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SERI's Photovoltaic Research Project: A Foundation for Tomorrow's Utility-Scale Electricity

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ABSTRACT

Photovoltaic (PV) research activities at the Solar Energy Research Institute (SERI) provide the foundation for new PV technologies having lower cost, higher performance, and better reliability than today's photovoltaics. Privately owned PV companies are already developing some of these technologies and identifying new commercial applications. This paper focuses on recent progress and future directions in PV research managed by SERI for the U.S. Department of Energy (DOE). The primary emphases of the research are on thin-film single-junction and multijunction devices. However, work also continues on advanced crystalline silicon sheet materials. Improvements in materials and processing, solar cell design, and cell fabrication techniques have led to continuing improvements in cell efficiencies in nearly all material areas. Recent research has identified the criticality of source-material purity and device-processing conditions for different PV materials. Attention to total device design and processing has increased our understanding of metallic contacts, transparent conductors, and intermediate layers. Sophisticated models have been developed to quickly assess device concepts. Enhanced measurement and characterization techniques, along with increased interactions among PV scientists, are adding to the strong foundation of photovoltaics. Future directions in PV research are given in the recent *Five Year Research Plan* prepared by DOE. The plan is predicated on partnerships among the federal government, private companies, universities, and electric utilities. As part of a consensus review of the plan, this multifaceted PV community identified the specific technical goals and pertinent R&D needed for success. These technical goals and future research are described in detail.

INTRODUCTION

Photovoltaics is an attractive technology for utility-scale electricity generation. PV provides a diversified mix of electricity-supply options. Large-scale PV systems are modular and thus require only short, well-defined lead times for deployment (recent experiences of U.S. utilities have shown that PV systems come on-line on schedule and within budget). PV also provides another high-technology product to help increase U.S. industrial competitiveness.

Providing industry with a knowledge base for further development is the cornerstone of DOE's *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 that pursue the most pertinent PV research and development (R&D) and effectively transfer the results of these efforts within the community. The target of the plan is an ambitious, yet attainable goal: to improve the efficiency and reliability of PV 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 will place photovoltaic electricity in a competitive position with electricity generated by other sources. To achieve it, the research activities of the plan are directed toward the long-term technical goals shown in Table 1. These goals include module efficiencies and cost targets that will meet the 6¢/kWh electricity cost goal.

There are still many opportunities to improve the performance and reduce the cost of PV. Thin-film single-junction and multijunction devices are practical approaches to achieving the plan's goals, as are advanced crystalline silicon sheet materials, which are produced at a high throughput and yield high cell efficiencies. For these new-generation technologies to achieve performance and cost goals, significant resources and research talent, and well-coordinated multidisciplinary research teams, are required.

The federal government has assigned SERI the responsibility for the Advanced Research and Development (AR&D) Project

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

	Flat-Plate Systems	Concentrator Systems
Module Efficiency (25°C)	15%-20%	25%-30%
Module Cost	\$45-\$80/m²	\$60-\$100/m²
Balance-of-System Costs		
-- area-related	\$50-\$100/m² [a]	\$125/m²
-- power-related	\$150/m²	\$150/m²
System Life Expectancy	30 years	30 years

[a] Balance-of-system costs vary depending on the type of flat-plate system (fixed, one-axis, or two-axis tracking).

in photovoltaics for DOE's Photovoltaic Energy Technology Division. The project's primary research emphasis is on establishing and developing such promising new approaches to photovoltaic cells as thin-film single-junction and multijunction concepts. SERI's PV activities include the management of subcontracted R&D, the development of state-of-the-art measurement and device fabrication capabilities, work in basic and applied research by in-house laboratories, and the transfer of R&D results to industry. Research activities are undertaken with promising PV 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, along with more than 60 subcontracted research groups in universities, industry, and nonprofit laboratories.

Table 2 presents the budget distribution for SERI's PV AR&D Project for FY 1988 and prior years. The table shows the budget distribution by material area for subcontracted programs and in-house research costs. The relative emphasis on material areas in the in-house programs is similar to that in the subcontracted areas. The table shows that more than 55% of the funds available for research were subcontracted to industry and university laboratories. (Note that SERI's 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 Conversion Program and the University Participation Program. The objective of the New Ideas research is to identify new materials and device configurations and to conduct preliminary R&D in the most promising new areas. The University Participation Program provides a mechanism for establishing and maintaining the infrastructure of dedicated personnel and facilities needed to conduct fundamental research at universities. The intent of this program is to pursue promising ideas and to educate future

Table 2. SERI Photovoltaic AR&D Project Budget History

Task Area	FY 78-85 ($M)	FY 86 ($M)	FY 87 ($M)	FY 88 ($M)
In-House				
Research	42.5	8.7	9.1	8.6
Capital Equipment	12.2	0.9	0.8	0.2
Subcontract[a]				
Amorphous Silicon Thin Films	36.1	7.2	9.2	6.7
Polycrystalline Thin Films	29.1	2.9	2.9	2.2
High-Efficiency Concepts (III-V)	22.2	2.4	3.0	1.2
Crystalline Silicon	20.7	0.4	0.4	0.6
New Ideas	16.0[b]	1.0	0.5	0.1
University Program	1.0	1.2	1.3	1.4
Total Subcontracts	125.1	15.1	17.3	12.2
Total Program	179.8	24.7	27.2	21.0

[a]Amounts include approximately 15% for program management, fees, etc.
[b]Includes $9.0 million for photoelectrochemical cell research.

engineers and scientists, unencumbered by milestone restrictions and excessive reporting requirements.

This paper describes trends in current research by reporting the recent accomplishments of SERI subcontractors and in-house researchers. These 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 that cut across the material areas, are described under the section on "Support Activities."

TECHNICAL ACCOMPLISHMENTS

Amorphous Silicon Thin Films

The Amorphous Silicon Research Project (ASRP) Office was established within SERI's PV Program Branch in 1983 as DOE's management center for amorphous silicon research. The ASRP was given the responsibility for implementing national energy policy in amorphous silicon by coordinating all DOE-funded R&D in this area. The objectives of this 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. This research is directed toward the achievement of the National PV Program's FY 1990 goals, which are 10% efficiency for single-junction and 13% efficiency for multijunction a-Si submodules at least 1000 cm^2 in 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 the preparation and evaluation of starting materials to the demonstration of proof-of-concept cells and submodules. Fundamental research activities involving basic and supporting research are done by universities and research laboratories, including in-house research at SERI. Fundamental research includes studies on light-induced effects; material deposition rates; 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 by SERI's PV Measurements and Performance Branch.

The first government/industry program began in 1984 and ended in early 1987. Four subcontract awards, totaling about $18.6 million, were cost-shared about 30% by industry. A major accomplishment was Solarex Corporation's achievement of the program's primary technical goal, an 8% efficient, 1000-cm^2 (total area) submodule measured at SERI under standard conditions (defined below). Other significant technological advances included Chronar's SERI-verified, single-junction, monolithic, 5% efficient (2790-cm^2 total area) a-Si submodule; 3M Company's a-Si 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-size cell efficiencies have also improved significantly as a result of the first initiative. SERI measured several a-Si:H cells from Solarex that had 11.5%-11.8% conversion efficiencies, which is the state of the art for 1-cm^2 single-junction cells. Three specific technical advancements can explain this increase in efficiencies: (1) the development of high-quality, textured SnO_2:F having a low electrical sheet resistance and high optical transmission; (2) the development of a multilayer back-reflecting contact consisting of ITO/Ag layers; and (3) the development of graded p/i interface structures using transitional doping or compositional grading in the amorphous Si,C:H p-layer. These textured SnO_2:F front contacts and reflecting back contacts have resulted in increases in the cell's short-circuit current density (J_{sc}) to 18-19 mA/cm², especially through an enhancement in the red spectral response of the cells (e.g., 62% at 700 nm). Using graded p/i interface structures has resulted in higher open-circuit voltages (V_{oc}), through reduced interface recombination, and improvements in fill factors (FF). Further improvements can be expected from the extrapolation of present work, and efficiencies around 14% for a-Si single-junction cells appear to be possible.

Because of the success of the first government/industry program, SERI initiated a second three-year program in January 1986 directed toward single-junction and multijunction a-Si cell and submodule research. Following a public solicitation, four companies were awarded contracts in 1987: ARCO Solar, Solarex, Chronar, and Energy Conversion Devices (ECD). The primary goals of this research program, now cost-shared more han 50% by industry, is to achieve the FY 1990 efficiency goals for submodules stated earlier.

ARCO Solar's work is directed toward the development of a four-terminal submodule using a-Si and $CuInSe_2$ (discussed further under "Polycrystalline Thin Films"). To this end, ARCO has developed a single-junction a-Si submodule with a transparent ZnO back contact that has a SERI-verified 8.2% efficiency (844-cm² aperture area).

Solarex, using DC glow discharge, is focusing on the development of multijunction submodules in which amorphous silicon-germanium is used in the bottom cell. They have reported a 10.8% efficiency for an a-Si,Ge:H (1.6 eV) single-junction cell and have also fabricated an a-Si,C/a-Si,Ge multijunction cell (shown in Figure 1) with a SERI-verified efficiency of 10.3%. A full spectrum of multijunction devices has been fabricated, including a-Si/a-Si, a-Si,C/a-Si, a-Si/ a-Si,Ge, and a-Si,C/ a-Si,Ge, all yielding impressive device performance results. A triple-stacked cell, a-Si,C/ a-Si/a-Si,Ge, was also reported as 8.3% efficient.

Five a-Si/a-Si submodules (1000-cm² each) have been fabricated by Solarex with a back i-layer thickness of 0.24 µm. These cells exhibited a SERI-verified average conversion efficiency of 5.8% and showed only a 7.5% drop in performance after 90 hours of AM1.5 light soaking. An a-Si,C/ a-Si,Ge submodule with a total area of 1007 cm² was measured by SERI to be 6.2% efficient.

Chronar, using a vertical RF glow-discharge system, is performing studies on increasing the efficiency of both single-junction and multijunction submodules using a-Si:H materials with the same bandgap. SERI has verified Chronar's single-junction p-i-n module, shown in Figure 2, at an efficiency of 5.8% (2779-cm² total area). Chronar's amorphous silicon p-i-n/p-i-n same-bandgap multijunction modules have demonstrated a SERI-verified efficiency of 6.0% (2530-cm² aperture area). These submodules were tested outdoors by SERI under open-circuit and load conditions and degraded less than 15% over 160 days.

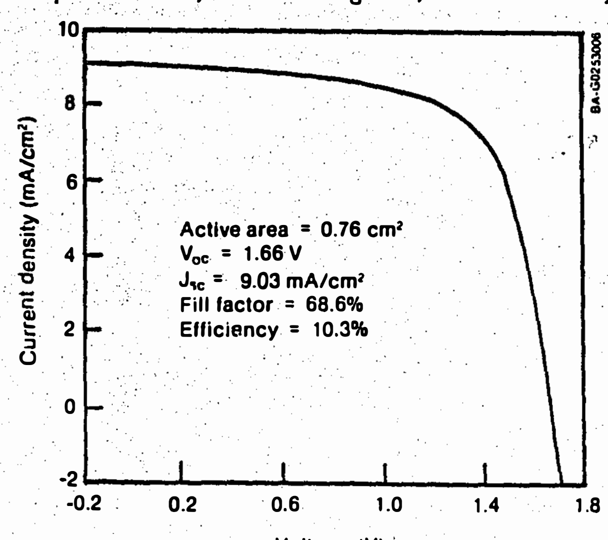

Figure 1: I-V characteristics of Solarex's 10.3% efficient a-Si, C/a-Si,Ge multijunction cell.

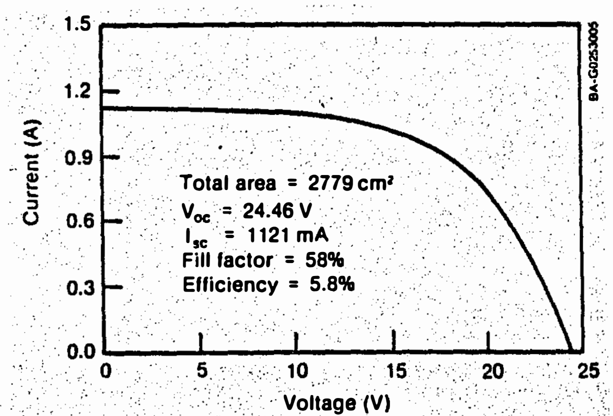

Figure 2: I-V characteristics of Chronar's 5.8% efficient (2779-cm² total area) single-junction p-i-n module.

To try to increase the J_{sc}, Chronar has also investigated eight different back-contact systems for application to p-i-n cells. Typical values of the cell quantum efficiency at 700 nm (a useful indicator) were 0.21 for Ti, 0.29 for Al, 0.44 for Ag, and 0.49 for ITO/barium sulphate paint. The highest individual quantum efficiency observed, 0.55, was for a cell metallized with ITO/Ag. The substitution of Ag for Al has increased the J_{sc} by 12.7%, adding 1.6 mA/cm² to the cell performance characteristics.

ECD's efforts are concentrated on research to determine the limit of a-Si-based alloy materials with the overall goal of demonstrating 18% efficiencies in all-amorphous-silicon-based multijunction solar cells. Single-junction a-Si,Ge:H:F p-i-n cells in which i-layers are fabricated with a bandgap of 1.5 eV have achieved efficiencies up to 10%, which is the state of the art for low-bandgap, single-junction devices. SERI has confirmed total-area (0.25-cm²) efficiencies up to 12.7% for three-junction cells (see Figure 3). This device has an a-Si:H:F (1.75-eV) top and middle cell and an a-Si, Ge:H:F (1.45-eV) bottom cell. A dual-bandgap multijunction cell has been reported as 11.6% efficient (0.268-cm² total area), with J_{sc} = 10.14 mA/cm², V_{oc} = 1.64 V, and FF = 0.696. These results from ECD are the best in world performance for two-terminal, multijunction solar cells made from all-amorphous-silicon alloy materials.

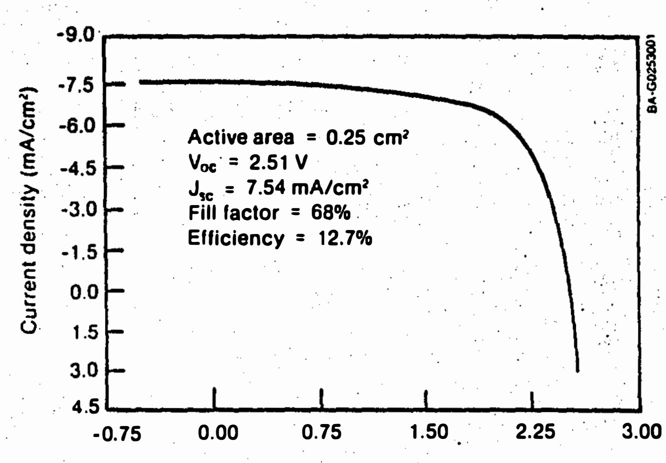

Figure 3: I-V characteristics of ECD's 12.7% efficient, 0.25-cm², three-junction a-Si solar cell.

Significant advances have also been 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 behavior of a-Si 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 that 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. Recent results from Xerox implicate hydrogen diffusion as the initiator or rate-limiting step in all metastable effects observed in a-Si:H films (3). Recombination of electrons and holes before external collection is generally accepted as the initiator in the light-induced creation of defects.

In the area of alternative deposition techniques for a-Si, several groups are investigating chemical vapor deposition (CVD) methods, such as photochemical vapor deposition (photo-CVD), thermal CVD, and laser-induced CVD, to either improve photostability or device performance or to potentially reduce manufacturing costs. SERI's researchers have developed an innovative technique for maintaining window transparency during photo-CVD. The technique is also a convenient method for incorporating fluorine into the a-Si film. At present, the most promising method is photo-CVD using mercury-sensitized gases. Recently, an all photo-CVD a-Si:H solar cell fabricated at the Institute of Energy Conversion (IEC), University of Delaware, was measured by SERI to be 10% efficient. The University of Delaware is the first American university to achieve this historic milestone in a-Si, by any deposition method.

The main thrust of SERI's 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 to improve their photovoltaic performance characteristics. Studies of the microstructure of a-Si alloy films are leading to an understanding of the role of microvoids in determining the electronic properties and stability behavior of the films (see Figure 4). It was concluded that lowering the microvoid density and better hydrogen incorporation will produce good PV-quality films. Using this understanding of microvoids, a universal parameter was developed for describing the photoconductivity of a-Si alloys. Recently, researchers developed two original approaches for minimizing or eliminating microvoids: (1) periodic etching with XeF_2 during deposition, and (2) 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. Recently, H. Branz of SERI proposed a comprehensive defect-conversion model to explain metastable effects in doped films that may be applicable to undoped films.

In the area of transparent conducting oxide films, new starting materials were found that are less costly, less toxic, and safer to handle than tetramethyltin. Harvard researchers showed that dimethyldichlorotin (a solid at room temperature with a low vapor pressure) is a promising starting material. Solarex demonstrated that tin tetrachloride (a liquid at room temperature) can also be used. 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 a-Si appear promising: with the continued commitment of the partners, the government/industry program goals should be met, 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 to further reduce manufacturing costs. User interest in this technology is also increasing. Several joint demonstration projects between U.S. manufacturers and utility companies have begun during the past 1-1/2 years; the largest is a grid-connected electric power generating system, installed by Alabama Power Company, made up of modules fabricated by Chronar Corporation; it is operating at a peak power of ~75 kW.

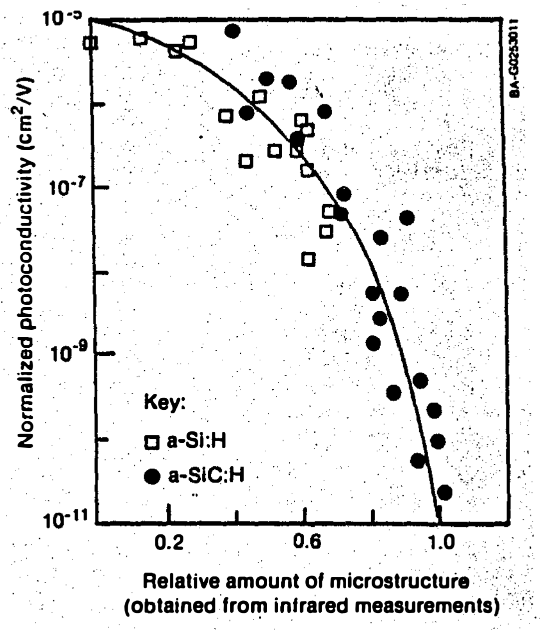

Figure 4: Effect of microstructures (microvoids) on the photoconductivity of two a-Si alloy materials. Data for other a-Si alloy materials follow the same universal curve.

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/m²), and long-term 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 μm thick), which lowers material and processing costs. Polycrystalline thin-film $CuInSe_2$ and CdTe cells have each achieved SERI-verified efficiencies over 10%. Reported active-area efficiencies of small $CuInSe_2$ cells are in the 11%-13% range at four laboratories (SERI, ARCO Solar, Boeing, and IEC). A 9.6% efficiency for a Boeing $CuInSe_2$ device (91.0-cm² active area), shown in Figure 5, consisting of four interconnected cells, has been verified at SERI, as has a 9.2% efficient, 844-cm² $CuInSe_2$ submodule made by ARCO (see Figure 6). A SERI-verified, 10.6% efficient, 1.11-cm² CdTe solar cell fabricated by Southern Methodist University is shown in Figure 7. $CuInSe_2$ cells have demonstrated their stability under 9000 hours of controlled illumination. Innovative cell designs are now addressing past difficulties in contacting CdTe.

Polycrystalline cells still require further development to achieve the 15%-20% conversion efficiency goals. To this end, two strategies are being used: (1) continued development of single-junction cells and innovative research on two-junction cells, and (2) the development of scalable, low-cost deposition techniques for $CuInSe_2$ and CdTe thin films.

Improvements in single-junction technologies have been steady and reliable, with several areas showing progress. To increase the bandgap, and thus the cell efficiency, Boeing investigated $CuInGaSe_2$ solar cells and a new, three-layer antireflection

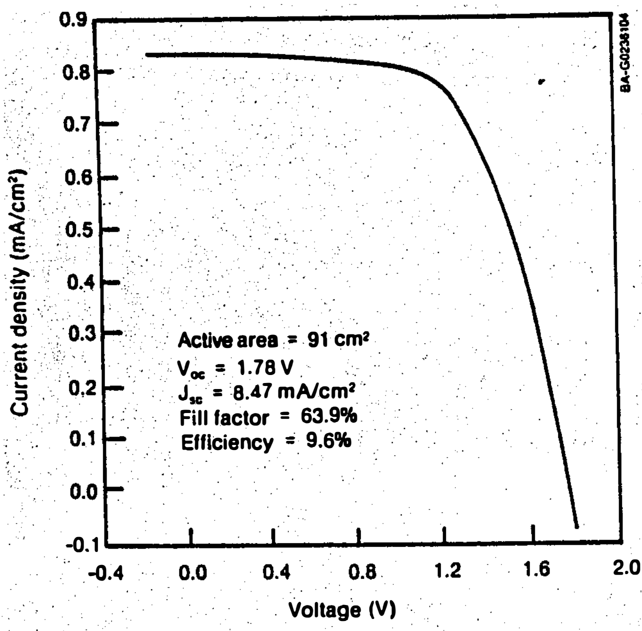

Figure 5: I-V characteristics of Boeing's 9.6% efficient (91.0-cm² active area) $CuInSe_2$ submodule.

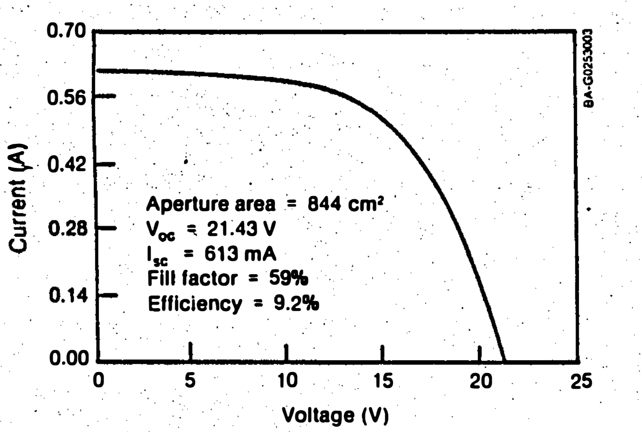

Figure 6: I-V characteristics of ARCO's 9.2% efficient, 844-cm² $CuInSe_2$ submodule.

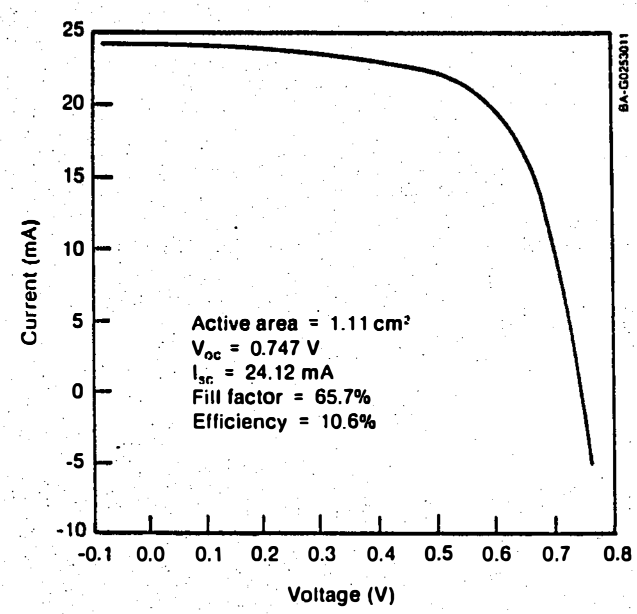

Figure 7: I-V characteristics of Southern Methodist University's 10.6% efficient, 1.11-cm² CdTe solar cell.

(AR) coating. With a Ga content of about 25% (1.14 eV), an efficiency of 10.2% (1.07-cm²) was verified by SERI. Boeing also enhanced the J_{sc} of its $CuInSe_2$ and $CuInGaSe_2$ devices more than 16% with a new MgF_2/ Al_2O_3/Ta_2O_5 AR coating (n = 1.38/1.62/2.05). IEC also developed a unique technique for etching $CuInSe_2$ films to fabricate specular films. The total reflectance of these films was increased from 5% to 15% after the removal of ~0.5 μm of the $CuInSe_2$ film through this process.

ARCO Solar is also experimenting with its $CuInSe_2$ devices by substituting gallium for up to 15% of the indium in the junction region and then grading the gallium content down to pure $CuInSe_2$ to avoid any significant reduction in the red response. ARCO recently reported achieving a 12.5% (active-area) efficiency with these cells.

The second approach, the development of two-junction $CuInSe_2$-based cells, is necessary for the more ambitious long-term efficiency goals, since 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. In a major contribution to this goal, researchers at IEC and Ametek have both been successful in developing a transparent ohmic back contact for a CdTe solar cell. This has been the first practical step to using CdTe or one of its alloys as the top cell in a four-terminal structure.

Another two-junction approach being pursued by ARCO Solar, described in the previous section, involves the combination of an a-Si top cell and a $CuInSe_2$ bottom cell in a four-terminal device structure. IEC is also investigating the a-Si/$CuInSe_2$ cell, but with a two-terminal structure, and has reported fabricating a 6% efficient a-Si on $CuInSe_2$ device using this configuration. In both these configurations, the multijunction cell offers the potential of higher efficiencies, but it is estimated that the a-Si device removes up to 50% of the radiation in the wavelength region to which an efficient $CuInSe_2$ device responds. As part of its bottom-cell research, ARCO has reported fabricating a 3.6-cm² (active area) $CuInSe_2$/(Cd,Zn)S/ZnO solar cell having 12.5% efficiency. This is the highest efficiency reported to date for a device of this configuration. And, in larger area submodules, ARCO has submitted a-Si and $CuInSe_2$ submodules, each 900 cm² in total area, that were measured by SERI with AM1.5 efficiencies of 8.2% and 9.2% (844-cm² aperture area), respectively (see Figures 6 and 8). In a mechanically stacked, four-terminal multijunction configuration, these submodules demonstrated a total efficiency of 10.4% and a power output of 8.78 W under standard AM1.5 conditions. The 50-cell $CuInSe_2$ submodule had a reported power output of 7.8 W, with a short-circuit current (I_{SC}) = 518 mA, V_{oc} = 21.43 V, and FF = 0.59. This is the best performance to date of a single-junction $CuInSe_2$ thin-film submodule.

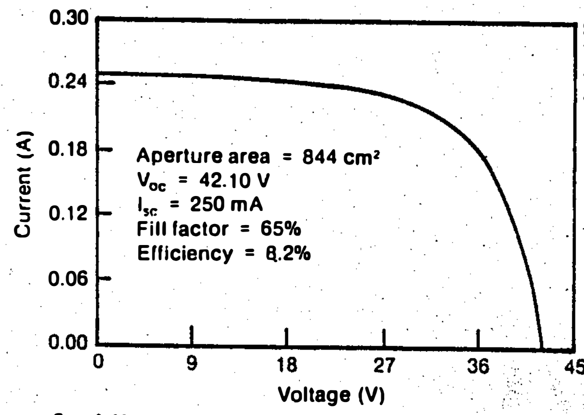

Figure 8: I-V characteristics of ARCO's 8.2% single-junction (844-cm² aperture area) a-Si submodule.

Developing scalable, low-cost fabrication methods for polycrystalline thin films is also important in providing industry with a foundation for future large-area, high-throughput commercial processes. Research on alternative methods for fabricating $CuInSe_2$ cells includes a method by International Solar Electric Technology (ISET) for electrodeposition/ selenization, research by the University of Illinois on both a reactive sputtering method and a hybrid sputtering/ evaporation method, and continued research by Boeing (described earlier), IEC, and SERI on the evaporation method. A one-step electrodeposition process for $CuInSe_2$ was also recently invented by SERI researchers.

ISET has carried out new experiments to solve the sticking problems encountered in its electrodeposition of $CuInSe_2$ films. Using 3- to 4-mil-thick Mo foil as a substrate, researchers have deposited a thin (200 Å) proprietary film before deposition of the Cu/In layers in their process. This has produced 2.5-μm-thick, 60-cm² films that have demonstrated a significant improvement in film sticking quality. This proprietary layer is now being tested on Mo-coated glass substrates that ISET uses in typical devices.

A major program development in the Polycrystalline Thin Film Project in FY 1987 was the recompetition of subcontracted research. This recompetition attracted new industrial participants in the CdTe solar-cell area and resulted in cost-shared research programs. Several organizations are now involved in developing scalable, low-cost fabrication methods for CdTe. Southern Methodist University (SMU) is investigating close-spaced sublimation methods, IEC is carrying out research in evaporation, and Ametek and ISET are involved in the electrodeposition of these materials. A new subcontractor, Photon Energy, has its own proprietary process for CdTe. Novel research in the metal-organic chemical vapor deposition (MOCVD) of CdTe and its alloys is being done at Georgia Tech Research Institute and the Jet Propulsion Laboratory (JPL). Work is also continuing at all of these facilities on optimizing the parameters for achieving high-quality films for device fabrication.

One of the new groups, Ametek Applied Materials Laboratory, has made a significant contribution to the advancement of thin-film CdTe technology. Through its electrodeposition process, Ametek recently fabricated a world-record, SERI-verified (see Figure 9), 11.0% efficient 1-cm² thin-film CdTe n-i-p solar cell on a tin-oxide-coated glass substrate. In Ametek's n-CdS/i-CdTe/p-ZnTe configuration, the n-CdS is deposited by spray pyrolysis, the i-CdTe by electrodeposition, and the p-ZnTe by evaporation. Initial stability tests of the new Ametek design have been very promising; no degradation was reported after 3000 hours of testing at 100 mW/cm² illumination. Since the CdTe/ contact degradation problem was previously a major unresolved issue facing the technology, these results are of great significance to the field. An active-area efficiency of 9.3% has been reported for Ametek's large-area (51-cm²), monolithically series-interconnected 10-cell submodule; the total-area efficiency was reported as 6.1%. Further improvements in the submodule design are expected to reduce area losses to less than 15%. Ametek has also reported fabricating a 9.2% efficient, 1-cm² n-i-p cell with a transparent ITO back contact, which was mentioned earlier.

JPL has reported a 9.4% efficient CdTe cell fabricated by MOCVD in collaboration with Ametek using Ametek's n-i-p structure, glass/SnO_2/CdS/CdTe/ZnTe/Ni. The CdTe layer was 1.6 μm, ~40% thinner than Ametek's, yet the current was ~22 mA/cm²; i.e., it was not reduced. This is the highest reported efficiency for a CdTe cell made by MOCVD.

SMU has used pulverized CdTe as the source material for its close-spaced sublimation process, which has resulted in a glass/SnO_2/CdS/CdTe/HgTe/Ag-epoxy SERI-verified 10.6% efficient device (see Figure 7). From the dark I-V in forward bias, researchers have measured the contact resistance of their new HgTe/CdTe contact to be less than 1 Ω-cm², the lowest value reported to date.

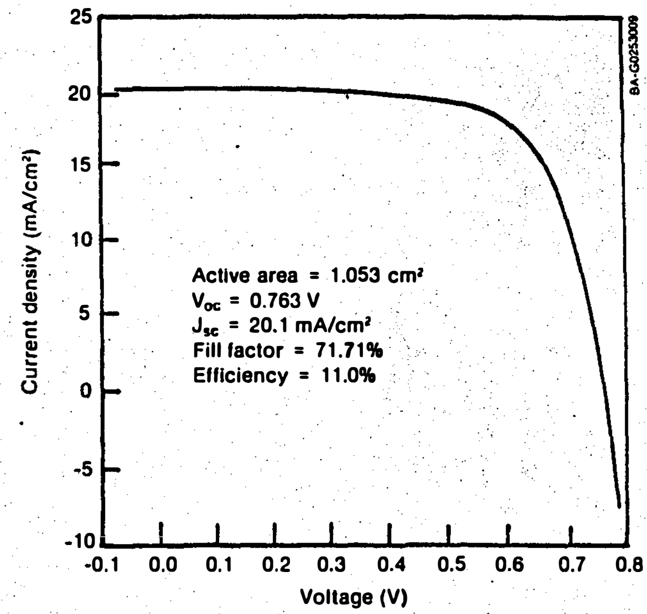

Figure 9: I-V characteristics of Ametek's 11.0% efficient, 1-cm² n-i-p CdTe solar cell.

Another new SERI subcontractor, Photon Energy, has produced large-area CdTe/CdS submodules by a proprietary low-cost, wet-chemical method. Small-area (0.3-cm²) CdTe cells cut from their larger modules have been reported at 10.6% efficiency and have had a near-record voltage for CdTe (over 800 mV) and a state-of-the-art fill factor of 70%. The best Photon Energy submodule (see Figure 10) produced 4.75 W, with a SERI-verified efficiency of 6.1% (773-cm² aperture area). This is the highest efficiency for a CdTe device of this size in the world.

The primary emphasis of SERI's in-house research in polycrystalline thin films is on the fabrication of promising ternary thin-film solar cell materials and devices to (1) understand the defect chemistry and charge transport in these materials that control their photovoltaic properties; (2) understand the role of the oxidation process in thin films of $CuInSe_2$ and CdS/$CuInSe_2$; (3) modify these materials to optimize device performance; and (4) 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 $CuInSe_2$, SERI researchers have also demonstrated a V_{oc} of 640 mV for specially designed CdS/$CuInSe_2$ devices. Although this voltage degrades, investigations of these surface modifications could provide avenues to future, more stable, voltage improvements.

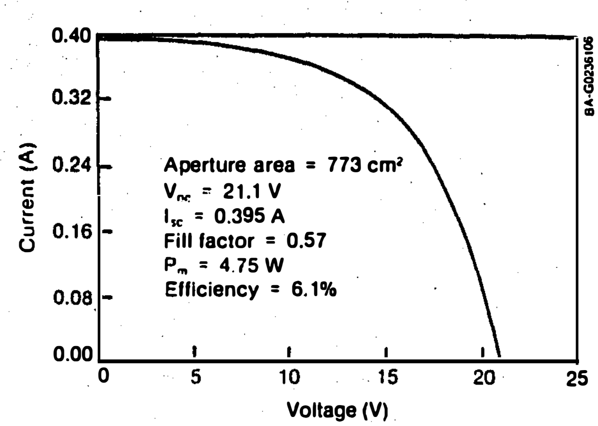

Figure 10: I-V characteristics of Photon Energy's 6.1% efficient (773-cm² aperture area) CdTe submodule.

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

High-Efficiency Concepts

Research in this area covers two main approaches: (1) thin-film GaAs and (2) multijunction concentrator cells. The objective of thin-film GaAs research is to understand techniques for large-area, single-crystal, thin-film growth for industrial development of 20% efficient, flat-plate modules. The objectives of concentrator cell research 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 greater than 30% efficient concentrator cells. The research also offers the high-payoff potential of exceeding 35% efficiency in the longer term. While the technical advances needed to achieve the two near-term goals are quite different, the emphasis in each area on improving the understanding and control of deposition processes benefits both areas.

Several important achievements by SERI subcontractors and in-house researchers in FY 1987 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 the reactor size limited growth areas to several square centimeters, and it demonstrates the feasibility of scale-up for this process. Recently, SERI measured a CLEFT-grown, two-junction AlGaAs/GaAs solar cell fabricated by Kopin. The efficiency of the 1-cm^2 device, shown in Figure 11, was 22.4%. The cell was approximately 8 µm thick with a single-layer AR coating. It was one of a group of seven cells (produced in two separate runs) that Kopin had measured to be more than 20% efficient. The major importance of these results rests in the uniformity of the performance of the cells.

Spire Corporation reported a 0.25-cm^2, single-junction GaAs cell with a record (AM1.5) efficiency of 23.7% (see Figure 12). This one-sun efficiency is the highest measured to date by SERI on a single-junction device. Researchers at Kopin have also developed a 23.7% GaAs solar cell. Spire also reported a 4-cm^2, two-terminal GaAs/Ge multijunction device with 24.4% efficiency. Researchers at Spire attribute these successes to improvements in crystal-growth control and device processing.

Varian Associates has had success in developing a monolithic multijunction cell of AlGaAs/GaInAs. Five key, SERI-verified results are (1) a 10% efficient, 3-cm^2 GaInAs (1.15-eV) single-junction cell under graded layers with a 1.75-eV AlGaAs cell; (2) a 16.8% efficient, 4-cm^2 AlGaAs (1.75-eV) solar cell; (3) a 14.9% efficient, 4-cm^2 AlGaAs (1.93-eV) solar cell; (4) a 22.7%, 4-cm^2 GaAs single-junction heteroface cell; and (5) a 23.6% efficient (4.1-cm^2) three-terminal AlGaAs/GaAs multijunction cell of 1.93-eV AlGaAs on GaAs under an AM1.5 spectrum (see Figure 13). Using SERI data, Varian also redesigned its GaAs cell to reduce the sheet resistance of the emitter layer. The cell was n-on-p with a grid designed originally for 100X AM0 concentration. It had a reported peak (AM1.5) efficiency of ~28% at 400 suns.

SERI's own research has also progressed on the innovative, lattice-matched GaInP/GaAs multijunction structure shown in Figure 14. Recent studies have centered on measurements of absorption and reflection coefficients of GaInP and the bandgap as a function of growth parameters. The reflection coefficient was somewhat higher in the blue region and the absorption coefficient lower than those of similar III-V compounds. The growth parameters have an effect on the degree of ordering of the Ga and In atoms through effects on adatom surface mobility. Researchers have recently achieved 10.5% efficiency in a GaInP/GaAs multijunction cell. And SERI researchers have grown GaP layers on Si substrates with far lower defect densities than those reported in the literature. Control of the interfacial contamination, resulting in better nucleation and coalescence of the first-deposited GaP, has led to these results. This research is aimed at developing GaAsP/Si multijunction cells.

In a cooperative effort between SERI researchers and Spire Corporation, a GaAsP solar cell (0.25-cm^2) was fabricated (grown on a GaAs substrate) with a 17.7% efficiency (see Figure 15). SERI's previous 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 this record-high-efficiency device.

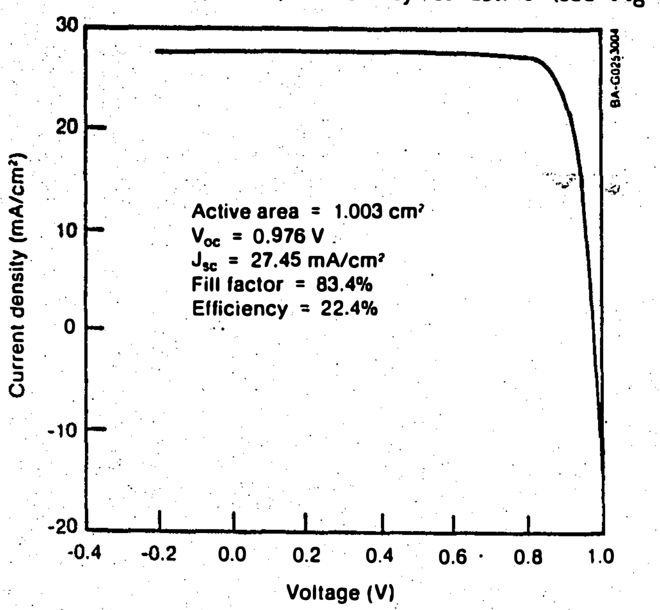

Figure 11: I-V characteristics of Kopin's 22.4% efficient, 1-cm^2 GaAs CLEFT device.

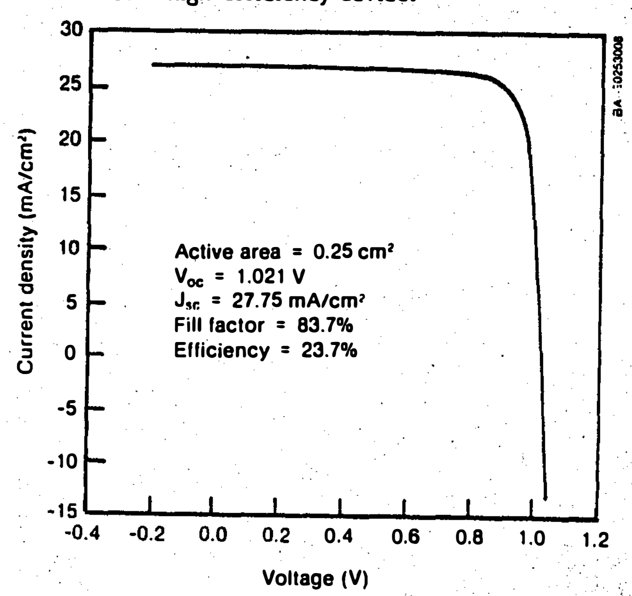

Figure 12: I-V characteristics of Spire Corporation's 23.7% (AM1.5) efficient, 0.25-cm^2 single-junction GaAs cell.

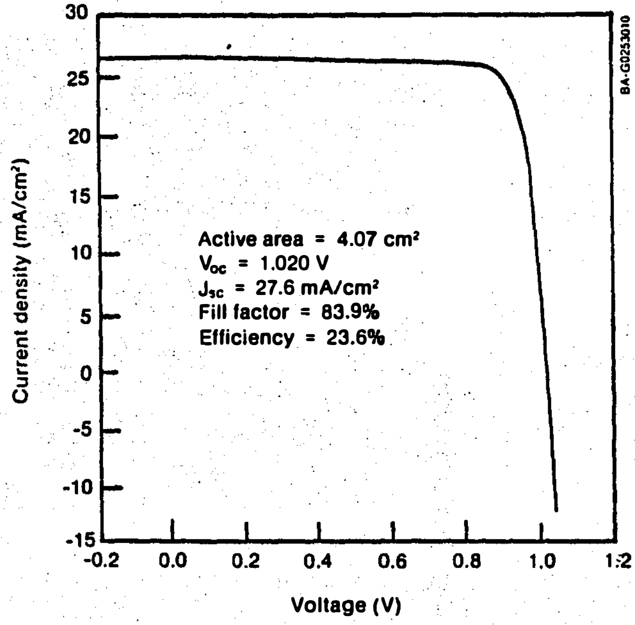

Figure 13: I-V characteristics of Varian's 23.6% efficient, 4.1-cm², three-terminal AlGaAs/GaAs multijunction cell.

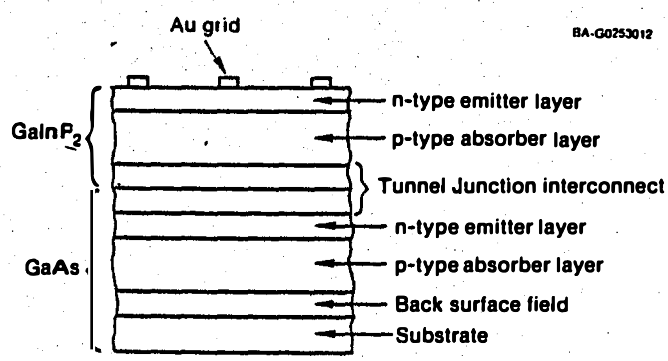

Figure 14: Schematic of new lattice-matched GaInP/GaAs multijunction cell invented by SERI researchers.

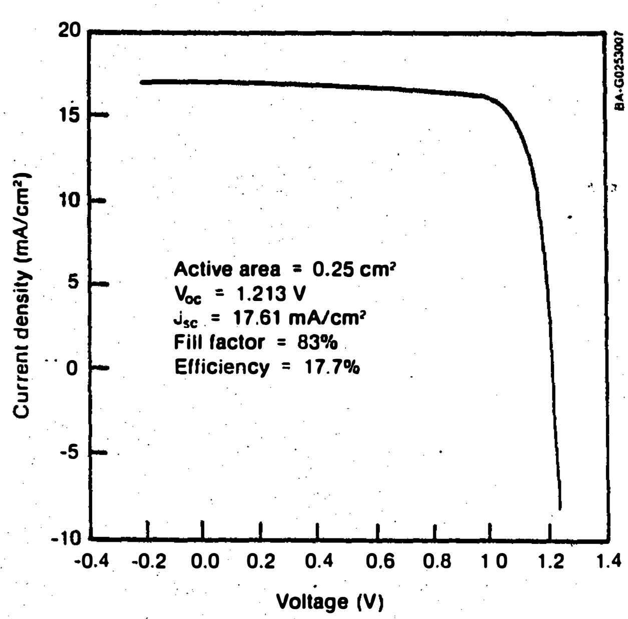

Figure 15: I-V characteristics of the SERI/Spire 17.7% efficient, 0.25-cm² GaAsP solar cell on a GaAs substrate.

In another collaborative effort between Spire and SERI, the effects of hydrogen passivation of Spire's GaAs-on-Si solar cells are being studied using SERI's Kaufman ion-beam system. The SERI results exceed previous results in passivating these devices. An increase in V_{oc} of nearly 60 mV has been observed with a low-energy (~300-eV) beam for 10 min. The study is continuing to evaluate the effects of various parameters in the hydrogen treatment on device characteristics. In Spire's research on GaAs-on-Si, there has been a significant reduction in defect densities (to 2×10^7 cm^{-2}) as determined by SERI. This has led to an increase in solar cell efficiencies to 15.2% (SERI-verified), compared with 11.2% last year and 8.7% two years ago.

Crystalline Silicon

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

SERI's subcontracted research in FY 1987 supported seven university groups. Three projects, with Cornell University, Arizona State University, and the State University of New York-Albany, investigated the initial and post-cell-processing properties of various types of silicon materials. Particular emphasis was placed on understanding the roles of oxygen, carbon, hydrogen, and fast-diffusing elements, and a second area of investigation was directed at cell processing steps that 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 that form shallow doping profiles and denuded zones was investigated at North Carolina State University. Research at the University of Kentucky and MIT aimed at identifying crystal-growth regimes that can simultaneously provide high-area production rates for silicon sheet and low (zero) dislocation densities. This approach involved modeling the crystal growth and thermal stresses in existing and advanced ribbon configurations. SERI also supported research at the University of Illinois to characterize the physical parameters of silicon near its melting point and to measure residual stress in the ribbons -- data needed to make iterative improvements in the crystal-growth models. In FY 1988 a new university research program is being initiated through a joint Sandia/ SERI solicitation under Sandia's Crystalline Silicon Research Project.

SERI's in-house research 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-Ω-cm material. A number of high-purity, gallium-doped crystals have been grown with resistivities ranging from 200 to 0.2 Ω-cm. The observed minority lifetimes for these crystals were were 21 ms for 200-Ω-cm, 16 ms for 13-Ω-cm, 7 ms for 2-Ω-cm, and 0.4 ms for 0.5-Ω-cm material. The 0.2-Ω-cm crystal could not be measured because of its high conductivity. The crystals are now being readied for commercial wafering and polishing before distribution to Si cell researchers for cooperative device work (e.g., to the Georgia Institute of Technology, Spire, Stanford University, and the University of New South Wales).

Other in-house research in SERI's PV Measurements and Performance Branch included the first atomic-level imaging of grain boundaries in polycrystalline silicon. This provided the first verification of silicon-hydrogen bonding during the passivation process and silicon-shallow-acceptor bonding during or after electronic neutralization.

Support Activities

Several 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. Both these programs, although innovative and fundamental in nature, have consistently contributed to goal-oriented materials research activities in other areas of the SERI PV Project. A recent assessment report (4) concludes that the success ratios of subcontracts under the New Ideas program from 1979 through 1986 was very high (50%-75%) as measured by the criteria of new products, patents, processes, or follow-up research support.

SERI's in-house research in theoretical solid-state physics focuses on the theory of semiconductors, to better understand the electronic and structural properties underlying the interaction of semiconductor systems with sunlight. This has led to innovative concepts and the selection of novel materials and configurations for further R&D. Accomplishments include development of the theory of the electronic structure of new compounds (e.g., LiZnP, LiZnN) suggesting new, potentially PV-applicable semiconductors, some of which have been grown at SERI. Other theoretical work predicted previously 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 at SERI.

The Crystal Growth 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 $MgSnP_2$ (the latter may not be physically stable compounds). The growth of these new, theoretically predicted PV compounds allows initial investigations of such basic properties as bandgap, absorption coefficient, and lattice constant — the promising materials may be investigated later in thin-film form.

SERI's PV Measurements and Performance Branch combines extensive diagnostic and characterization facilities with SERI's outdoor test facility to characterize cells and modules. 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. Over the past year, more than 4000 materials and devices were evaluated and tested in the branch's laboratories. These activities, which range from fundamental chemical and compositional determinations of cell interfaces to long-term outdoor module testing and evaluation, are the results of cooperative interactions with subcontractors, SERI researchers, and the PV industry. During the past year, this SERI program has worked with more than 130 organizations worldwide, representing universities, industry, and government laboratories. The branch provides measurement, testing, characterization, and device fabrication/modeling support to many PV R&D groups.

Cell efficiency measurements, and verification of the efficiency records given throughout this paper, are a specific SERI/DOE program responsibility. SERI researchers are responsible for the establishment of 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 these strict characterization procedures. The accepted standard conditions for reporting efficiencies are as follows: for one-sun (flat-plate) applications, 1000-W/m^2 irradiance, 25°C temperature and AM1.5 global illumination (ASTM E-892), and for concentrator applications, 28°C temperature and AM1.5 direct illumination (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 analysis techniques to characterize variations in solar radiation resources. Analyses 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 (1) a much-improved (15% uncertainty versus 35% uncertainty) direct-beam insolation model that is being implemented by Sandia for better designs of PV systems; and (2) cooperative efforts within the PV research community that combine SERI's spectral irradiance models with researchers' device models to examine the sensitivity of the devices to variations in spectral irradiance.

CONCLUSIONS

Improvements in materials and processing, cell design, and cell fabrication techniques for a 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 reliable photovoltaic electricity devices with long lifetimes will emerge. The continued federal/industry partnership should accelerate the attainment of the long-term goals in Table 1. The result will be the opportunity for the U.S. to use PV as a secure, inexhaustible supply of utility-scale electricity.

ACKNOWLEDGMENT

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REFERENCES

This paper has drawn liberally, without reference, from the research results of SERI subcontractors and in-house researchers. Many of these results, except for some recent ones reported here, are described in the Proceedings of the 19th IEEE Photovoltaic Specialists Conference (5), the Proceedings of the SERI 8th Photovoltaic Advanced Research and Development Review Meeting (6), and in the *Annual Report, Photovoltaic Program Branch, FY 1987* (7). Many new results are expected to be reported at the upcoming 20th IEEE Photovoltaic Specialists Conference in Las Vegas, Nevada, to be held September 26-30, 1988.

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