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Current Status of Polycrystalline Thin-Film PV Technologies

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ABSTRACT

In the past 18 months, thin-film solar cell technologies based on CdTe and CIS have made significant technical progress. Most of the improvements have occurred at the level of solar cells, modules, systems, and reliability testing in both CdTe and CIS. Total-area efficiencies of 14.7% for a thin-film CdTe solar cell deposited on a low-cost, sodalime glass fabricated by Golden Photon, Inc; was verified by NREL. Siemens Solar Industries has fabricated a world-record, aperture-area efficiency of 11.1% and a power output of 40.6 W for a thin-film CIGSS module. Solar Cells, Inc. has fabricated a large-area, thin-film CdTe module with an aperture-area efficiency of 9.1% and power output of 61.3 W; Golden Photon, Inc., has also fabricated a power module with an aperture-area efficiency of 9.2% and power output of 31.0 W. Key research issues for CdTe and CIS are discussed in this paper. Several polycrystalline thin-film arrays based on CdTe and one based on CIGSS have been deployed worldwide. Stability data indicated by both thin-film CIS and thin-film CdTe modules and systems are encouraging. Many companies worldwide are actively pursuing early commercialization efforts based on both speciality products and power modules.

INTRODUCTION

We report the many technical advances that have occurred in the past 18 months in thin-film CdTe- and CIS-based solar cell technologies. Considerable progress was made in the area of solar cells, module fabrication, system deployment, and reliabilty testing of modules and systems. In the case of devices, thin-film CdTe solar cells with total-area conversion efficiency of 14.7%, fabricated by Golden Photon, Inc.; was verified by NREL. A world-record, aperture-area efficiency of 11.1% was achieved for a thin-film CIGSS module (area = 3664 cm^2), fabricated by Siemens Solar Industries (SSI), also verified by NREL. For thin-film CdTe modules, Solar Cells, Inc. (SCI) has fabricated a large-area, thin-film CdTe module with an aperture-area efficiency of 9.1% and a power output of 61.3 W (area = 6728 cm^2), and Golden Photon Inc. (GPI) has also fabricated a 9.2% thin-film CdTe module with a power output of 31.0 W (area = 3528 cm^2). Some of the key R&D issues for thin-film CIGS solar cells are: the role of Na, the inclusion of Ga in the absorber layer, and the various heterojunction partners (buffer layers) that could potentially replace the chemical bath deposition (CBD) CdS. For thin-film CdTe solar cells, the development of a novel transparent conductor (TC) such as Cd$_2$SnO$_4$, the role of thin CdS, chemical and heat treatments, interdiffusion at the CdS/CdTe interface, and contacts are presented. As part of the Thin-Film Photovoltaics Partnership Program, National Teams in CIS and CdTe have been established. The team charter is to elucidate the critical R&D issues and help U.S. industry solve problems prior to market entry. Major players in CIS and CdTe thin-film PV technologies worldwide have been identified, and their current status is discussed. Several thin-film PV arrays based on CdTe and one based on CIGSS have been deployed worldwide. System sizes vary from 0.4 to 25 kW. Stability data indicated by both thin-film CIS and thin-film CdTe modules and arrays are encouraging for emerging thin-film technologies.

THIN-FILM CADMIUM TELLURIDE SOLAR CELLS

Fig. 1 shows the thin-film CdTe solar cell structure. The basic superstrate structure is glass/SnO$_2$/CdS/CdTe/contact. Typically, SnO$_2$ (TO) is used as the front transparent contact. Most recently, a new TC has been developed by NREL, namely, Cd$_2$SnO$_4$ (CTO). CTO has superior electrical and optical properties for similar film thickness as compared to conventional TO [1]. The biggest improvement in solar cell performance results from the thin CdS buffer layer. By thinning the CdS, GPI has been successful in fabricating a total-area efficiency of 14.7%. This has resulted in current density (J$_{sc}$) of more than 26 mA/cm^2. An insulating TO layer of about 1000 Å is used between the TO and CdS. The thin-film CdTe absorber layer can be deposited by numerous methods, such as atmospheric pressure chemical vapor deposition (APCVD), atomic layer epitaxy (ALE), close-spaced sublimation (CSS), electrodeposition (ED), laser ablation, physical vapor deposition (PVD), screen printing (SP), spray, sputtering, and metal organic chemical vapor deposition (MOCVD). All processes have resulted in efficiencies in the range of 10% to 15.8%. A critical step in achieving high-efficiency devices is a CdCl$_2$ chemical and heat treatment done for 15 to 20 min at about 420

absorber layer, thus minimizing grain-boundary effects and enhancing solar cell performance. Another effect observed as a result of the heat treatment is the intermixing that occurs at the CdS/CdTe interface. According to some estimates the amount of sulphur in the solid solution varies from 2% to about 5.6% [2,3]. A major issue in thin-film CdTe solar cells is the back contact stability. Several back contacts have been used by various groups worldwide. The back contacts used thus far are Au, Cu/Au, Ni, Ni/Al, ZnTe:Cu, and graphite (Cu, HgTe). Although stable performance has been demonstrated at the module level, this area needs close attention for long-term performance of these devices.

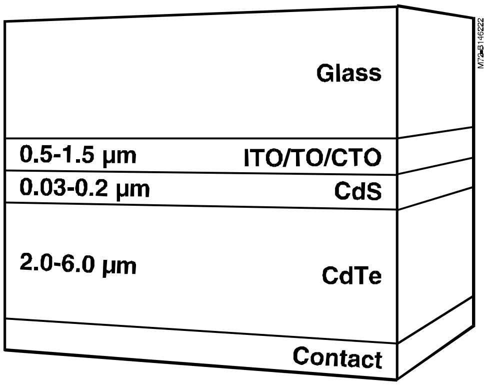

Figure 1: Thin-film CdTe solar cell structure

THIN-FILM COPPER INDIUM GALLIUM DISELENIDE SOLAR CELLS

Fig. 2 shows the thin-film CIGS solar cell structure. The substrate structure typically is ZnO/CdS/CIGS/Mo/glass. The glass substrates are 7059 or low-cost sodalime glass. Other substrates such as alumina, polymer, and stainless steel have also been used for device fabrication. The highest total-area efficiency of 17.7% obtained by NREL, however, has been achieved using a low-cost sodalime glass substrate. For the has been the diffusion of Na from the sodalime glass through the grain boundaries of the Mo back contact deposited by sputtering, and into the CIGS absorber layer. The following observations have been reported by various groups: grain growth and improvements in the morphology of the film [4], past few years, a critical issue that has recived much attention increase in the hole density from C-V measurements, and improvements in fill factor (FF) and open-circuit voltage (V_{oc}), which consequently improves solar cell performance. Extrinsic doping is also being investigated by using Na_2S or Na_2Se [5]. Another observation is that the presence of Na in the absorber layer allows more flexibility in the stoichiometry of the CIGS films. The role of gallium (Ga) in the absorber layer is another active research topic. Thus far, the optimum Ga in the absorber layer for best device performance is about 27% (Ga/Ga+In). Devices with total-area efficiency of 15.5% have been fabricated by the University of Delaware, Institute of Energy Conversion (IEC) using Ga content up to 40% in the absorber layer, which corresponds to a bandgap of about 1.3 eV. Efforts to increase the Ga beyond 40% in the absorber layer have not been successful thus far. The Ga is either distributed uniformly in the absorber layer or is tailored from back to front or from front to back of the absorber layer, depending on the deposition conditions of the CIGS film grown by physical vapor deposition. In the case of selenization, there is a buildup of the Ga at the CIGS/Mo interface due to the low temperature processing at about 420
been used to increase the bandgap of the CIGS absorber layer.

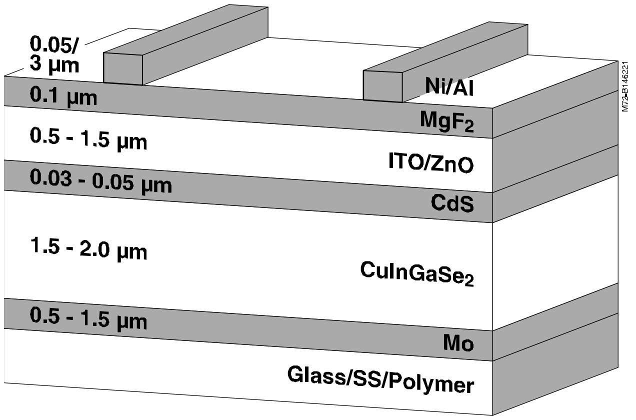

Fig. 2: Thin-film CIGS solar cell structure.

The CBD CdS that is used as the heterojunction partner (buffer layer) has resulted in the highest solar cell efficiency. However, efforts are underway to replace the CBD CdS with a non-cadmium containing alternate buffer layer, to give the thin-film CIS technology a simpler set of deposition processes. Table 1 summarizes the various buffer layers and the deposition methods used to replace CBD CdS in Japan, Europe, and United States. Although devices have been fabricated using these alternate buffer layers, none can compete at the present time with the performance of devices fabricated with CBD CdS. ZnO is normally the TC of choice for the top contact. However, recently some groups have used ITO instead of ZnO because of the superior electrical and optical properties for similar film thicknesses. ZnO is deposited by MOCVD or RF sputtering, whereas ITO is deposited by RF sputtering. Reactive sputtering of ZnO has also been investigated, but some stability issues relating to the plasma need additional work.

Table 1: Alternate Heterojunction Partners (Buffer Layers)

Material	Process	Material	Process
• Ga_2S_3	PVD	• SrF_2	PVD
• Ga_2Se_3	PVD	• $ZnIn_xSe_y$	PVD
• $(InGa)_2Se_3$	PVD	• ZnO	ALE, MOCVD
• $In(OH)_3$	CBD	• $Zn(O,S,OH)_x$	CBD
• In_xSe_y	PVD	• ZnS	PVD
• In_2S_3	PVD	• ZnSe	Sputter
• SnO_2	CBD	• ZrO_2	CBD
• $Sn(S,O)_2$	CBD		

ALE = atomic layer expitaxy; CBD = chemical bath deposition; PVD = physical vapor deposition

NATIONAL THIN-FILM TEAMS

As part of the Thin-Film Photovoltaics Partnership Program at NREL, National Teams in CIS and CdTe were established a few years ago. The team members select the various working group leaders and the critical research topics. For the National CIS Team, there are four working groups. The research topics are: i) Present Junction, ii) New Junction, iii) Mo/Substrate Impact, and iv) Transient Effects [6]. The research topics for the National CdTe Teams are: i) High-Efficiency Devices and ii) Stability. A protocol is being developed to establish the stability of CdTe modules for the industry groups [7]. An Accelerated Life Testing (ALT) procedure, which was developed as part of the teaming activities, is currently being used by the industry groups.

MODULE DEVELOPMENT AND TESTING

Various groups worldwide are actively developing both thin-film CIS and thin-film CdTe modules for both speciality products and power modules. The major players for thin-film CIS technology development are DayStar Technologies, U.S.A.; Energy Photovoltaics (EPV), U.S.A.; Global Solar Energy (GSE), U.S.A.; International Solar Electric Technology (ISET), U.S.A.; Lockheed Martin Astronautics (LMA), U.S.A.; Nordic Solar Energy, Sweden; Optical Coating Laboratory, Inc. (OCLI), U.S.A.; Matsushita Electric, Japan; Showa Shell, Japan; Siemens Solar Industries (SSI), U.S.A.; and the Center for Solar and Hydrogen Energy (ZSW), Germany. GSE is a joint venture between ITN/Enery Systems (ITN/ES) and Tucson Electric. ITN/ES is also the lead organization for the Vapor Phase Manufacturing (VPM) consortium that is funded by DARPA for more than $27 million for about 5 years [8]. GSE is setting up a 1.5 MW thin-film CIS manufacturing plant in Tucson, Arizona. Most of the groups use PVD or the two stage selenization process for the CIGS film growth. Module sizes vary from 900 cm^2 to about 4000 cm^2. Table 2 summarizes the prototype modules developed by the various groups worldwide for both CIS and CdTe. A world-record, aperture-area efficiency of 11.1% and power output of 40.6 W (area = 3664 cm^2) have been achieved by SSI, verified by NREL. There are 16 minimodules that are connected in series, packaged in a standard SSI M55 frame. EPV fabricated its first power module with an aperture-area efficiency of 6.25% and power output of 19.7 W (area = 3156 cm^2). ZSW's prototype module has demonstrated an aperture-area efficiency of 10% and power output of 7.1 W (area = 717 cm^2) [9].

Table 2: Performance of Polycrystalline Thin Film Photovoltaic Modules

Group	Material	Area (cm^2)	Eff (%)	Power (W)
Solar Cells Inc.	CdTe	6728	9.1*	61.3*
Siemens Solar**	CuInGa (S,Se$_2$)	3664	11.1*	40.6*
Siemens Solar	CuInGa (S,Se$_2$)	3859	10.3*	39.7*
BP Solar**	CdTe	4540	8.4	38.2
Golden Photon	CdTe	3528	9.2*	31.0*
Energy PV	CuInGaSe$_2$	3156	6.25*	19.7*
Siemens Solar	CuInGa (S,Se$_2$)	938	11.1*	10.4*
Matsushita Battery	CdTe	1200	8.7	10.0
BP Solar	CdTe	706	10.1	7.1
ZSW	CuInGaSe$_2$	717	10.0	7.1
ISET	CuInGaSe$_2$	845	6.9*	5.8*

* NREL measurements; All aperture-area efficiency; ** Non-monolithic integration M72-B146211

A number of groups worldwide are also actively involved in developing thin-film CdTe modules. The major players (with deposition method in parentheses) are ANTEC (CSS), Germany; BP Solar (ED), England/U.S.A.; EcoSolar Systems (CSS), India; Polyplex (SP), India; Matsushita Battery (SP), Japan; and Solar Cells, Inc. (CSS), U.S.A. The highest wattage polycrystalline thin film (PTF) module has been fabricated by SCI. The module aperture-area efficiency is 9.1% and the power output is 61.3 W (area = 6728 cm^2). GPI has also fabricated a module with an aperture-area efficiency of 9.2% and power output of 31 W (area = 3528 cm^2). GPI has a nominal capacity of 2.5 MW for fabricating of thin-film CdTe modules at its facilities in Golden, Colorado. SCI is currently installing a multimegawatt manufacturing facility in Toledo, Ohio. This is depicted in Fig. 3.

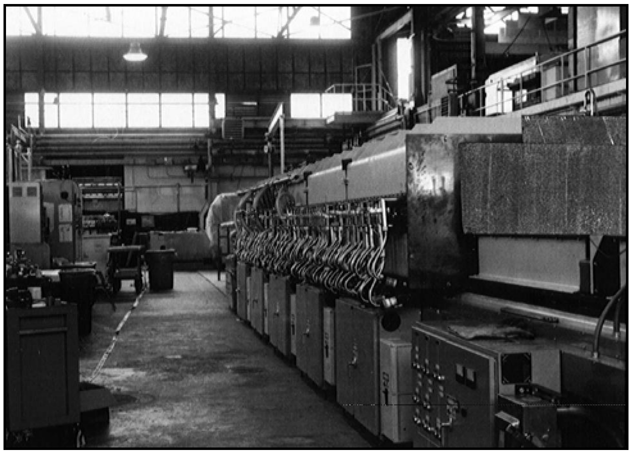

Fig. 3: A high-throughput manufacturing line for depositing semiconductor films at SCI.

One of the key parameters for the successful introduction of thin-film PV products is the reliability of the products. To make sure that thin-film products are reliable, several thin-film CIS-based modules fabricated by SSI have been tested at NREL from 1988 to 1997, as shown in Fig. 4. The thin-film CIS-based products do demonstrate stable performance over this extended period of testing. However, there have been some modules that were exposed to extreme humidity that have not been very stable. Ingress of moisture into modules leads to some unstable performance for thin-film CIS-based modules. Thin-film CdTe modules made by SCI have also been exposed to natural sunlight at various locations in the United States.

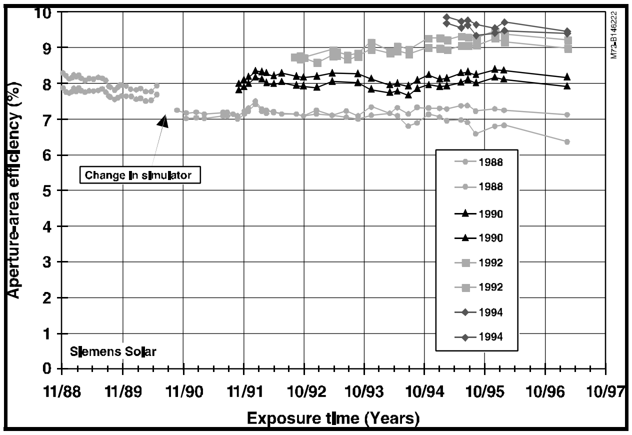

Fig. 4: Stability testing of SSI's thin-film CIS-based modules at NREL.

Fig. 5 demonstrates the stable performance of four SCI modules being tested at the South West Technology Development Institute (SWTDI) in Las Cruces, New Mexico, for nearly 800 days. Similar results have been observed for SCI modules tested at NREL.

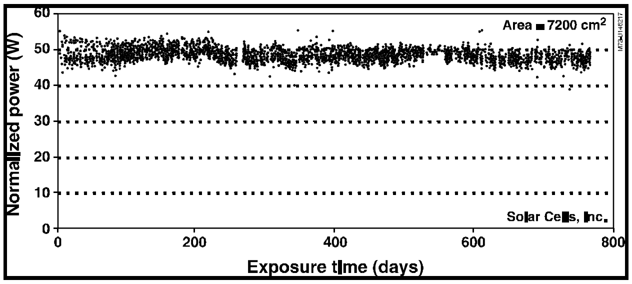

Fig. 5: Stability testing of four SCI thin-film CdTe modules at SWTDI in Las Cruces, New Mexico.

THIN-FILM PV ARRAYS

Several arrays based on thin-film CdTe and one based on thin-film CIGSS are being tested worldwide. The arrays deployed are summarized in Table 3. System sizes vary from about 0.4 to 25 kW. There are two 25-kW thin-film CdTe arrays supplied by GPI and SCI (Fig. 6) that are deployed at Edwards Air Force Base in California. These are being used by NASA as a power source to convert water into hydrogen for use in fuel cells. Two 10-kW SCI thin-film CdTe arrays have been deployed--one at PVUSA, Davis, California and the other at Toledo, Ohio. Both arrays are connected to the local utility grid and are performing very well.

Table 3: Thin-Film CdTe and CIS PV Arrays

Group	Material	Size (kW)	Location	Comments
SCI	CdTe	25	CA	Edwards Air Force Base
GPI	CdTe	25	CA	Edwards Air Force Base
SCI	CdTe	10	CA	PVUSA
SCI	CdTe	10	OH	Toledo Edison
SCI	CdTe	1.2	OH	Toledo Edison
SCI	CdTe	1.0	Tunisia	Military
SCI	CdTe	1.0	CO	NREL - OTF
SSI	CIGSS	1.0	CO	NREL - OTF
SCI	CdTe	0.4	FL	FSEC

GPI - Golden Photon, Inc.; SCI - Solar Cells, Inc.; SSI - Siemens Solar Industries; OTF - Outdoor Test Facility
FSEC - Florida Solar Energy Center

Several 1-kW thin-film CdTe arrays have also been installed worldwide. SCI has one installation in Tunisia, and GPI has several installations in Indonesia, Brazil, South Africa, and United States, mainly for water pumping. Most recently, a 1-kW thin-film CIGSS array supplied by SSI has been deployed at NREL's Outdoor Test Facility (OTF). The SCI CdTe arrays demonstrate remarkable stability for more than 2 years of testing. This is shown in Fig. 7 for a 1-kW AC thin-film CdTe array connected to the local utility, and is being tested at NREL's OTF. As can we seen in the figure, there is very little seasonal variation in the system power output as the module temperature varies between 30 and 65

Fig. 6: A 25-kW thin-film CdTe array deployed at Edwards Air Force Base, California.

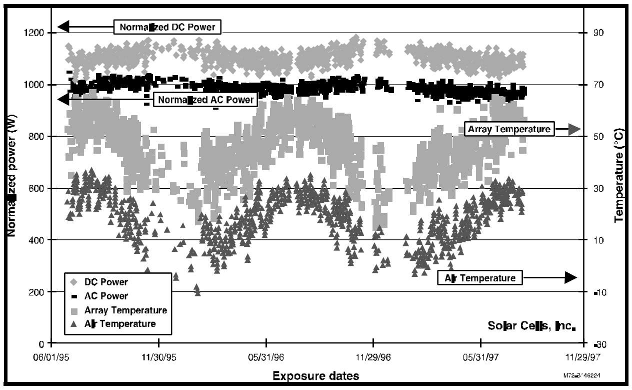

Fig. 7: Stability testing of SCI's 1-kW AC thin-film CdTe array at NREL's OTF.

THIN-FILM RESEARCH FOR THE FUTURE

As thin films become successful, they will encounter new challenges associated with providing electricity on a global scale. Today, these issues seem far away. But as concerns over global warming grow, the need for PV to displace significant energy will also grow. Table 4 lists some issues that will need greater attention.

SUMMARY

Considerable progress has been made worldwide in the area of thin-film PV technologies based on CdTe and CIS. NREL verified total-area efficiency of 14.7% with a J_{sc} of more than 26 mA/cm^2 for a thin-film CdTe solar cell deposited on a low-cost, sodalime substrate fabricated on GPI's manfacturing line. A world-record, aperture-area efficiency of 11.1% and power output of 40.6 W was achieved for a thin-film CIGSS module fabricated by SSI, also verified by NREL. SCI has fabricated the highest wattage PTF module with an aperture-area efficiency of 9.1% and power output of 61.3 W. Also, GPI has fabricated a thin-film CdTe module with an aperture-area efficiency of 9.2% and power output of 31 W, verified by NREL. Critical R&D issues for both thin-film CdTe and CIS have been discussed. Several PTF arrays based on thin-film CdTe and one based on thin-film CIGSS have been deployed worldwide. Stability data indicated by both thin-film CdTe and thin-film CIS modules and systems are encouraging for emerging thin-film PV technologies. Several companies worldwide are actively pursuing early commercialization efforts based on both speciality products and power modules.

Table 4: R&D Challenges for the Future

Material	R&D Topic	Why?
CdTe	Thinner CdTe (0.5 µm)	*Avoid Te-availability limits; minimize Cd use and waste streams (increase acceptability);* increase throughput
CIS	Thinner "CIS" (0.5 µm CIGS, CISS..)	*Increase throughput, avoid In-availability limits*; minimize Se use and waste streams (increase acceptability)
CIS	Higher band gap alloys	*Better outdoor performance*, less restrictive module designs (cell width, scribes and ZnO); replacement of some In by Ga
CIS	High-rate deposition	*Increase throughput*
Hybrids	Multi-junctions with CIS and CdTe	Higher performance
All	Degradation mechanisms	Subtle, long-term effects possible
All	Recycling	Reclamation, infrastructure

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