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POLYCRYSTALLINE THIN FILM PHOTOVOLTAIC TECHNOLOGY

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ABSTRACT

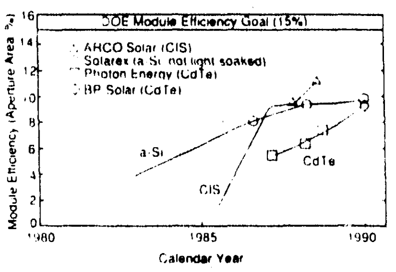
Low-cost, high-efficiency thin-film modules are an exciting photovoltaic technology option for generating cost-effective electricity in 1995 and beyond. In this paper we review the significant technical progress made in the following thin films: copper indium diselenide, cadmium telluride, and polycrystalline thin silicon films. Also, the recent U.S. DOE/SERI initiative to commercialize these emerging technologies is discussed.

KEYWORDS

Cadmium telluride, copper indium diselenide, modules, photovoltaics, polycrystalline thin films, silicon film, solar cells.

INTRODUCTION

Substantial technical progress has been made in polycrystalline thin film photovoltaic technology. The three most promising polycrystalline thin films are: copper indium diselenide ($CuInSe_2$, CIS), cadmium telluride (CdTe), and polycrystalline thin silicon films (p-Si) deposited on low-cost substrates. In this paper, we review the status of their performance, assess the future potential in the near term, and report on the recent U.S. DOE/SERI initiative to commercialize these emerging products. Figure 1 shows the progress made by thin-film module efficiencies in recent years.



Notes: All modules 1000 cm² area or more. a-Si efficiencies prior to light-induced change

Figure 1 Progress in thin-film photovoltaic module efficiencies

COPPER INDIUM DISELENIDE

For the past several years, $CuInSe_2$ has made considerable progress and currently is considered the leading thin-film material in terms of efficiency and long-term reliability (Zweibel and coworkers, 1990). Practical efficiencies of 16% are possible with existing cell design, with theoretical limits of 23.5% for $CuInSe_2$ devices (Sites 1988, Fig. 2). Several methods are available for depositing thin-film $CuInSe_2$. This is reported by Ullal and coworkers (1991).

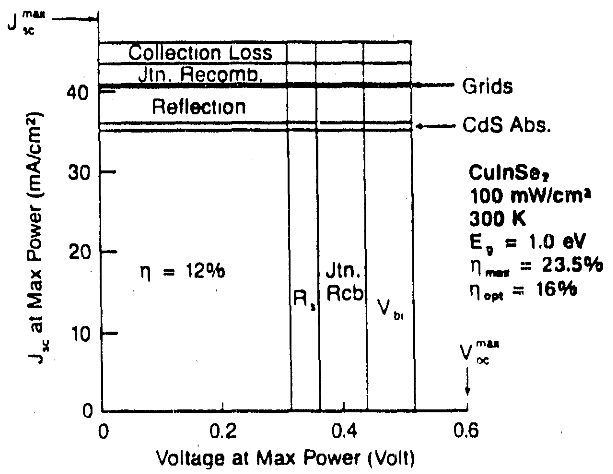


Figure 2 Various loss mechanisms in $CuInSe_2$ devices

Mickelsen and Chen at Boeing Aerospace were the first to report on 10% efficient $CuInSe_2$ solar cells by coevaporation in 1982. Since then, Boeing has improved the device performance to a total-area efficiency of 12.5% by the addition of Ga (Ga:In, 27:73). The most significant improvement has been in V_{oc} of the device to 555 mV. The addition of Ga increases the band gap to 1.15 eV from about 1.0 eV. Several other groups have reported $CuInSe_2$ cell efficiencies of 10%; among them are: ARCO Solar (now Siemen Solar Industries), Institute of Energy Conversion at the University of Delaware, International Solar Electric Technology (ISET), Fuji, University of Stuttgart, and Solar Energy Research Institute. Other new entrants to this field are Solarex and Martin Marietta. Both groups are in the early stages of cell research and module design and development.

The first major device design improvement was done by Choudary and coworkers in 1986. The new design improved the blue response of the $CuInSe_2$ devices by replacing the thick CdS layer (2.4 eV) with a "thin CdS" layer (< 500 Å) and a wide band gap ZnO (3.2 eV) window layer. This improved cell design is shown in Fig. 3. This enhances the current density by about 15% (6 mA/cm²). Subsequent improvements led to a $CuInSe_2$ cell with a reported efficiency of 14.1% (active-area) made by Siemens Solar. This device contains a small amount of Ga (<7%).

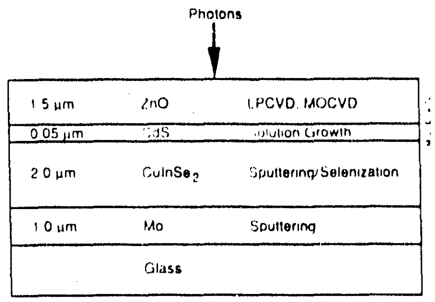


Figure 3 Solar cell structure of a thin-film $CuInSe_2$ device

Recently, ISET has fabricated solar cells with total area efficiencies of 11.5% for 1 cm^2 and 10.6% for 4 cm^2 (verified by SERI). In the ISET process, Cu and In layers are deposited by E-beam evaporation on Mo-coated glass substrates. The Cu-In layers are then exposed to a Se-bearing gas (hydrogen selenide) that reacts to form high-quality $CuInSe_2$. A thin layer of solution-grown CdS is then deposited on the $CuInSe_2$ layer for heterojunction formation. This is followed by a layer of ZnO for efficient current collection.

In the late 1980s, Siemen Solar demonstrated the effectiveness of their improved cell design and process innovations by reaching 11.1% efficiency (aperture area, SERI measurement) and power output of 10.4 W for a module size of about 1 ft^2. This was followed by even larger modules of about 4 ft^2 and reported power output of 40 W (Fig. 4). One square-foot $CuInSe_2$ modules have been tested outdoors at SERI for nearly 2 years (Fig. 5) for their reliability, under both open-circuit and load conditions. No appreciable change in performance has been observed over this extended period of testing. This is an important landmark in the $CuInSe_2$ technology. Furthermore, Siemens Solar won recognition for its progress in $CuInSe_2$ technology by receiving an award from Photovoltaics for Utility Scale Applications (PVUSA) for delivery of 20 kW of $CuInSe_2$ modules to be installed in Davis, CA this year.

Figure 4 A 3900 cm^2 large-area thin-film $CuInSe_2$ module fabricated by Siemens Solar with a reported power output of 40 W

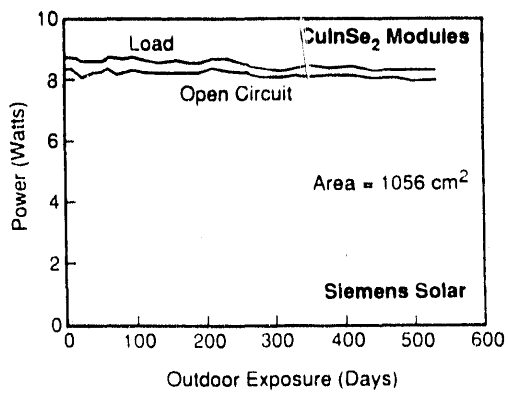


Figure 5 Stability performance of $CuInSe_2$ modules tested outdoors at SERI under load and open-circuit conditions

CADMIUM TELLURIDE

Cadmium telluride is normally referred to as the "dark-horse" of the thin film PV technology. However, with a band gap of 1.45 eV it has an optimum match with the solar spectrum. A practical efficiency of 18% is possible with existing device design, and theoretical limits are as high as 27.5% (Sites, 1988, Fig.6; i.e., even higher than $CuInSe_2$ or silicon).

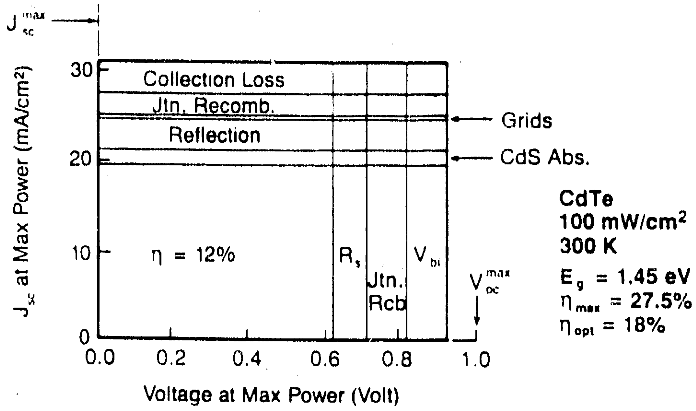


Figure 6 Various loss mechanisms in CdTe devices

Y. S. Tyan and E. A. Perez-Albuerne of Kodak were the first to report achieving 10% efficiency in 1982. Since then many groups have reported efficiencies of 10%, including AMETEK, ARCO Solar, BP Solar, Georgia Institute of Technology, ISET, Jet Propulsion Laboratory, Korea Institute of Science and Technology, MonoSolar, Photon Energy, SOHIO, Southern Methodist University, Matsushita Battery, and University of Queensland. The most recent result is a 14%-efficient thin-film CdTe device reported by Skarp and coworkers (1991). Several methods for depositing thin-film CdTe are reported elsewhere (Ullal and coworkers, 1991). Currently, the most promising low-cost methods are spraying, close-space sublimination, and electrodeposition.

AMETEK and BP Solar deposited their thin-film CdTe by electrodeposition. AMETEK has since donated their PV technology to the Colorado School of Mines Foundation for future commercialization. BP Solar is actively pursuing electrodeposition and has reported achieving 9.5% aperture-area efficiency on 1 square-foot modules. The stability results reported in the outdoor testing of their modules are encouraging. This early success has prompted BP Solar to deploy test systems such as a 54 W thin-film CdTe array for water pumping in Saudi Arabia. This system is shown in Fig. 7.

Figure 7 A 54 W thin-film CdTe array for water pumping deployed by BP Solar in Saudi Arabia

Photon Energy has successfully used the spray process to fabricate high-efficiency cells of 12.3% for small areas and 7.3% efficiency for near square-foot modules. Both efficiencies have been verified by SERI. They have also fabricated the first ever 4-ft^2 prototype CdTe module. The stability results of Photon Energy's CdTe devices tested at SERI for 550 days have also been encouraging (Fig. 8). Due to the simplicity of their process, Photon Energy does not appear to require economies-of-scale (i.e., 10 MW/year) to achieve low-cost production ($1-$2/W). They could potentially achieve this at 3 MW/year. Photon Energy has also been selected to provide 20 kW CdTe modules for the PVUSA project.

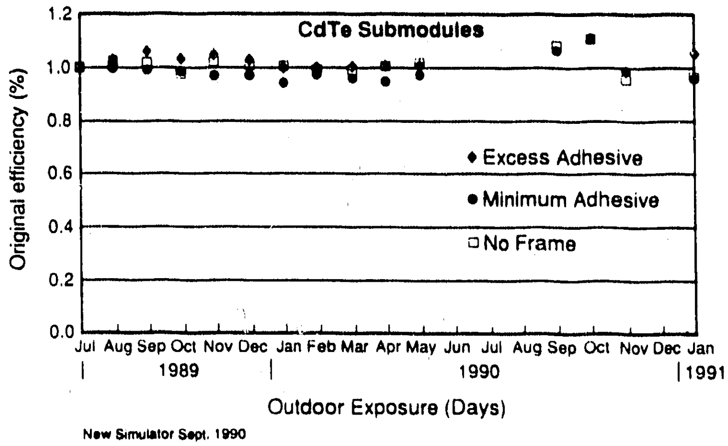


Figure 8 Stability performance of CdTe submodules tested outdoors at SERI

One of the key issues in the thin-film CdTe PV technology is the handling of the spent CdTe modules. Although details of this are given by Zweibel and coworkers (1990), a cradle-to-grave approach is being proposed where the thin-film CdTe modules are recycled. The cadmium used in the modules is never lost to the environment. A schematic of this approach is shown in Fig. 9.

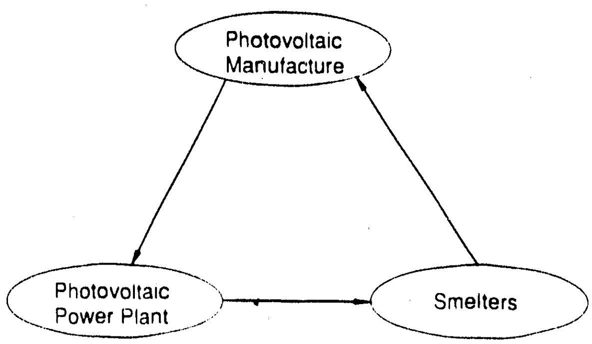


Figure 9 Thin-film CdTe PV technology; a cradle-to-grave approach to handle spent modules

POLYCRYSTALLINE THIN SILICON FILMS

Another promising technique for making low-cost thin films is being developed by AstroPower. In their approach, polycrystalline thin silicon films are being deposited on a low-cost ceramic substrates. Currently, the silicon film is about 100 µm thick, which is projected to be reduced to less than 50 µm in the future. This reduced film thickness of the silicon photovoltaic device, along with an optical coupler for confining the incident photons via light trapping mechanism, will be used to enhance the module performance. To date AstroPower has fabricated small-area laboratory devices with an efficiencies of 15.7% and commercial-size (100 cm^2) devices of 10.9% (Barnett and coworkers, 1990). AstroPower has also been awarded a PVUSA contract to deliver 20 kW to be installed in Davis, CA for their emerging technology.

POLYCRYSTALLINE THIN FILM MODULE DEVELOPMENT INITIATIVE

Due to the rapid success of both $CuInSe_2$ and CdTe PV technologies, U.S. DOE/SERI has awarded several subcontracts as part of our new module development initiative. The research is mainly directed towards industrial groups that are focused on the commercialization of these emerging technologies. More details are given in a paper by Zweibel and coworkers (1990).

CONCLUSIONS

Polycrystalline thin film photovoltaic modules are strong candidates to generate cost-effective PV electricity of 12¢/kWh by about year 1995. They also have a strong potential to meet even more ambitious long term cost goals of under 6¢/kWh. Several companies are actively pursuing the research and development of thin films such as copper indium diselenide, cadmium telluride, and polycrystalline thin silicon film to accomplish this important U.S. DOE goal. Advanced module designs and manufacturing technology are currently being investigated to lower the cost and develop stable large-area photovoltaic modules. Potentially, this could have a significant impact on global PV generation for both remote and bulk power generation as we enter the 21st Century.

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