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POLYCRYSTALLINE THIN-FILM SOLAR CELLS AND MODULES

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This paper describes the recent technological advances in polycrystalline thin-film solar cells and modules. Three thin film materials, namely, cadmium telluride (CdTe), copper indium diselenide ($CuInSe_2$, CIS) and silicon films (Si-films) have made substantial technical progress, both in device and module performance. Early stability results for modules tested outdoors by various groups worldwide are also encouraging. The major global players actively involved in the development of these technologies are discussed. Technical issues related to these materials are elucidated. Three 20-kW polycrystalline thin-film demonstration photovoltaic (PV) systems are expected to be installed in Davis, CA in 1992 as part of the Photovoltaics for Utility-Scale Applications (PVUSA) project. This is a joint project between the U.S. Department of Energy (DOE), Pacific Gas and Electric (PG&E), Electric Power Research Institute (EPRI), California Energy Commission (CEC), and a utility consortium.

1. INTRODUCTION

High-efficiency, low-cost polycrystalline thin films are an exciting photovoltaic technology option for the widespread utilization of PV power for both remote and bulk-power applications. During the past few years, polycrystalline thin film solar cell efficiencies in the range of 10% to 14% have been obtained by 23 groups worldwide. Progress at the module level has also been impressive. Modules with power outputs of ~7 W to 40 W for sizes varying from 1 ft^2 to 4 ft^2 have been reported by five groups. Outdoor stability testing of these thin-film modules are encouraging. Yields in the early stages of development are increasing steadily. The major global players actively involved in the research and development are AstroPower, BP Solar, Boeing Aerospace and Electronics, Energy Photovoltaics, Fuji Electric, International Solar Electric Technology, Martin Marietta, Matsushita Battery, Microchemistry, Photon Energy, Siemens Solar, Solarex and Solar Cells. Significant contributions have been made by universities and other groups in the area of fundamental research, modeling and device fabrication. Among them are Colorado State University, Georgia Institute of Technology, Institute of Energy Conversion at the University of Delaware, National Renewable Energy Laboratory (NREL), University of South Florida, and University of Stuttgart.

2. THIN-FILM CADMIUM TELLURIDE

For the past few years, the rate of progress of thin film CdTe solar cells has been rather dramatic. Worldwide, at least 15 groups have reported cell efficiencies in the range of 10% to 14%. These results are summarized in Table I. The thin-film CdTe solar cell structure is shown in Figure 1. On low-cost sodalime glass, tin oxide (TO) or indium tin oxide (ITO) has been used as the transparent conductor (TC). A layer of CdS is deposited either by evaporation or dip-coating. The CdTe absorber layer is deposited

Table I Performance of Thin Film CdTe Solar Cells

Type	Process	Area (cm^2)	Eff. (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF	Group
Glass/TO/CdS/CdTe	Electrodeposition	0.02	14.2	23.5	819	0.74	BP Solar
Glass/TO/CdS/CdTe	ALE	0.12	14.0	23.8	804	0.73	Microchemistry
Glass/TO/CdS/CdTe	CSS	1.08	13.6*	23.12	846	0.696	USF
Glass/ITO/CdS/CdTe	Electrodeposition	0.02	13.1	27.9	720	0.65	Univ. of Queensland
Glass/TO/CdS/CdTe	Spray	0.30	12.7*	26.21	799	0.605	Photon Energy
Glass/TO/CdS/CdTe	Electrodeposition	1.0	12.7	23.8	807	0.68	BP Solar
Glass/TO/CdS/CdTe	CSS	1.125	12.6*	20.16	836	0.746	USF
Glass/CdZnS/CdTe	Screen Printing	0.3	12.5	23.6	870	0.61	KAIST
Glass/CdS/CdTe	Screen Printing	1.02	11.3	21.1	797	0.67	Matsushita
Glass/ITO/CdS/CdTe/ZnTe	Electrodeposition	1.068	11.2*	22.36	767	0.696	AMETEK
Glass/TO/CdS/CdTe	Spray	0.296	11.2*	23.08	838	0.578	Photon Energy
Glass/ITO/CdS/CdTe	PVD	0.191	11.0*	20.09	789	0.692	IEC
Glass/ITO/TO/CdS/CdTe	CSS	0.38	11.0	22.8	750	0.65	Battelle Europe
Glass/TO/CdS/CdTe	MOCVD	0.08	10.9*	22.10	745	0.66	Georgia Tech
Glass/TO/CdS/CdTe/HgTe	CSS	1.112	10.6*	21.62	745	0.658	SMU
Glass/ITO/CdS/CdHgTe	Electrodeposition	1.48	10.6	27.0	620	0.63	ISET/Monosolar
Glass/IO/CdS/CdTe	CSVT	0.1	10.5	17.0	750	0.62	Kodak (75 mW/cm^2)
Glass/TO/CdTe	CSVT	4.0	10.5	28.1	663	0.56	ARCO Solar
Glass/TO/CdS/CdTe	MOCVD	1.34	9.9	19.58	812	0.62	USF

Note: Active area = total area for superstrate cells, IO = Indium Oxide, ITO = Indium Tin Oxide, TO = Tin Oxide
*NREL Measurements

by several of the methods listed below. Various deposition methods, such as atomic layer epitaxy, electrodeposition, close spaced sublimation, laser ablation, metal organic chemical vapor deposition, physical vapor deposition, screen printing and spraying have resulted in high efficiency devices. Various contacts have been used to finish the device. One of the most important steps for achieving a high efficiency devices has been the use of a thin-layer of dip-coated or solution-grown CdS. This has significantly improved the blue response of the thin-film CdTe devices from 500 nm to about 300 nm and is shown in Figure 2. The highest current measured at NREL is 26.2 mA/cm^2 for a small-area Photon Energy thin-film CdTe solar cell. The other important processing step has been the critical chemical and heat treatments, which are done at about 420°C for 15-20 min (1,2). This results in enhanced grain growth of the thin film CdTe absorber layer, thus minimizing grain boundary

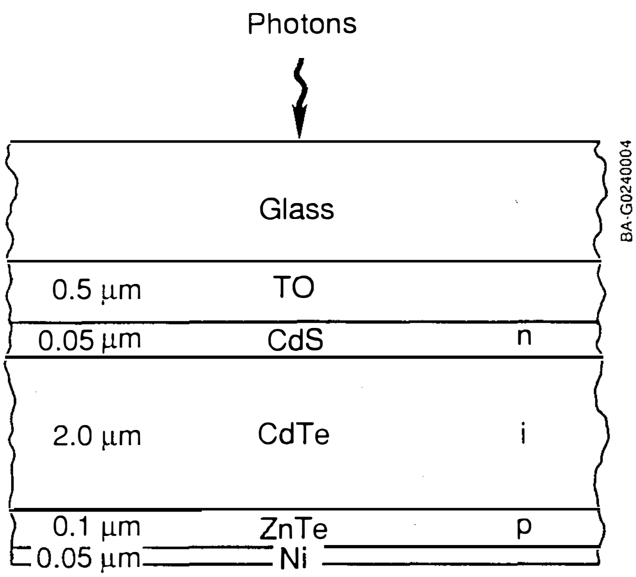

Figure 1 Solar cell structure of thin-film CdTe device

effects and improving device performance. The highest total-area efficiency of 13.6% for an area of 1.08 cm^2 verified by NREL has been achieved by Prof. Ting Chu at the University of South Florida. Dip-coated CdS has been used for this device (3). With a band gap of 1.45 eV, CdTe has an excellent match with the solar spectrum. The theoretical efficiency for CdTe is 27.5%; and practical efficiencies of 18% are possible with the existing device design (4).

There are five groups worldwide that are actively involved in the research and development of thin-film CdTe power modules. They are BP Solar in England, Photon Energy in USA, Matsushita Battery in Japan, Microchemistry in Finland, and Solar Cells in USA. The performance of thin-film CdTe modules is summarized in Table II. Module sizes of 1 ft^2 to 4 ft^2 with power outputs of 7 W to 22 W have been fabricated thus far by the various groups. The outdoor stability results of thin-film CdTe modules tested by three groups has been encouraging. BP Solar reports that after two years of outdoor testing in Spain one's module performance changed from 6.4% to 6.0% (5). Several Photon Energy modules tested outdoors at NREL for more than 600 days have been stable (6,7). Matsushita Battery modules tested for a few years in Australia, Japan, and India indicate no loss in performance, provided the modules are well encapsulated and there is no ingress of moisture (8). The manufacturing cost of these modules is considered lower than that of conventional silicon technology (5,9,13).

3. THIN-FILM COPPER INDIUM DISELENIDE

During the decade of the 1980s, CIS solar cells have made rapid progress given the limited

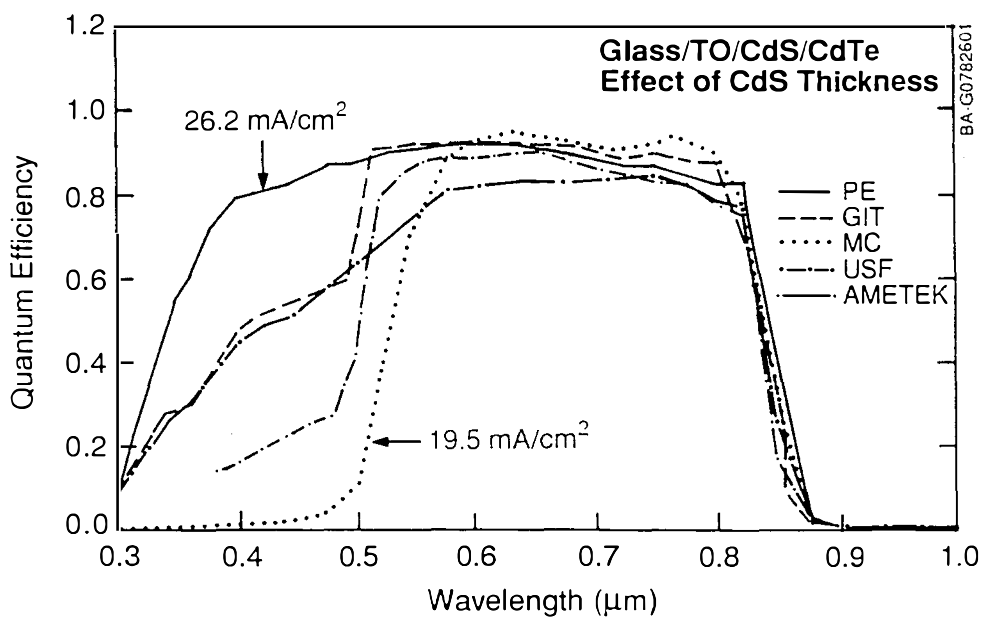

Figure 2 Quantum efficiency plots of thin- film CdTe solar cells

Table II Performance of Polycrystalline Thin Film Photovoltaic Modules

Group	Material	Area (cm^2)	Eff (%)	Power (W)
Siemens Solar	$CuInSe_2$	3883	9.7*	37.8*
AstroPower	Si-Film**	3984	9.5	34.2
Photon Energy	CdTe	3323	6.4*	21.3*
Siemens Solar	$CuInSe_2$	938	11.1*	10.4*
Matsushita Battery	CdTe	1200	8.1	9.73
BP Solar	CdTe	706	10.1	7.1
Photon Energy	CdTe	832	8.1*	6.8*

*NREL Measurements; **Non-monolithic integration; All aperture-area efficiency

number of groups actively involved in the development of this material. Seven groups worldwide have reported solar cell efficiencies in the range of 10% to 14%. This is summarized in Table III. The highest active-area cell efficiency of 14.1% has been reported by Siemens Solar for a device area of 3.5 cm^2. The typical solar cell structure is shown in Figure 3, and consists of a low-cost sodalime glass on which is deposited 1-2 μm of Mo as the metal contact. CIS films are deposited by the methods listed below. The methods used for CIS deposition are coevaporation, close spaced vapor transport, E-beam/selenization, electrodeposition/selenization, elemental sputtering, hybrid evaporation/sputtering, sputtering/selenization, reactive sputtering, spraying, sputtering/laser assisted annealing, and sputtering/rapid isothermal processing. The devices are completed by depositing a thin layer of CdS by dip-coating and a layer of ZnO by MOCVD or sputtering. The two most successful processes have been coevaporation and selenization using hydrogen selenide (H_2Se) gas. Most recently, University of Stuttgart has been successful in fabricating 11.5% devices by selenization without the use of the H_2Se gas. A solid source of selenium was used in this method (10). The theoretical efficiency for CIS is 23.5%; and practical efficiencies of 16% are possible in the next few years (4).

There are seven companies involved in the research and development of CIS devices. They are Boeing Aerospace and Electronics, Energy Photovoltaics, Fuji Electric, International Solar Electric Technology, Martin Marietta, Siemens Solar and Solarex. All of the companies, except Fuji Electric of Japan are based in the USA. To date, Siemens Solar is the only group that has fabricated large area power modules. The module size varies from 1 ft^2 to 4 ft^2 with the power varying from 10.4 W to about 40 W; this is shown in Table II.

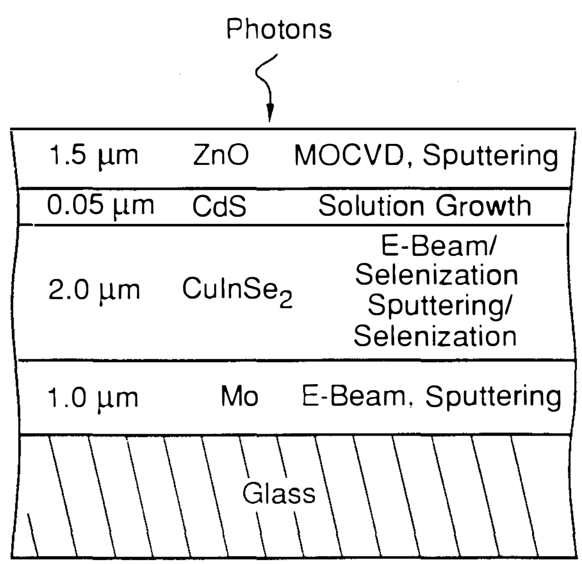

Figure 3 Solar cell structure of thin-film CIS device

Table III Performance of Thin Film Copper Indium Diselenide Solar Cells

Type	Process	Eff (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF	Area (cm^2)	Group	Comments
ZnO/CdS/CIGS/Mo/Gl	Sputter/ Selenization	14.1	41.0	508	0.677	3.5(a)	SSI	Ga/In<10%
ZnO/CdZnS/CIGS/Mo/Gl	Evap	12.9*	35.3	555	0.657	0.96(a)	Boeing	Ga/In = 0.27
ZnO/CdS/CIS/Mo/Gl	Evap	12.8	41.0	453	0.69	0.315(a)	Stuttgart, SIM, ENSCP	no Ga
ZnO/CdS/CIS/Mo/Gl	Sputter/ Selenization	12.5	36.7	446	0.700	3.56(a)	SSI	no Ga
ZnO/CdS/CIS/Mo/Gl	E-Beam/ Selenization	12.4*	38.3	483	0.666	0.99(a)	ISET	no Ga
ZnO/CdS/CIGS/Mo/Gl	Evap	12.4	28.0	658	0.68	0.38(a)	Stuttgart	Ga/In = 0.40
ZnO/CdS/CIGS/Mo/Gl	Evap	12.1	35.2	505	0.68	0.25(a)	Stuttgart	Ga/In = 0.21
ZnO/CdS/CIS/ l	Evap/ Selenization	11.5	40.0	449	0.64	0.25(a)	Stuttgart	no H_2Se
ZnO/CdS/CISS/Mo/Gl	Evap	11.5	30.7	568	0.66	0.20(a)	Stuttgart	S/In = 0.40
CdS/CIS/Mo/Al mina	Evap	11.3*	38.9	446	0.653	0.93(a)	NREL	no ZnO
ZnO/CdS/CIS/Mo/Gl	E-Beam/ Selenization	11.28*	36.75	475	0.647	4.0(a)	ISET	no Ga
ITO/CdZnS/CIS/ o/Gl	Evap	10.6*	37.4	442	0.639	0.94(a)	IEC	no Ga
ZnO/CdZnS/CIS/Mo/Gl	Evap	10.5	37.8	419	0.664	0.08(a)	Fuji	no Ga
ZnO/ZnSe/CIS/Mo/Gl	Sputter/ Selenization	10.0	40.1	391	0.641	3.5(a)	SSI	no CdS
ZnO/CdZnS/CIGS/	Evap	10.0	32.4	503	0.614	0.08(a)	Fuji	Ga/In = 0.37

Notes: All currents normal d to 100 mW/cm^2, (a) active and (t) total area; all measurements global AM1.5
*NREL measurement

The CIS modules made by Siemens Solar and tested outdoors at NREL for over 1000 days are remarkably stable (7). The modules have been tested under both load and open-circuit conditions. This is a landmark result for the CIS technology. Yields for this technology are also improving (11), as control of stoichiometry and uniform deposition over large areas improves. ISET has estimated that the manufacturing cost for a 1 MW CIS plant would be $2.50/W and for a 5 MW plant, $1.32/W (12).

4. SILICON FILM

An attractive technique to deposit silicon film on low-cost ceramic substrates is being pursued by AstroPower of USA. Silicon films of about 100 μm thickness are deposited on conducting ceramic substrates. This thickness is expected to be reduced to less than 50 μm in the future. The reduced thickness of the device and an optical coupler for confining the incident photons via a light-trapping mechanism will be used to enhance the performance of the Si-film cells. The best result to date for a small area, 1 cm^2 device is 15.7% and for a commercial size cell (100 cm^2) is 10.9%. The theoretical efficiency for this device design is in the range of 18% to 19% (13). Modules of 4 ft^2 have a reported efficiency of 9.5% and a power output of 34.2 W. AstroPower is currently in production with a capacity of 0.5 MW for FY91.

This capacity will increase to 3 MW in FY92. Mitsubishi Electric of Japan is the other group investigating the growth of Si-film on ceramic substrates.

5. TECHNICAL ISSUES

Various technical issues need to be addressed to improve device performance, to allow for long outdoor reliability, and to assure manufacturability. Perhaps the most significant issue associated with CdTe is long-term outdoor reliability. Although good results have been reported for some modules by BP Solar, Matsushita Battery, and Photon Energy, concern exists about the sensitivity of these modules to water vapor. Module encapsulation design is a critical area. Related to this issue is a known concern over CdTe/contact stability. Again, various CdTe contacts appear to be stable (e.g., Cu/Ni, p-ZnTe/Ni, Cu-doped graphite, Hg-doped graphite, HgTe), but proven stability requires long-term outdoor and accelerated tests. Although the CdTe/contact is the focus of most research, there is also work under way to investigate the interface between CdS and CdTe. Several groups have speculated that an alloy of CdS and CdTe forms, either during deposition or during a post-heat treatment (14). Since this is a crucial area in terms of device performance, many groups are actively engaged in investigating it.

In CIS, the dominant issue at both the cell and module levels is compositional uniformity. Not only does variation in composition cause device performance losses, but it can cause module reliability issues such as poor adhesion or cell-to-cell mismatch. Manufacturability is also reduced through lower yield. Improved process control and perhaps improved large-area deposition (e.g., Cu/In alloy deposition rather than separate layers) are avenues for further research. Another problem is the adhesion of CIS/Mo. Although several approaches using Ga or Te interlayers have been developed (15,16), Mo/CIS adhesion can still be a problem, as can Mo/ZnO contacts (perhaps because of a $MoSe_2$ interlayer). Recently, work at the University of Stuttgart has reopened interest in Ga and S alloys of CIS (17). Research in these areas provides a potential opportunity for efficiency enhancements.

Common to both CIS and CdTe is a need to optimize CdS and TCs. Several groups have observed that when solution-grown CdS is used instead of vacuum-evaporated CdS, voltages improve. We are interested in the cause of this improvement. Finally, TC deposition uniformity and optimization for transmission and conductivity remain areas of focus. Especially for CIS, the optimization of ZnO is a challenge because of long-wavelength light absorption in the conductive ZnO. Besides improved ZnO material quality, another possible strategy for reducing this kind of loss is to use higher band gap CIS alloys that do not absorb long-wavelength light.

6. DEMONSTRATION PROJECTS

As part of the PVUSA project -- a joint project between the U.S. DOE, PG&E, EPRI, CEC and a utility consortium, three awards have been made to polycrystalline thin-film PV technologies. All PV system sizes are nominally rated at 20 kW. AstroPower will be delivering its Product I Silicon Film on ceramic substrates, Photon Energy will be delivering its thin-film CdTe modules, and Siemens Solar will be delivering its thin-film CIS modules in 1992.

7. SUMMARY

Substantial technical progress has been made by polycrystalline thin-film solar cells and modules. Worldwide, 23 groups have reported efficiency in the range of 10% to 14%. Solar power modules with an output of 7 W to 40 W has been reported by five groups. Preliminary stability results of modules tested at various locations are also encouraging. Projected cost estimates of \$1-\$2/W for 10 MW capacity manufacturing facilities make polycrystalline thin-film photovoltaic technologies attractive options in the mid-1990 and beyond, for both remote and bulk power applications in the developed and the developing world.

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