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Photovoltaics: From the Laboratory to the Marketplace

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Photovoltaics:
From the Laboratory to the Marketplace

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ABSTRACT

Photovoltaics (PV), the direct conversion of sunlight to electricity, is experiencing significant improvements in technology performance and lowered costs. Fostering these improvements, the SERI Photovoltaic Advanced Research and Development (PV AR&D) Project supports research and provides services to the U.S. PV industry. The PV AR&D Project is funded by the U.S. Department of Energy (DOE) Photovoltaics Division under the Office of Utility Technologies. This paper presents the recent advances and future direction of the PV project. The project, implemented through SERI in-house research and subcontracts has about half of the funds competitively awarded to industry and universities. Research areas are Fundamental and Supporting Research, Advanced Thin-Film Materials, High-Efficiency Materials, Module Development, and Systems Development. Materials of interest include amorphous silicon, copper indium diselenide, cadmium telluride, crystalline silicon, gallium arsenide and related alloys, transparent conductors, antireflection coatings, substrates, and encapsulants.

The PV project inherently provides technology transfer that helps industry shorten the time to bring R&D advances to the marketplace. SERI annually performs over 10,000 measurements for the entire PV community, participates in collaborative research, and welcomes visiting scientists. Through subcontracted R&D, SERI funds government/industry cost-shared partnerships, university participation and new ideas programs, and the Photovoltaic Manufacturing Technology (PV MaT) initiative. Two specific areas of recently increased national focus are (1) manufacturing processes for cost-effective PV modules, and (2) systems development for high-value utility applications. The SERI research approach is based on facilitating direct contact between industry, electric utilities, and others interested in PV technology. This approach heavily relies on SERI/industry partnerships. The arrangements vary to address generic and company-specific problems to improve the U.S. industry's competitive position and accelerate greater electric utility deployment of PV systems.

INTRODUCTION

Electricity from photovoltaic (PV) systems continues to expand in competitiveness as industry quickens its pace in applying laboratory advances to marketplace products. The PV advantages are zero cost for fuel, low operation and maintenance costs, high reliability, system modularity, and its benign environmental impact. Many semiconductor materials are available to make PV solar cells, and there are various ways to fabricate PV cells and produce systems. This diversity presents another PV advantage -- that it does not rely on some unique property of one exotic approach. In this sense, PV is a generally robust technology.

Stand-alone PV systems and consumer products remain the backbone of today's PV marketplace. Still, electric utilities are increasing their field experience with high-value applications and utility-scaleable PV systems. And research is providing a better understanding of PV materials, devices, and manufacturing processes, and how to integrate components into systems. This research is helping industry satisfy the requisites of an expanding world marketplace (Table 1 [1,2]) for safe, clean, cost-competitive PV electricity.

Country	1985	1986	1987	1988	1989	1990 (est.)
United States	7.6	7.0	8.65	11.3	14.7	--
Japan	10.8	13.4	12.45	13.0	14.2	--
Europe	3.7	4.3	4.7	6.9	7.9	--
Rest of World	1.4	2.3	2.8	4.0	5.3	--
Total (MW)	23.5	27.0	28.6	35.2	42.1	52-55

Table 1. World PV module shipments (megawatts) [1,2].

Critical technical barriers to more reliable and higher-performance PV systems are being overcome by the shared efforts of government, industry, universities, and utilities. However, institutional and economic factors also pose limiting constraints to PV's competitive edge for utility-scale systems. SERI takes on a significant responsibility in developing and implementing a national energy research program mandated by federal law. This paper describes the recent progress and future direction of SERI's PV research activities carried out for the U.S. Department of Energy (DOE).

The U.S. DOE National Photovoltaics Program sponsors research and development to result in a technology base from which private enterprise can choose options for further development and competitive application in U.S. electricity markets. Table 2 [3] identifies the long-term PV technology prospects. Under the direction of the Photovoltaics Division of the Office of Utility Technologies, the national program conducts research in areas of Fundamental and Supporting Research, Advanced Thin-Film Materials, High-Efficiency Materials, Module Development, and Systems Development. SERI and Sandia National Laboratories manage the day-to-day research activities, perform research at their own facilities, and provide services and technical support.

THE SERI PHOTOVOLTAIC ADVANCED RESEARCH AND DEVELOPMENT PROJECT

The SERI Photovoltaic Advanced Research and Development (PV AR&D) Project conducts and manages national research and provides services to the PV community and electric utilities for resolving key technology-limiting problems and for overcoming critical institutional and economic constraints. The PV project is implemented through SERI's Solar Electric Research Division (Figure 1). Approximately 80 highly qualified scientists, engineers, technicians, managers, analysts, and other professionals at SERI conduct this research with over 50 subcontracted research groups at universities, in industry, and at non-profit laboratories.

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

* Balance-of-system costs vary depend on the type of flat-plate system (fixed, one- or two-axis tracking).

Table 2. **Federal/Industry long-term (year 2000) technical goals [3]** (1986 dollars; based on levelized electricity cost of 6¢/kWh).

SERI's PV activities involve conducting basic and applied research within our own laboratories, developing state-of-the-art measurement and device fabrication capabilities, managing subcontracted R&D, and transferring R&D results to industry. Through subcontracted R&D, the project funds government/industry cost-shared partnerships, a new-ideas program, a university participation program, and the Photovoltaic Manufacturing Technology (PV MaT) project. The modes of operation used in the PV AR&D Project inherently provide technology transfer and help industry shorten the time required to bring laboratory advances to the marketplace. SERI annually performs over 10,000 measurements for the entire PV community, participates in

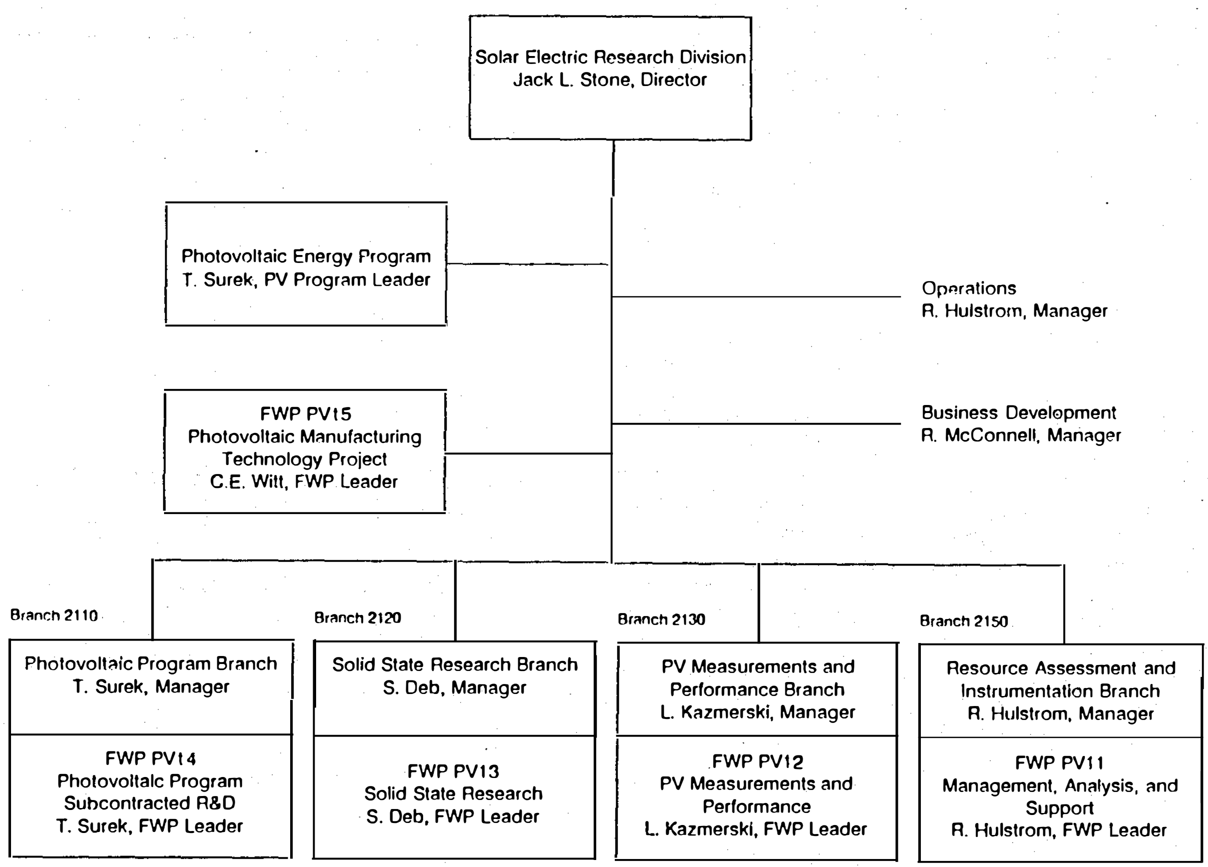


Figure 1. **SERI Solar Electric Research Division and Photovoltaic Advanced Research and Development Project (shaded areas) organization.**

collaborative research, welcomes visiting scientists, manages competitively solicited subcontracted R&D, and provides support to other PV projects such as the Photovoltaics for Utility-Scale Applications (PVUSA) project.

Research activities are undertaken on promising photovoltaic materials. These include thin films of amorphous silicon (a-Si), polycrystalline thin films of copper indium diselenide ($CuInSe_2$ or CIS) and cadmium telluride (CdTe), thin films of gallium arsenide (GaAs), high-efficiency materials (primarily silicon and Group III-V alloys), and crystalline silicon sheet materials. The research includes studies of single- and multijunction devices made from these materials and other alloys. Table 3 shows the distribution of subcontract funds by material category. The SERI in-house funding emphasis is similar to that of the subcontracted program. Over half of the PV AR&D budget is allocated yearly to subcontracts. In FY 1989, this included nearly 50 subcontracts. Approximately two-thirds of the subcontracts were with universities, with funding near $4.5 million.

	FY 1978-'88 ($M)	FY 1989 ($M)	FY 1990 ($M)
SERI In-House			
Research	68.90	8.90	7.33
Capital Equipment	14.10	0.60	0.60
Subtotal: In-House	83.0	9.50	7.93
Subcontracts[a]			
A-Si Thin Films	59.20	7.90	6.17
Polycrystalline Thin Films	37.10	3.50	4.83
High-Efficiency	28.80	2.10	1.91
Crystalline Silicon	22.10	0.50	0.48
New Ideas	17.60[b]	0.40	0.41
University Program	4.90	0.80	0.43
PV MaT	N/A	N/A	1.77
Subtotal: Subcontracts	169.70	15.20	15.99
Total: PV AR&D Project	**252.70**	**24.70**	**23.93**

(a) Includes about 15% for program management, fees, etc.
(b) Includes $9.0M for photoelectrochemical cell research.

Table 3. SERI PV Advanced R&D Project Budget History

Technical Accomplishments

Considerable research progress continues to evolve through the U.S. National Photovoltaics Program. In addition to increasing sunlight-to-electricity efficiency records, SERI in-house researchers and subcontractors made important advances in measurement and modeling techniques, deposition approaches, and theoretical findings, all with implications on the stability and performance of various devices. In addition, SERI has invented or developed new solar cell devices, equipment and processes. The following subsections describe the research activities and selected accomplishments. The subsections are grouped according to the major materials areas, and cross-cutting activities are described under the Support Activities subsection.

Amorphous Silicon Thin Films. The Amorphous Silicon Research Project (ASRP) was established at SERI by DOE in 1983. The ASRP oversees all DOE-funded research on amorphous silicon (a-Si), from cell research, to module testing, to systems evaluations. The objectives are to improve and understand the optoelectronic properties of a-Si-based alloy materials and improve the conversion efficiency of single- and multijunction solar cells and modules. The technology base is being developed to achieve the near-term goal (1993) for modules with stabilized efficiencies of 10%-12%. Future technical goals are aimed at achieving 15%-efficient modules.

The major ASRP components are SERI internal research and subcontracted research (Table 4). The internal research consists of fundamental research on materials, cells, and film deposition, cell and module testing, and reliability studies. The subcontracted work is divided into two programs, a government/industry program (cost-shared partnerships) and a fundamental research program. Currently, we are executing the third three-year amorphous silicon partnership program aimed at producing multijunction modules of 10% (same band gap) and 12% (different band gap) stabilized efficiencies. The previous three-year ASRP partnership program was recognized for excellence in technology transfer by the Federal Laboratory Consortium.

Research Organization	Research Area
Subcontracted Government/Industry Program	
Energy Conversion Devices & United Solar Systems Corp.	Multijunction module R&D.
Glasstech Solar	Multijunction module R&D.
Solarex Corp.	Multijunction module R&D.
(Additional awards expected)	Multijunction module R&D.
Subcontracted Fundamental Research	
Harvard University	Transparent conductive oxides.
JPL	Deposition characterization.
NIST	Deposition characterization.
(Approximately 10 additional awards expected)	Instability, low bandgap alloys, modeling, new deposition and measurement methods.
Solar Energy Research Institute	
Solid State Research Branch	Metastable effects, alloys, and novel deposition methods.
PV Measurements and Performance Branch	Impurity analyses, reliability, cell and module measurements.

Table 4. Research organizations supported by the DOE/SERI Amorphous Silicon Research Project.

Federal research support has helped industry to establish the single-junction and same-band-gap multijunction module technology currently in production. Technology transferred from the laboratory to production includes all-laser patterning techniques for modules, new polymer encapsulants, glass-to-glass encapsulation, alternative dopant gases for p-layers, and improved transparent conducting oxides (TCO). Figure 2 shows the module efficiency progress and Figure 3 shows the dramatic increase in the size of amorphous silicon modules of comparable efficiencies.

The general goal for module reliability is to develop thin-film modules that could last 30 years in the field while maintaining their electrical output performance within acceptable limits (such as 90% of their initial rating). For a-Si modules, reliability depends primarily on the a-Si light-induced degradation and, more generally, the module construction, especially the encapsulation.

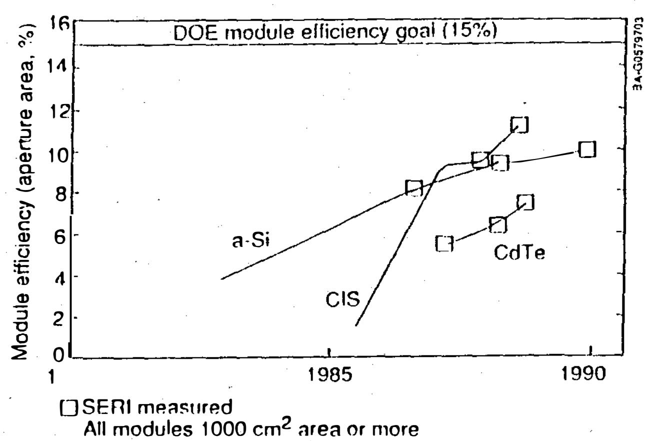


Figure 2. Thin film module efficiency progress.

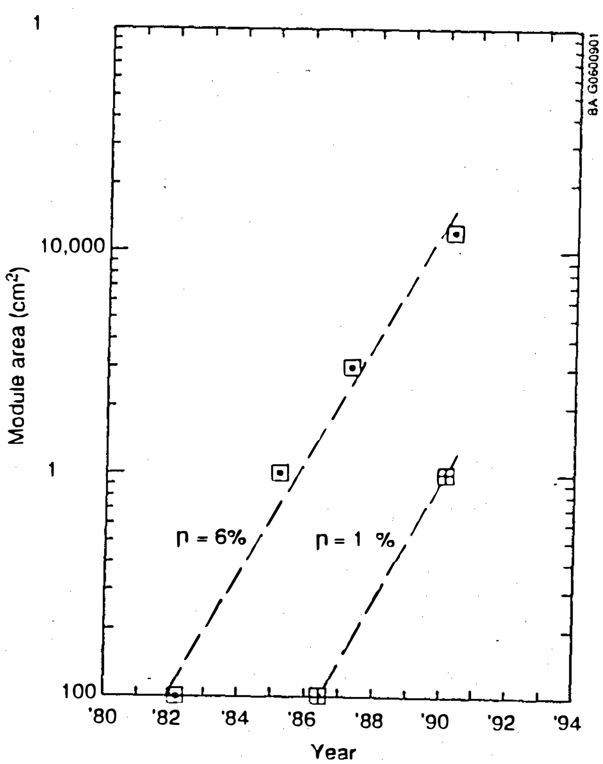


Figure 3. Amorphous silicon: progress in module area for a given efficiency (η).

Amorphous silicon films experience a light-induced degradation effect, which reduces performance within the first few weeks to months after deployment and then stabilizes after about one year. Laboratory results indicate that this is a self-limiting effect, intrinsic to the a-Si film, and a function of the i-layer thickness. In the past, typical single-junction modules tested at SERI exhibited a 30% (or greater) decrease in power within the first year; thereafter, the power output appeared to stabilize. (Any further degradation may be from problems with the encapsulation.) Improved stability over single-junction modules is observed in multijunction modules, resulting in stabilization near 80% of the initial power. Cell and material research is leading to further improvements that will be transferred to future module designs.

Amorphous silicon cell technology advances include better single- and multijunction device designs and stability improvements. Thin film cell initial conversion efficiencies (total-area) are shown in Table 5. Recently, more stable amorphous silicon devices have been tested with performances that extrapolate to about 90% of initial efficiency after one year's operation (for different-band-gap, multijunction devices with very thin i-layers).

Advances in materials research are providing better TCO and an increasing knowledge to improve PV performance and stability. During 1990, the fundamental research subcontract activities were recompeted and SERI issued a request for letters of interest on fundamental amorphous silicon research (subcontract negotiations are underway). These studies will continue research on interfaces, microcrystalline doped layers, the role of hydrogen in a-Si film stability, low-band-gap alloys for the bottom junction of multijunction cells, and alternative deposition processes and dopants.

	Total-area η (%)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	Total area cm^2	Comments
Energy Conversion Devices	12.4 (13.3)*	2.54	6.96	70	0.25	a-Si/a-Si/a-SiGe
Glasstech Solar	10.1	0.85	17.0	70	1.0	a-Si‡
Solarex	11.7	0.877	19.0	70.5	0.26	a-Si
Siemens Solar	9.7	0.871	15.6	71	4.05	a-Si
Siemens Solar	1 1.6 (13.1)	0.496	37.0	63	4.05	CIS
Siemens Solar	13.0 (14.6)†				4.05	4 terminal a-Si/CIS
Photon Energy	12.3	0.783	24.98	63.7	0.313	CdS/CdTe
Kopin	23.3	1.01	27.55	83.8	4.00	GaAs CLEFT
Kopin	21.0	4.034	6.55	79.6	16.00	GaAs CLEFT minimodule

* numbers in ( ) represent active-area efficiencies
† mechanically stacked, combined from single cell measurements
‡ i-layer deposited at 2 nm/s, 110 MHz plasma

Table 5. Summary of best thin film cell efficiencies measured at SERI.

Polycrystalline Thin Films. Significant progress has been made in understanding the materials and device fundamentals and in improving the efficiencies of polycrystalline CIS and CdTe thin-film solar cells and modules. Alternative production approaches and outdoor stability tests of modules are encouraging. A government/industry cost-shared three-year partnership program began, wherein industry supplied 30% or more of the subcontract funds. Also, each subcontract was required to have a university subtier participant; this allows industry to lead the R&D while gaining the support of research at universities. Table 6 shows a recent listing of industry and university participants in the program, although negotiations are under way for additional subcontracts.

Understanding polycrystalline fundamentals is challenging because they depart significantly from the conventional properties and behaviors of familiar materials such as single-crystal silicon or gallium arsenide. Standard measurement and characterization procedures and device modeling are more complex for polycrystalline thin films. Reasons include the numerous grain boundaries, multicomponent compounds with unknown defect structures, and the difficulty of fully characterizing gradients within the various semiconductor layers of the polycrystalline materials. Using the SERI-patented spectroscopic scanning tunneling microscope, our researchers obtained the first atom-specific images of CIS and identified vacancies in the material, thus helping explain potential defect mechanisms.

Research Organization	Research Area
Subcontracted Research	
California Institute of Technology	Contact investigation of $CuInSe_2$/Mo interface.
Colorado State University	Characterization and modeling of CdTe and $CuInSe_2$ cells.
Georgia Institute of Tech.	MOCVD of CdTe and $Cd_{1-x}Zn_xTe$ cells.
Glasstech and Glasstech Solar	Large volume CdTe fabrication.
Institute of Energy Conversion	Selenized and evaporated $CuInSe_2$; CdTe cells; device modeling.
International Solar Electric Technology	E-beam/sputtering Cu,In layers and selenization; submodules.
Photon Energy	900 to 3900 cm^2 CdTe modules.
Purdue University	Modeling of $CuInSe_2$ and CdTe cells.
Solarex Corporation	Sputtered $CuInSe_2$ submodules.
University of Colorado	Rapid thermal processing Cu/In/Se films made by electroplating or sputtering.
University of Illinois	Sputtered/evaporated $CuInSe_2$ cells.
University of South Florida	MOCVD and close space sublimation of CdTe and ZnTe cells.
University of Toledo	Innovative fabrication of CdTe.
Solar Energy Research Institute	
Solid State Research Branch	Growth, characterization and device fabrication of $CuInSe_2$.
PV Measurements and Performance Branch	Characterization, analyses, reliability, cell and module measurements.

Table 6. Research organizations supported by DOE/SERI for polycrystalline thin film research.

Recent studies on CIS-based materials have provided comprehensive information on processing parameters versus properties (electrical, optical, microstructural, and morphological), identified all secondary phases produced in CIS films and ways to remove them, and provided thermodynamic values and related equations of thermodynamic properties to elucidate CIS and $CuGaSe_2$ materials fabricated by various processes. Modeling studies are guiding ways to help increase the open-circuit voltage (V_{oc}) and short-circuit current (J_{sc}) of CIS cells, and to understand and develop newer cell designs for higher-efficiency CIS and CdTe devices. Polycrystalline thin-film cell and module efficiencies are progressing, along with improved alternative fabrication processes. CIS and CdTe cells have reached 13.1% and 12.3% efficiency, respectively (Table 5). Module efficiencies are at 11.1% and 7.3%, respectively (Figure 2). Larger-area CIS modules (3700 cm^2 [4 ft^2]) have reached 9.7% efficiency.

Earlier polycrystalline thin film fabrication processes relied on relatively expensive processes, such as in-situ three-source evaporation for CIS. More cost-effective CIS fabrication methods have been achieved, such as Cu and In deposition by sequential sputtering and then selenization by hydrogen selenide gas at elevated temperatures. Furthermore, methods such as rapid thermal processing are being developed to improve upon the established selenization processes. These improvements include not only faster production rates but better utilization of H_2Se feedstock or its replacement with safer selenium feedstocks. This in turn lowers the potential environment, safety and health risks associated with working with H_2Se.

The reliability of polycrystalline thin films is evidenced by the SERI database for stability tests of prototype modules. SERI outdoor tests on Siemens Solar (previously ARCO Solar) CIS modules have shown less than 5% variation in the module performance over a 600-day test period. Results for Photon Energy's experimental CdTe modules showed no change in performance for outdoor tests over 250 days. Contact stability for CdTe had been troublesome in the past, but research is continuing to provide successful resolutions for stable metal contacts. Similarly, solutions are being found to CIS issues associated with Cu and In adhesion to Mo-coated glass substrates. Generally, some reliability engineering problems exist, but polycrystalline thin films do not exhibit any sort of intrinsic light-induced instability. Module tests at SERI will remain a continual focus. The good results so far indicate polycrystalline thin-film reliability problems will be only those associated with any module type, (e.g., proper contact design and selecting the best encapsulants).

High-Efficiency Materials and Cells. The research in this area cover two main approaches: thin-film GaAs research, and multijunction concentrator concepts. The thin-film objective is to understand single-crystal thin-film growth and fabrication processes to assist industry in developing devices for 20%-efficient flat-plate modules. Concentrator research objectives are to understand and control the complex crystal growth processes, and to understand and resolve problems inherent in multijunction device fabrication using ternary and quaternary alloys of III-V compound semiconductors. These two research approaches each contribute to the other's goals by emphasizing controlling deposition and processing mechanisms. The thin-film GaAs research is only through subcontracts, whereas the concentrator approach also includes SERI in-house research.

One SERI in-house effort has focused on developing lattice-matched $GaInP_2$/GaAs multijunction cells (Figure 4) that have the potential for greater than 30% efficiency under one sun and even higher under concentrated sunlight. So far the approach has led to an efficiency of 27.3% (one-sun) for this SERI-developed multijunction device. In addition, high-quality tunnel junctions were fabricated, and an $AlInP_2$ back surface heterojunction was implemented into a $GaInP_2$ homojunction, thereby increasing the V_{oc} by 100 mV. These advances and further optimization of device structures will be integrated into multijunction cells that should surpass 30% efficiency under concentrator conditions.

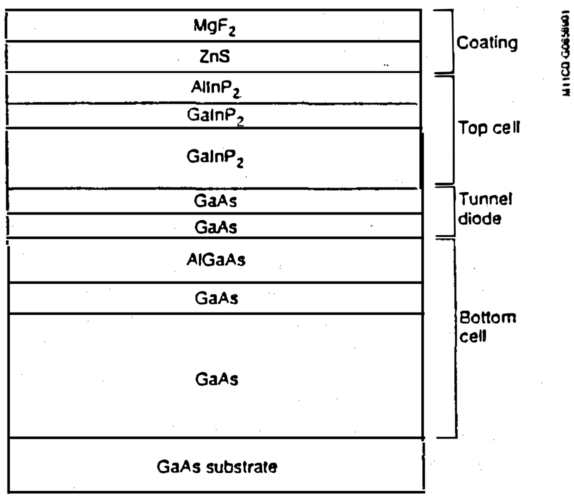
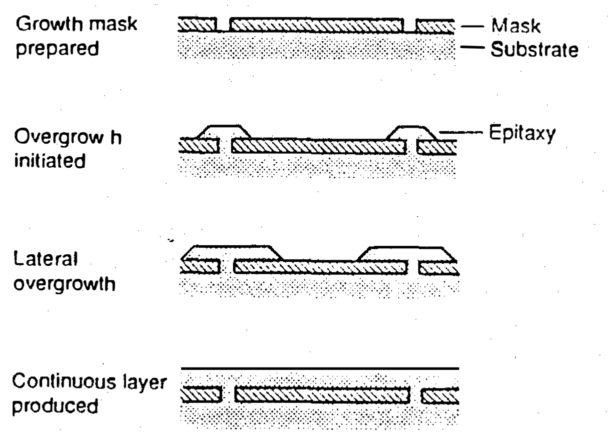


Figure 4. **Schematic cross section of the $GaInP_2$/GaAs multijunction cell (not to scale).**

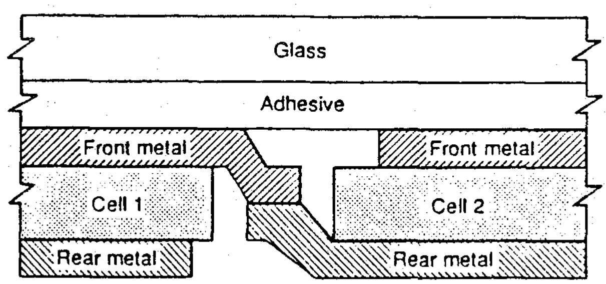
Another SERI in-house effort has already surpassed 30% efficiency under concentration. This work, partially supported by the Naval Research Laboratory for space concentrator cells, has led to another SERI-developed device, a 3-terminal, monolithic InP/GaInAs tandem solar cell. This device has met a milestone of the U.S. DOE National Photovoltaics Program Plan [1] -- demonstrating and confirming concentrator solar cells with a terrestrial efficiency greater than 30% at 100 suns concentration (100X). The cell efficiencies measured 30.7% (100X), and 31.8% (50X). Other record efficiencies achieved by this type of tandem cell were for space applications (AMO illumination): 23.9% (AMO one-sun illumination); and 28.9% (AMO 40X direct illumination). Ongoing efforts should lead to additional efficiency increases for both types of SERI concentrator cells.

The subcontracted high efficiency research focuses on four areas, as outlined in a recent recompetition of the program: (1) large-scale, cost-effective, safe epitaxy technology, (2) substrate cost issues, (3) materials characterization and solar cell loss analysis, and (4) new materials. Thin-film GaAs research performed at the Kopin Corporation has produced 23.3% efficient cells and 21% efficient minimodules (Table 5) for their patented CLEFT (cleaved lateral epitaxial films for transfer) technology. The monolithic minimodule consisted of four series-connected cells, thus demonstrating the proof of concept for integrated cell/module fabrication processing (Figure 5).

The continuing research in the high-efficiency area provides both a philosophical and technological alternative to the traditional amorphous and polycrystalline thin-film approaches to cost-effective photovoltaics. Relying on the known high conversion efficiency and the stability of III-V based cells, this high-efficiency approach considers fabrication processes that minimize trade-offs in performance required to reduce production costs.



5a. CLEFT growth process.



5b. CLEFT minimodule showing two monolithically interconnected cells.

Figure 5. **Schematic cross sections of the cleaved lateral epitaxy films for transfer (CLEFT) technology (not to scale).**

Crystalline Silicon. The objectives include identifying and developing new technologies for the growth of high-quality crystal silicon for use in flat-plate and concentrator modules. Equally important are objectives of improving the fundamental understanding of the correlation of cell processing and performance with changes in crystallographic defects and electronic properties of silicon. The approach relies on the close university/industry/SERI coordination to pursue these objectives. Subcontracted university research teams are pursuing the effects of point defects and impurities. The goal in this area is to assist silicon PV manufacturers to improve product performance.

At SERI, crystal growth researchers have focused on lower-cost alternatives to float-zoning and Czochralski growth that will maintain low levels of oxygen impurities in the silicon. Investigations are proceeding on techniques for forming thinner Si crystalline materials with low defect density. Also, SERI researchers identified new optical-processing techniques to fabricate crystalline silicon solar cells. In a rapid, single step, they obtained high-reflectivity, ohmic rear contacts, with texturing for increased optical confinement of reflected light.

Fundamental and Supporting Research Activities. Several PV AR&D Project activities cut across the materials areas described in previous sections. Subcontracted research in this area includes the New Ideas for Photovoltaic Conversion and the University Participation Programs. The University Participation Program has provided multiyear funding to university centers of excellence. Currently, four groups are under subcontract. The New Ideas for Photovoltaic Conversion Program objective is to identify new materials, device configurations, and concepts that have potential, and to conduct preliminary R&D on those that offer the most promise. Although innovative and fundamental in nature, both the University Participation and New Ideas for Photovoltaic Conversion Programs have consistently contributed to goal-oriented research in other materials areas of the SERI project. For example, at North Carolina State University, Professor G. Lucovsky recently produced a new microcrystalline silicon material. The material can either replace a-Si:Ge as a low-band-gap alloy in a multijunction device, or it can potentially be used as a 1.4-eV material in single-junction devices.

SERI's in-house research on solid state theory focuses on achieving a better understanding of the electronic and structural properties of existing and future PV semiconductors. This has led to innovative concepts and the selection of novel materials and configurations for further R&D. Accomplishments include systematic predictions of the composition dependence of alloy band gaps for various II-VI and III-V materials, and novel structures with direct band gaps [e.g., Si_6Ge_6/Ge and $(GaP)_1(GaAs)_1/GaAs$ superlattices].

SERI's PV measurements and performance laboratories provide measurement, testing, characterization, and device development support to R&D groups involved in PV and energy-related technologies. The laboratories are the DOE lead center for standardized and traceable cell and module evaluation (including efficiency, reliability, standards, and reference components. The laboratories are also a center for diagnostic and failure analysis based on micro- to macro-analysis techniques, ranging from atoms to arrays. Potential problems with ethylene-vinyl-acetate (EVA) encapsulants were identified in collaborative research with industry, and manufacturers were then able to decide how to further improve their modules. SERI's involvement in establishing consensus qualification tests for thin-film modules [4] have been instrumental in supporting industry's further development of module design and fabrication techniques that should lead to long-term, reliable module performance in the field.

The SERI solar radiation research activities help develop a fundamental understanding of the relationships between the natural spectral solar radiation environment and the design, performance, and performance measurements of PV devices. The approaches address the needs for data, instrumentation, and measurement and analysis techniques. The SERI-patented Atmospheric Optical Calibration System (AOCS) working unit was completed, tested, and calibrated for outdoor evaluations. The AOCS gives researchers a real-time comparison of actual atmospheric conditions with selected standard conditions (e.g., optical turbidity and scattering, and water vapor content). The engineering report on final field verification tests is planned for April 1991.

PV Manufacturing Technology (PV MaT) Project. This newly implemented project was conceived as a DOE/industry partnership for advancing PV manufacturing technologies, reducing module production costs, increasing module performance, and expanding U.S. commercial production capacities. The PV MaT project is directed toward R&D on manufacturing process technology and is not intended to fund the acquisition of production line equipment. SERI is responsible for implementing PV MaT procurements and subcontracts. The project is managed by SERI's Solar Electric Research Division.

The PV MaT project consists of two phases. Phase 1 was a solicitation for letters of interest and subsequent three-month subcontracts, with the goal to identify (1) current capabilities in manufacturing and process development, (2) manufacturing potentials envisioned to lead to significantly increased production capacities and reduced manufacturing costs, (3) problems impeding the achievement of those potentials, and (4) cost and other requirements involved in overcoming the problems in manufacturing technology.

Phase 2 will address the problems identified in Phase 1, as well as other related issues. It is planned to last five years and consist of at least two requests for proposals (RFPs) on company-specific technologies, as well as one or two additional RFPs on generic manufacturing problems. The first company-specific RFP is only open to Phase 1 awardees. The second company-specific RFP will be open to all interested parties and will be issued about two years after the first RFP. The phase 2 subcontracts will be awarded for up to three years and funded on a year-to-year basis. Overall, the PV MaT project is expected to last five years. It is expected to include significant cost-sharing by the PV industry participants.

Program Management, Analysis, and Support. Systems development for high-value utility applications is an area of recently increased program focus. The SERI approach is based on facilitating direct contact between industry, electric utilities, and others interested in PV technology. Under a subcontract with SERI, the Southern Company Services (SCS), Inc., will design, install, test, and monitor five experimental PV systems. These will be for small-scale utility applications deployed at various locations within the operating companies of SCS's organization. The five systems are (1) cathodic protection of underground storage tanks, (2) cathodic protection of transmission line structures, (3) transmission line aircraft warning lights, (4) remote transmission line switching, and (5) remote area lighting. SCS will also perform economic analyses and develop a performance specification/design guide for each application for incorporation into company planning manuals. This ongoing subcontract is managed by staff members in the SERI Solar Electric Research Division.

Other system activities of the SERI PV AR&D Project include our support of the Photovoltaics for Utility Scale Applications (PV USA) Project. SERI is continuing to provide technical review committee members, instrument calibration, and consultation on module/system qualification and data acquisition. The PV USA Project, a "Buy American" public/private partnership, was launched in 1986 with two primary goals: (1) assess promising PV technologies in a side-by-side utility setting, looking toward cost-effective commercialization by the mid-1990s; and (2) create a program to transfer PV knowledge between government, the PV industry, and U.S. utilities [5]. The founding sponsors are DOE, the Pacific Gas and Electric Company (PG&E) in California, the Electric Power Research Institute (EPRI), and the California Energy Commission.

PV USA is planned around five major procurement activities for modules and turnkey systems: Emerging Module Technologies-1 (EMT-1), EMT-2, Utility Scaleable-1 (US-1), US-2, and US-3. EMT procurements are designed for newer module technologies that have not yet been fielded in system sizes of 20 kW or larger. The US procurements are for larger-scale turnkey systems (e.g., 200 and 400 kW) of successfully proven EMT modules and other available and qualified PV technologies. It is important to note that several of the PV USA awards encompass technologies developed in the past under the SERI PV AR&D Project. These technologies include amorphous silicon (Chronar Corporation, Sovonics, and Utility Power Group), CIS (Siemens Solar), and CdTe (Photon Energy). The SERI PV AR&D Project will continue to support PV USA and will become more involved with additional systems activities as directed by DOE.

CONCLUSIONS

Through the SERI PV AR&D Project, national PV research and services to industry have led to significant improvements in PV technology performance and lowered cost. New generations of PV technologies continue to provide gains in sunlight-to-electricity conversion efficiencies, a bottom-line measure of research progress. Lower cost, increased field experience, and a greater scientific understanding of PV reliability and manufacturing processes are providing industry with means to compete in the expanding electricity marketplace. The continued government/industry partnerships, the PV MaT project, the university research involvement, and the increased breadth of electric utility end-use systems from current high-value applications to tomorrow's large-scale bulk power systems should accelerate the growth of PV as an environmentally safe and secure supply of cost-competitive energy.

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REFERENCES

This paper has drawn liberally, and often without reference (e.g., Figures 4 and 5), from the research results of SERI subcontractors and in-house researchers. Further information is available in the annual SERI branch report that can be obtained by contacting the managers identified in Figure 1. Additional references are cited below.

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4 DeBlasio, R., Mrig, L., Waddington, D., "Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules," SERI/TR-213-3624, DE90000321, January 1990. (Available from NTIS).

5 PV USA Project Management Office, PG&E, 3400 Crow Canyon Road, San Ramon, CA 94583 (or telephone the PV USA Project Office (415) 866-5569)