing production line; developing and integrating a high-rate CIGS deposition process for a moving flexible substrate onto their manufacturing line; designing, assembling, and optimizing a Parallel Detector Spectroscopic Ellipsometer (PDSE) for transfer onto the thin-film CIGS production line; and developing an alternative back-contact material that is compatible with CIGS processing on a flexible substrate.

Siemens Solar Industries is concentrating their research on the development and integration of new optimized cell fabrication processes into their manufacturing line for the production of 17%-efficient, 125-μm thick cells. Also, they will develop large-area cell production capability for 200-mm-diameter, 4.5-watt prototype solar cells and low-cost prototype modules. Siemens environmental, safety, and health activities will be directed toward reducing their hazardous waste by over 50% through recycling and re-use of slurry materials in their wire-saw process and a more than 70% reduction in caustic waste.

Solar Cells, Inc. (SCI) is developing, designing, and implementing an improved ethylene vinyl acetate (EVA) lamination process, an improved potting procedure, and an

improved scribing technique for the SCI cadmium telluride (CdTe) module production line. They will also complete qualification testing of their frameless, 60-cm x 120-cm module with pigtails, as well as other advanced module designs such as: (1) investigating a junction box instead of pigtails; (2) evaluating module sizes other than 60 cm x 120 cm; (3) developing alternative module voltage configurations; (4) and developing alternative encapsulation materials or processes. Additionally, SCI will work toward refining and improving their environmental, safety, and health programs throughout their facilities and initiating activities related to obtaining ISO14000 certification.

Solarex is performing R&D in several parallel areas. The first area involves Solarex working with a lower-tier subcontractor to develop a process to produce silicon feedstock from commercial-grade H_2SiF_6. Also, Solarex will refine production-line process areas for improved product and materials handling to increase production line yield and reduce labor costs. They will improve process measurement and control in their production line and reduce rework by implementing an improved information system. Solarex will also make improvements in their casting and wafer-sawing processes, while developing manufacturing techniques that are environmentally more benign. Solarex will demonstrate and implement a cost-effective, robust, cell process that produces a minimum average cell efficiency of 15% and improves their cell-line electrical yield. Finally, they will develop an encapsulation system that meets their technical and reliability requirements and can be laminated and cured more quickly in the present Solarex laminators.

Spire Corporation is addressing automated photovoltaic module assembly. They will develop a series of automated, flexible systems, including (1) an integrated module-edge processing system, combining automated edge trimming, edge sealing, and framing processes, (2) an automated junction-box installation system, (3) a final module test system combining high-voltage isolation testing and performance testing in a SPI-SUN SIMULATOR™, and (4) an automated buffer storage system. Solar-cell laminates and other module materials provided by the industry will be used by Spire to evaluate the automated processes developed in the program. The systems will be capable of assembling modules made with either crystalline-silicon solar cells or thin-film solar-cell laminates.

4. PVMAT - TECHNOLOGIES AND RESOURCES TO DATE

Table 2 shows, by technology area, the total funding for PVMaT for Phases 2 through 4 (the problem solution phases). The more mature crystalline-silicon technologies have the largest share of the funding. The amorphous-silicon area is second in size and probably benefitted from the large U.S. research funding of the 1980s in its apparent initial lead in thin-film efforts. But we are now seeing CIS join CdTe as a promising candidate for manufacturing improvements leading to viable products. See Global Solar Energy in Section 3 above for a description of the first CIS subcontract in the problem-solving stage of PVMaT.

TABLE 2. PVMaT FUNDING BY TECHNOLOGY
(through Phase 4)

Technology	Funding (US $K)	Percent by Technology
Amorphous Silicon	17,184	26
Cadmium Telluride	8,206	13
Concentrators	6,162	9
Crystalline Silicon	26,588	41
Generic/Balance of Systems/Systems	7,500	11
TOTALS	**65,640**	**100**

Table 3 shows the relative cost-sharing by phase for the PVMaT project to date. The subcontracts awarded in 3 and 4A1 are generally of the more generic or system component and integration type, with less emphasis on process-specific module manufacture. In addition, these awards were constrained to less effort, both in resources and time. The offerors in these areas have also been smaller companies, generally meeting the "small business" criteria for PVMaT participation. Consequently, they have not been required to cost-share as heavily, and the data show that they have not.

TABLE 3. PVMaT FUNDING AND COST SHARE
(By Phase)

Solicitation	DOE Funds (US $K)	Private Funds (US $K)	Private Cost Share %
PVMaT 2A - Process Specific	30,738	21,316	41
PVMaT 2B - Process Specific	13,384	14,557	52
PVMaT 3 - Generic	2,220	751	25
PVMaT 4A1 - Product Driven BOS and Systems	5,280	1,742	25
PVMaT 4A2 - Product Driven Module Manufacturing	14,017	9,949	42
TOTALS	**65,640**	**48,317**	**42**

5. CONCLUSIONS

PV manufacturing processes, technology, and cost reduction have been substantially advanced by the U.S. DOE PVMaT project and the U.S. PV industry. PV manufacturing improvements continue in both the more mature crystalline-silicon approaches and the newer thin-film technologies. Finally, based on the response to the most recent PVMaT solicitation, Phase 5A, industry has identified many areas of PV manufacturing which require continued or new R&D, and the responding companies find it useful to share with the government program in supporting these R&D efforts.

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