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Polycrystalline Thin-Film Photovoltaic Technologies: Progress and Technical Issues

H.S. Ullal

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National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
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POLYCRYSTALLINE THIN-FILM PHOTOVOLTAIC TECHNOLOGIES: PROGRESS AND TECHNICAL ISSUES

Harin S. Ullal
National Center for Photovoltaics (NCPV)
National Renewable Energy Laboratory (NREL)
1617 Cole Boulevard
Golden, Colorado 80401 USA
Tel: 303-384 6486, Fax: 303-384 6430, E-mail: harin_ullal@nrel.gov

ABSTRACT: Polycrystalline thin-film materials based on copper indium diselenide (CuInSe2, CIS) and cadmium telluride (CdTe) are promising thin-film solar cells for various power and specialty applications. Impressive results have been obtained in the past few years for both thin-film copper indium gallium diselenide (CIGS) solar cells and thin-film CdTe solar cells. NCPV/NREL scientists have achieved world-record, total-area efficiencies of 19.3% for a thin-film CIGS solar cell and 16.5% for thin-film CdTe solar cell. A number of technical R&D issues related to CIS and CdTe have been identified. Thin-film power module efficiencies up to 13.4% has been achieved thus far. Tremendous progress has been made in the technology development for module fabrication, and multi-megawatt manufacturing facilities are coming on line with expansion plans in the next few years. Several 40-480 kW polycrystalline thin-film, grid-connected PV arrays have been deployed worldwide. Hot and humid testing is also under way to validate the long-term reliability of these emerging thin-film power products. The U.S. thin-film production (amorphous silicon [a-Si], CIS, CdTe) is expected to exceed 50 MW by the end of 2005.

Keywords: Cadminum telluride, copper indium diselenide, thin films.

1 INTRODUCTION

Remarkable progress has been made by emerging thin-film solar cells based on CIS and CdTe absorber materials. NCPV/NREL scientists have achieved a world-record, total-area efficiency of 19.3% for a thin-film CIGS solar cell using the NREL-patented, 3-stage physical vapor deposition technique for a Ga/(Ga+In) ratio of 26:64 [1,2]. When the Ga/(Ga+In) ratio was changed to 35:65 the total-area efficiency achieved was 18.4%. Researchers at NCPV/NREL has also achieved a total-area efficiency of 16.8% for a thin-film CIGS solar cell using a single-step chemical bath deposition (CBD) ZnS buffer layer. The advantage of the ZnS (3.6 eV) buffer layer is that it has a larger bandgap as compared to CdS (2.4 eV), which potentially could result in a higher short-circuit current (J_{sc}). For a thin-film CdTe solar cell, the total-area efficiency is 16.5% as demonstrated by NCPV/NREL scientist. A novel transparent conductor, namely, cadmium stannate (Cd_2SnO_4, CTO) has been used in the device fabrication. For thin-film CIS- based solar cells, technical research issues such as junction formation, chemical, electronic, optical and structural properties studies; effect of heat; moisture ingress; alternate substrates, such as stainless steel, polymers, and metal foils; and new encapsulation schemes continue to be investigated. In the case of thin-film CdTe solar cells, technical issues such as micro-nonuniformity and its impact on cell and module performance, vapor $CdCl_2$ heat treatments, accelerated life testing, contact stability, defect chemistry of the absorber films, and edge sealant for module packaging are research topics of intense investigation.

In the area of technology development for thin-film CIS-based power modules, aperture-area conversion efficiencies in the range of 12.2% to 13.4% have been achieved by several groups worldwide. The module efficiencies for thin-film CdTe are in the range of 7.0% to 11.0%. Hot and humid testing of thin-film modules is currently under way at the Florida Solar Energy Center, Cocoa, Florida, to validate the long-term reliability of these emerging thin-film products. Several large grid-connected thin-film arrays varying in size from 40 to 480 kW have been installed worldwide, and they are delivering electricity to the utility grid. Based on the progress made to date by the U.S. thin-film industry, more than 50 MW of thin-film products (a-Si, CIS, CdTe) are expected to be fabricated by the end of 2005.

2 THIN-FILM CIS AND CDTE MATERIALS AND DEVICES - R&D

For the past 20 years thin-film CIS and CdTe devices have demonstrated steady progress. The Understanding the chemical, electronic, optical, and structural properties of the materials, and the development of novel device design for solar cell fabrication and processing techniques have contributed to the success of the thin-film solar cell technology to about 20% total-area conversion efficiency for laboratory devices.

2.1 Thin-Film CIS Devices

CIS is a direct-bandgap semiconductor with a bandgap of ~0.9 eV. When Ga is added to the absorber film, the bandgap can be increased depending on the Ga content in the absorber film. The universally accepted device design for fabricating high-efficiency, thin- film CIGS solar cells is the following: MgF_2/ZnO/CdS/CIGS/Mo/glass and is shown in Fig. 1. Low-cost soda-lime glass is used as the substrate. NCPV/NREL scientists have achieved world -record, total-area efficiency of 19.3%. The solar cell parameters are Jsc = 34.6 mA/cm^2, open-circuit voltage (Voc) = 0.70 V, and filll factor (FF) = 0.796. The light current-voltage (I-V) curve is shown in Fig. 2. On an active-area basis the solar cell conversion efficiency is over 20%. This is the first time that Voc of 0.70 V has been achieved for the device with a Ga/(Ga+ In) ratio of 26:76 with a bandgap of 1.13 eV and high FF of 0.80. The high Voc and FF values are attributed to the superior junction formation of the device. The composition of the absorber film is measured

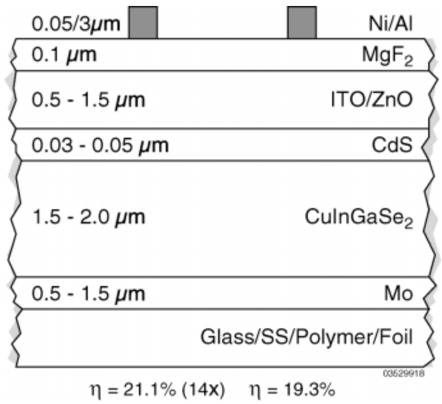

Figure 1: Thin Film CIS solar cell structure

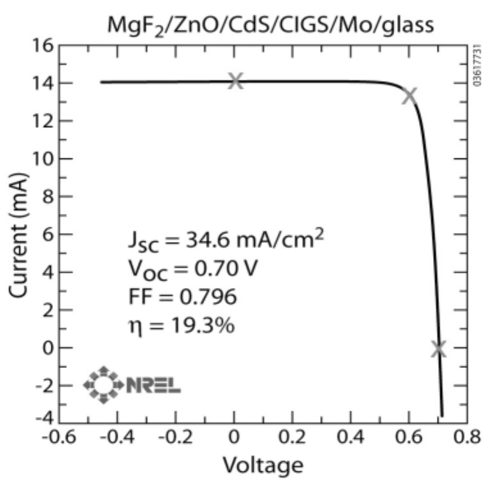

Figure 2: I-V curve for a 19.3% thin-film CIGS solar cell

by the wavelength-dispersive spectroscopy (WDS) technique. When the ratio of Ga/(Ga+In) is changed to 35:65, a total-area conversion efficiency of 18.4% was achieved with a band gap of 1.18 eV. The cell parameters are J_{sc} = 31.72 mA/cm^2, V_{oc} = 0.74 V, and FF = 0.785. Scanning electron microscopy (SEM) micrographs show significant changes in the structural properties of the absorber films with varying Ga content. For the high-efficiency device (19.3%), columnar structure has consistently been observed, whereas for the lower efficiency device (18.4%), smaller grains are observed due to varying growth kinetics and lattice -mismatch due to the higher Ga content in the absorber films. The role of the diffusion of the Na from the soda-lime glass substrates into the CIGS absorber film and its impact on device performance has been reported elsewhere [3].

One of the important processing steps to fabricating high-efficiency devices is the use of CBD CdS. The advantages of the CBD CdS are listed in Table 1. The CBD CdS is a dependable, reliable, reproducible, and low-cost process for the manufacture of thin-film CIS-based power modules. Several buffer layers have also been used to fabricate thin-film CIGS solar cells in work reported previously [3]. However, the performance characteristics do not compare well with the CBD CdS. NCPV/NREL scientists have also achieved a total-area, conversion efficiency of 16.8% for a thin-film CIGS solar cell using single-step CBD ZnS as the buffer layer [4]. The cell parameters are as follows: Jsc = 33.8

Table 1: Advantages of CBD CdS Process

- Thin Layers – 300 to 500Å
- Low Temperature Process – 60 - 90°C
- Low Cost Process – Dependable, reliable, reproducible
- Conformal Film Formation on Rough Surfaces – 400 - 600 Å (AFM)
- World Record Efficiencies – 19.3% - solar cells and 12.2% to 13.1% for power modules
- Stable Device Performance Demonstrated – ~ 15 years
- Equipment Cost – Low
- Excellent Process Yields – 85% Demonstrated
- Negligible Cost in Manufacturing Cost Structure
- Used in All Commercial CIS Based Products e.g., Global Solar, Honda Engineering, Shell Solar, and Wurth Solar

mA/cm^2, V_{oc} = 0.66 V, and FF = 0.754. The Voc is lower as compared to the CBD CdS, presumably because of interfacial defects due to ZnS precipitates and non-optimum junction formation with the CBD ZnS. The impetus to develop the CBD ZnS bandgap (Eg = 3.6 eV) buffer layer is to allow higher-energy photons to reach the junction to improve the Jsc above that obtained for the CBD CdS (Eg = 2.4 eV). In a joint collaborative research effort between International Solar Electric Technologies (ISET) and NCPV/NREL, an NREL-verified, total-area conversion efficiency of 13.2% was obtained for a thin-film CIGS solar cell using ISET's patented ink-based nanotechnology process for absorber formation [5].

2.1 Thin-Film CdTe Devices

With an optimum bandgap of 1.45 eV, CdTe is one of the most promising thin film solar cells because of the excellent match with the solar spectrum. In addition, only a few microns of CdTe are required for solar cell fabrication, because it is a direct-bandgap semiconductor and has a high absorption coefficient of >10^5 cm^{-1}. Thus, better than 90% of the solar spectrum is absorbed within 1 micron at the top of the solar cell very close to the junction region. A typical solar ell structure is glass/SnO_2/CdS/CdTe/contact and is shown in Fig. 3. NCPV/NREL scientists have achieved a world-record efficiency of 16.5% using a modified device structure. The front transparent contact used in this structure is CTO, which replaces the conventional SnO_2. There are several advantages of this new structure compared to the conventional solar cell. CTO has higher optical transmission, lower resistivity, and smoother surface roughness, as depicted from atomic force microscopy (AFM) micrographs [6]. A vapor $CdCl_2$ heat treatment

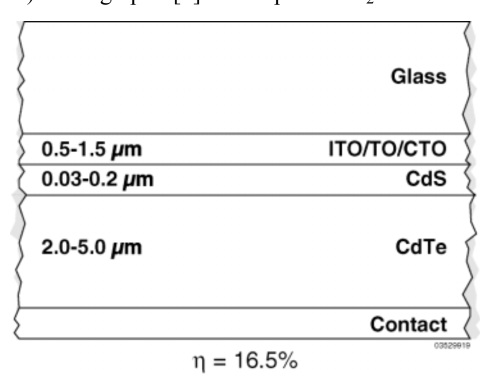

Figure 3: Thin-film CdTe solar cell structure

done at about 400°C for 20 minutes is a crucial processing step needed to fabricate high-efficiency devices. This processing step results in grain boundary passivation, enhanced grain growth, increased CdS/CdTe interface alloying, and reduced lattice mismatch between the CdS buffer and CdTe absorber layers. Numerous contacting schemes have been investigated by researchers and has been reported elsewhere [7].

Contact stability is an important aspect for long-term and reliable device performance. Accelerated life testing (ALT) is an active area of research to validate the long-term reliability of solar cells and power modules. Details of ALT has been reported previously [8]. Other research issues include micro nonuniformity and its impact on cell and module performance, vapor $CdCl_2$ heat treatments and defect chemistry (DC). DC is being investigated using several characterization techniques such as, cathodoluminescence, electroluminescence, light-beam-induced current, photoluminescence, time-resolved photoluminescence, and thermal admittance spectroscopy [9].

3 TECHNOLOGY DEVELOPMENT AND MODULE FABRICATION

Thin-film CIS and CdTe power module fabrication by several organizations worldwide is progressing at a steady pace. The major industrial players for thin-film CIS module processing are Energy Photovoltaics, USA; Honda Engineering, Japan; Global Solar Energy, USA; Shell Solar Industries (SSI), USA; Showa Solar, Japan; and Wurth Solar, Germany. Power module efficiencies for thin-film CIS-based material is in the range of 12.2% to 13.4%. In the area of thin-film CdTe manufacturing, First Solar (FS), USA, is the only company actively involved in multi-megawatt production of power modules. The best power module efficiency achieved by FS is 10.2%. Table 2 summarizes the champion aperture-area, polycrystalline thin-film module conversion efficiencies and power outputs made by various manufacturers worldwide. Figure 4 depicts the steady progress made in the aperture-area efficiency for the two thin-film module technologies (CIS and CdTe) for the past several years.

The Thin Film PV Partnership Program within the NCPV has undertaken a project to test the various thin-film PV modules in a hot and humid environment. Figure 5 shows the thin-film modules being tested at the Florida Solar Energy Center, Cocoa, Florida, to validate the long-term reliability of the thin-film PV power modules in such a harsh environment.

Table 2: Polycrystalline Thin Film Photovoltaic Modules

Organization	Material	Area (cm²)	Eff (%)	Power (W)	Date
BP Solar	CdTe	8390	11.0*	92.5*	09/01
Wurth Solar	CIGS	6507	12.2	79.2	05/02
First Solar	CdTe	6623	10.2*	67.5*	02/04
Shell Solar - GmbH	CIGSS	4938	13.1	64.8	05/03
Matsushita Battery	CdTe	5413	11.0	59.0	05/00
Global Solar	CIGS	7714	7.3*	56.8*	03/02
Antec Solar	CdTe	6633	7.0	46.7	11/01
Shell Solar	CIGSS	3626	12.8*	46.5*	03/03
Showa Shell	CIGS	3600	12.8	44.15	05/03

* NREL Confirmed; All aperture-area efficiency

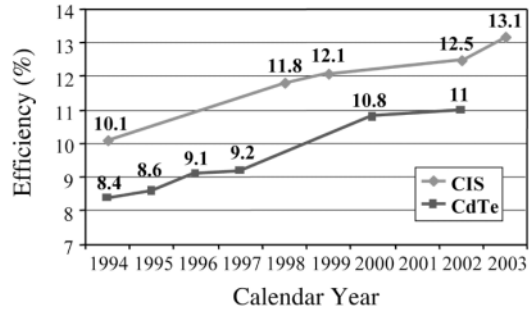

Figure 4: Progress of aperture-area, thin-film module efficiencies

FSEC

Figure 5: Hot and humid testing of thin-film modules at FSEC, Cocoa, Florida

4 THIN FILM PV SYSTEMS

As the production capacity of thin-film manufacturing continue to grow in MW production, a number of grid-connected thin-film PV systems have been installed worldwide. The U.S. thin-film production (a-Si, CIS, CdTe) is expected to exceed 50 MW by the end of 2005. Figure 6 shows an 85-kW building-integrated PV (BIPV) thin-film CIS-based solar facade deployed in North Wales, UK. The BIPV array uses SSI's Model ST36 thin-film CIS modules, which are mounted on a custom-engineered framing structure supplies by UniRac, USA. There are 2400 thin-film CIS-based modules in this facade, which is the largest thin-film CIS-based array installed in Europe. Another 245-kW thin-film CIS-based rooftop solar array shown in Fig. 7 has been deployed by SSI at their manufacturing facilities in Camarillo, California. This is the largest thin-film, grid-connected rooftop solar array in the world. The array consists of 6144 of SSI's ST40 thin-film CIS-based modules arranged in 13 rows that are wired into 256 module strings of 24 modules each [10]. Lightweight, flexible thin-film CIGS power modules are being used by the U.S. Army and Marines [11].

Shell Solar

Figure 6: 85-kW thin-film CIS-based BIPV facade, North Wales, UK

Figure 7: 245-kW rooftop, thin-film CIS-based solar electric array, Camarillo, California

The number of thin-film CdTe arrays deployed in Europe and the United States has increased significantly over the past few years. Figure 8 shows 80-kW thin-film CdTe array deployed in Dimbach, Germany, using FS modules. The electricity generated is sold to the local utilities. The world's largest polycrystalline thin-film 480-kW solar field shown in Figure 9 is deployed in Springerville, Arizona, by the local utility company Tucson Electric Power using thin-film CdTe modules supplied by FS. Typically, thin-film PV systems have better energy delivery, that is, kWh/kW installed, as compared to crystalline silicon systems because of the spectral response of thin-film modules. The thin-film arrays come online earlier in the day and are the last to turn-off at the end of the day. In addition, losses due to temperature coefficients are lower for thin film modules as compared to crystalline silicon modules.

5 CONCLUDING REMARKS

NCPV/NREL scientists have demonstrated world-record thin-film CIS solar cells with a total-area conversion efficiency of 19.3%, with a high Voc of 0.7 V and FF of 0.80. Both these device parameters indicate excellent junction formation at the CIS/CdS interface and excellent chemical, electronic, optical and structural properties of the CIS absorber material. NCPV/NREL scientists have also achieved a world-record, total-area conversion efficiency of 16.5% for a thin-film CdTe solar cell using a CTO front-contact for device fabrication. Technological improvements have resulted in an aperture-area conversion efficiency of 13.4% for a thin-film CIGS module. Several thin-film grid-connected arrays varying in size from 40-480 kW have been deployed worldwide. The U.S. thin-film production (a-Si, CIS, CdTe) is expected to exceed 50 MW by the end of 2005.

Figure 8: 80-kW thin-film CdTe solar array, Dimbach, Germany

Figure 9: 480-kW thin-film CdTe solar field, Springerville, Arizona

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14. ABSTRACT *(Maximum 200 Words)*
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