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Solar Photovoltaic Technology: The Thin Film Option

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Introduction

Photovoltaics (PV)- the direct conversion of sunlight to electricity- was first discovered by scientists at the Bell Labs in 1954. In the late 1960's and 1970's most of the solar cell technology has been used for space applications to power satellites. The main work horse for the PV technology has been crystalline silicon (Si) solar cells. Over the past 15 years this has led to cost reduction from \$35/kWh to about \$0.30/kWh at the present time. Demonstrated reliability of 20 years or more has resulted in acceptance by several utilities. However, cost reductions in crystalline Si solar cells have been limited by the cost of wafering of ingots and the attendant loss of material. A number of Si sheet solar cells are also being investigated. In the past decade the emphasis of the research and development effort has been focused on thin film solar cells, which have the potential for generating power at a much lower cost of \$1-2/Wp. Thin film solar cells that are presently being investigated and are generating global attention are: amorphous silicon (a-Si:H), cadmium telluride (CdTe), and copper indium diselenide ($CuInSe_2$, or CIS). In the past few years, considerable progress has been made by all three of these thin film solar cells. This paper reviews the current status and future potential of these exciting thin film solar cell technologies.

Advantages of Thin Films

The main advantage of thin films is the minimum amount of material requirement. For example, in the crystalline silicon technology the film thickness of the cell is roughly 300 microns, whereas in the case of the thin film solar cells the film thickness is 1-3 microns. This is primarily due to the high optical absorption of these thin film materials. This reduced material requirement results in considerable cost savings. In addition, several low-cost, high throughput and scalable methods are available for fabricating the thin film solar cells. Also, low-cost substrates such as soda lime glass and plastic are used in modules. Module fabrication is further simplified by monolithic interconnection of cells during the actual fabrication process. Thin film solar cells can also be used in both single and multijunction configurations with 15% - 20% efficiency ranges expected for optimal cell designs. The use of glass as the top encapsulant in a superstrate structure eliminates the problem of degradation of polymers such as EVA and PVB since they are not exposed to sunlight.

Amorphous Silicon

In 1974, David Carlson of RCA laboratories was the first to fabricate a-Si:H solar cells using the glow discharge technique (1). Since then several groups have reported improvements in solar cell efficiency, stability, and utility-scale application (2,3). About 22 groups around the world have reported efficiency of over 10%. For small area cells SERI has verified single junction efficiency of 11.5% - 11.8% for 1 cm^2 area devices made by SOLAREX. The improvements have primarily been a result of using: 1) high quality textured SnO_2:F with low electrical resistance and high optical transmission; 2) multilayer back reflecting contact consisting of ITO/Ag films to improve the red response; and 3) grading the p/i interface using transitional doping or compositional grading of the p^+ layer. Additionally, the ITO/Ag can be replaced with a ZnO/Ag red reflecting contact, and the grading can be eliminated by using a hydrogen glow between the p^+ and i layers. For small area multijunction devices, SERI has verified an active area efficiency of 13.3% for a triple junction cell of area about 0.25 cm^2 made by ECD. The top two cells are a-Si:H:F with a bandgap of 1.72 eV, and the bottom cell is an a-Si:Ge:H:F alloy with a bandgap of 1.45 eV. In the case of the large area solar power modules at least 4 companies in the U. S.; namely, ARCO Solar, Chronar, ECD, and SOLAREX are selling a-Si:H based products for various applications. The best reported solar power modules are listed in Table 1. These modules are fabricated as single or multijunction devices for improved reliability.

Cadmium Telluride

The first 10% thin film CdTe solar cell was reported by Y. S. Tyan and E. A. Perez -Albuerne of Kodak in 1982 (4). Since then several groups such as AMETEK, Monosolar, ISET, Photon Energy, SOHIO, Southern Methodist University (SMU), and Matsushita Battery have reported efficiency of over 10%. SMU has fabricated a 10.6% efficient cell with a total area of 1.11 cm^2 that has been verified by SERI. The cells were fabricated by using the closed space sublimation technique. SERI has also verified a total area efficiency of 11% for a 1.05 cm^2 device fabricated by AMETEK. Electrodeposition -- a low-cost approach -- was used to deposit the CdTe. Photon Energy uses a low-cost wet chemical process for fabricating CdTe modules of 1-4 ft^2 in area. SERI has verified a module efficiency of 6.1% with an aperture area of 773 cm^2. The light I-V curve is shown in Fig. 1. Matsushita Battery of Japan uses screen printing for CdTe module fabrication. British Petroleum of England is actively developing thin film CdTe modules using a low-cost electrodeposition method. The main problem encountered in thin film CdTe technology is the contact degradation. AMETEK has circumvented this problem by using an innovative cell design of n-CdS/i-CdTe/p-ZnTe. The cells have been tested for 3000 hours under 100 mW/cm^2 illumination and load. No change in device performance has been observed over this extended period of time. CdTe has also been used in multijunction configurations, with CdTe as the top cell with a bandgap of 1.45 eV, and $CuInSe_2$ as the bottom cell with a bandgap of 1.0 eV. CdTe based alloy cells can be tailored to have a bandgap of 1.7 eV, and can be used as a top cell. Additionally, CdTe can be used in conjunction with a-Si:H in a cascade structure. In this device configuration, a-Si:H with a bandgap of 1.72 eV is the top cell and CdTe with a bandgap of 1.45 eV is the bottom cell.

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Copper Indium Diselenide

R. Mickelsen and W. Chen of Boeing Aerospace were the first to report 10% efficient $CuInSe_2$ solar cells (5). Since then ARCO Solar, IEC, ISET, and SERI have reported efficiency over 10%. The rate of progress with this particular thin film material has been very impressive. Several methods for depositing $CuInSe_2$ such as coevaporation, coelectrodeposition, electrodeposition/selenization, sputtering/selenization, reactive sputtering, sputtering/evaporation, and MOCVD are currently being investigated. Boeing Electronics Company (BECO) has fabricated a 9.6% efficient $CuInSe_2$ submodule with an aperture area of 91 cm^2 by using the coevaporation method. This efficiency has been verified by SERI. Most recently BECO has reported fabricating a 11.4%, 1 cm^2 $CuGaInSe_2$ cell with a thin CdZnS film ($<$500 A) and ZnO window layer. The CdZnS has been deposited by solution growth (dip coating) and ZnO by sputtering. Using the sputtering/selenization method (6) ARCO Solar has fabricated the world's highest thin film CuGaI $_2$ cell efficiency (12.9% active area) and module efficiency 11.1% (Fig. 2) for an aperture area of 938 cm^2. Both have been verified by SERI. The module efficiency is 25% better than any existing thin film technology, and is comparable to the Si technology on a per square foot basis. $CuInSe_2$ has also been used as the bottom cell in a cascade (tandem) structure. For example, with a-Si:H with a bandgap of 1.72 eV as the top cell and $CuInSe_2$ with a bandgap of 1.0 eV as the bottom cell, ARCO Solar has fabricated a 14.6% efficient 4 terminal cascade device that has been verified by SERI. As mentioned above, $CuInSe_2$ can also be used as the bottom cell with CdTe or CdTe based alloy as the top cell.

Applications

Thin film solar cells, especially a-Si:H have been used for numerous applications. In the early 1980's the main applications were for consumer products such as calculators and wrist watches. Since then a wide variety of applications have emerged such as clocks, battery chargers, fence chargers, call boxes, rail road signals, RV generators, automobile applications for digital display, patio lights, street lights, bill boards, roof tiles, water pumping, etc. Large thin film solar arrays of various sizes of 1 to 75 kW have been installed in conjunction with utilities in various parts of the country, or are under construction. The largest amorphous silicon electric utility field experiment (75 kW) has been installed by Chronar and Alabama Power. Several large multi-megawatt thin film manufacturing plants are expected to come on line in the 1990's. The thin film option appears likely to meet the cost competitive goals of $0.06/kWh for electricity that will make PV competitive for multibillion dollar annual markets.

Acknowledgment

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Table I. A-Si Monolithic Modules

	V_{oc} (V)	I_{sc} (A)	FF (%)	Eff. (%) Aper. area	Eff. (%) Total area	Power (watts)	Area (cm^2)	
ARCO Solar	24.0	2.21	68.0	7.8		36.7	4700	S.J.
Fuji	44.8	1.16	57.7		6.3	30.1	4800	S.J.
ECD	1.68	19.56	63.7	5.8	5.1	21.0	4110	M.J. (Si/Si)
Chronar	23.9	1.15	64.0	6.7	6.2	17.6	2880	S.J.
Chronar	23.0	1.12	59.0	6.0	5.3	15.2	2880	M.J. (Si/Si)
Fuji	39.4	0.40	65.6		8.6	10.4	1200	S.J.
ARCO Solar				12.3		10.3	843	4T(A-Si/CIS)
Fuji	41.5	0.29	69.2		6.9	8.2	1200	M.J. (Si/Si)
Solarex	25.8	0.45	69.0		8.0	8.0	1000	S.J.
ARCO Solar	43.5	0.26	68.0	9.1		7.7	843	Semi-transparent
Teijin	16.0	0.65	64.4		6.1	6.7	1200	Polymer Sub.
Solarex	25.3	0.39	64.0		6.3	6.3	1000	M.J. (SiC/SiGe)
Chronar	22.8	0.41	63.0		6.4	5.9	930	S.J.

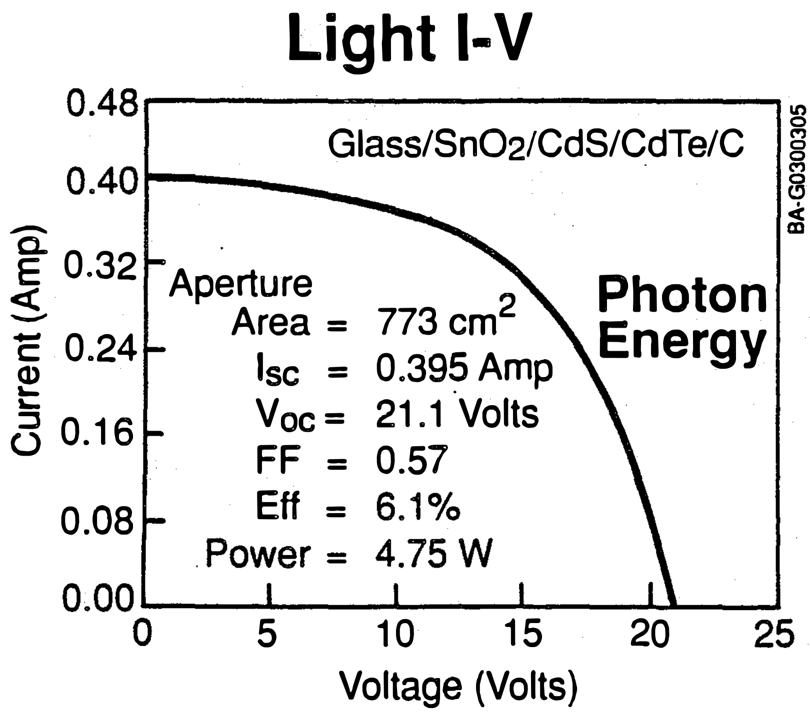

Figure 1. Light I-V curve of Photon Energy's 6.1%-efficient CdTe power module

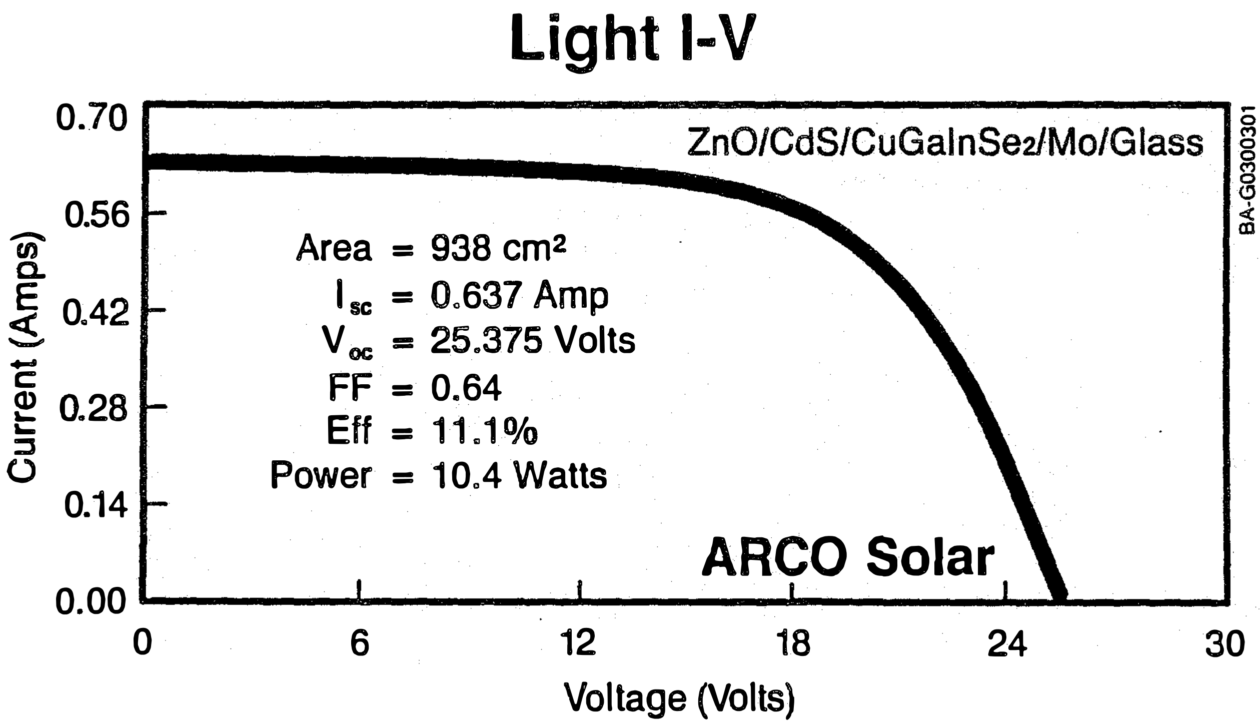

Figure 2. Light I-V curve of ARCO Solar's 11.1%-efficient $CuGaInSe_2$ power module