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U. S. POLYCRYSTALLINE THIN FILM SOLAR CELLS PROGRAM

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ABSTRACT

The Polycrystalline Thin Film Solar Cells Program, part of the United States National Photovoltaic Program, performs R&D on copper indium diselenide and cadmium telluride thin films. The objective of the Program is to support research to develop cells and modules that meet the U.S. Department of Energy's long-term goals by achieving high efficiencies (15% - 20%), low-cost ($50/m^2), and long-time reliability (30 years). The importance of work in this area is due to the fact that the polycrystalline thin-film $CuInSe_2$ and CdTe solar cells and modules have made rapid advances. They have become the leading thin films for PV in terms of efficiency and stability. The U.S. Department of Energy has increased its funding through an initiative through the Solar Energy Research Institute in $CuInSe_2$ and CdTe with subcontracts to start in Spring 1990.

INTRODUCTION

The Polycrystalline Thin Film Solar Cells Program is part of the United States National Photovoltaic Program. Other areas of research and development included in the national program are the fundamental and supporting research, flat plate thin-films, flat plate crystalline silicon, and concentrator cells [1].

Table I: Polycrystalline Thin Films Program Participants

Research Organization	Objective
ARCO Solar	High efficiency $CuInSe_2$ 900 to 3900 cm^2 modules
Boeing Aerospace & Electronics	Evaporated $CuGaInSe_2$ cells, 100 cm^2 submodules
Institute of Energy Conversion	Evaporated and selenized $CuInSe_2$; CdTe cells; device modeling
International Solar Electric Technology	E-beam/sputtering Cu,In layers and selenization; 50 cm^2 submodules
University of Illinois	Sputtered/evaporated $CuInSe_2$ cells
University of Arkansas	Laser-processed Cu/In/Se films made by electroplating or sputtering
California Institute of Technology	Contact investigation of $CuInSe_2$/Mo interface
Solar Energy Research Institute	Growth, characterization and device fabrication of $CuInSe_2$
Colorado State University	Characterization and modeling of CdTe and $CuInSe_2$ cells
AMETEK	Electrodeposition of n-i-p CdS/CdTe/ZnTe cells and 100 cm^2 submodules
Photon Energy	Spraying of 900 to 3900 cm^2 CdTe modules
University of South Florida	Close space sublimation of CdTe cells; MOCVD of HgZnTe for top cells
Georgia Institute of Technology	MOCVD of CdTe and $Cd_{1-x}Zn_xTe$ cells

The objective of the Polycrystalline Thin Film Solar Cells Program is to support research to develop cells and modules that meet the U.S. Department of Energy's long-term goals by achieving high efficiencies (15% - 20%), low-cost ($50/m^2), and long-time reliability (30 years). This paper covers the various research aspects of the subcontracts program in the polycrystalline thin film area. Table 1 summarizes the various research activities with the corresponding objectives of each of the subcontracts. The two main materials of interest are copper indium diselenide ($CuInSe_2$, CIS) and cadmium telluride (CdTe). Specific research areas include fundamentals, modeling, characterization, measurements, device design, solar cell fabrication, module design and development, module processing, and stability of both $CuInSe_2$ and CdTe [2]. Figure 1 shows the progress of the polycrystalline thin film module technology in the past few years.

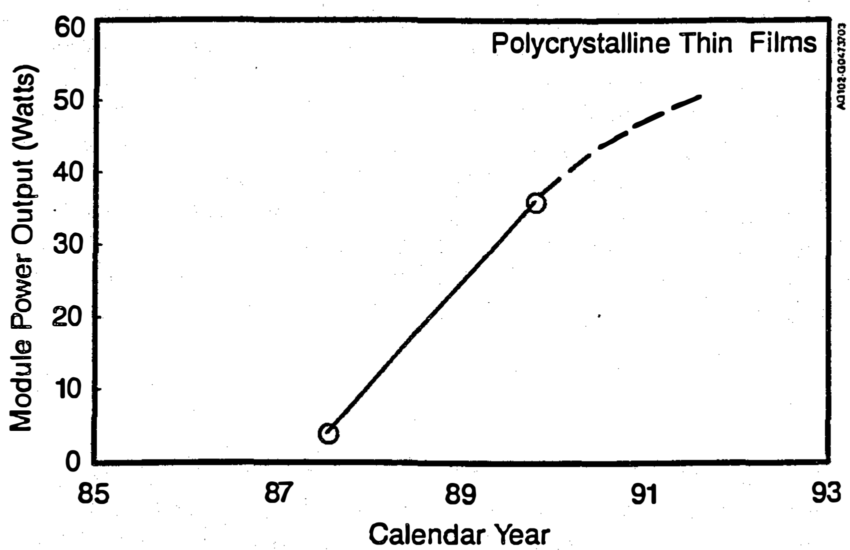

Figure 1 Progress of polycrystalline thin film module power output versus calendar year

COPPER INDIUM DISELENIDE

During the past decade, $CuInSe_2$ has made significant technical progress and is now considered the leading candidate thin-film photovoltaic material in terms of efficiency and long-term reliability of these devices [3].

Wagner and co-workers at Bell Labs first fabricated 12% efficient $CuInSe_2$ single crystal cells in 1974 [4]. Single crystals are expensive for practical applications. Nonetheless they demonstrated proof-of-concept for future research in thin-film $CuInSe_2$ devices for lower cost cells. Grindle et al. at the University of Maine were able to make 5% efficient cells [5] by thermally evaporating $CuInSe_2$ on low-cost substrates. This was followed by the successful work done by Mickelsen and Chen at Boeing Aerospace which was supported by U.S. DOE funding through the Solar Energy Research Institute (SERI). Boeing was able to make 10% efficient $CuInSe_2$ cells by coevaporation by 1982 [6].

Several groups followed the pioneering work of Boeing. Among those who initiated research programs were ARCO Solar, Institute of Energy Conversion (University of Delaware), and the Solar Energy Research Institute. All these groups were able to quickly reproduce the Boeing results in solar cell efficiency by making cells in excess of 10% [7,8]. Innovative device design (Fig. 2) first proposed by Choudary et al. [9] and reduced to practice by Potter et al. enhanced the blue response of these $CuInSe_2$ devices and improved the cell efficiency to 12.5% [10]. Further additions of small quantities of Ga (<10%) improved the reported cell efficiency to 14.1% (active area) for 3.5 cm^2 area device. Boeing also improved the cell performance to 12.9% (active area) for a 1 cm^2 device by the addition of 27% Ga in the $CuGaInSe_2$ cells [11]. The V_{OC} of this device was 555 mV, and was considered a significant improvement.

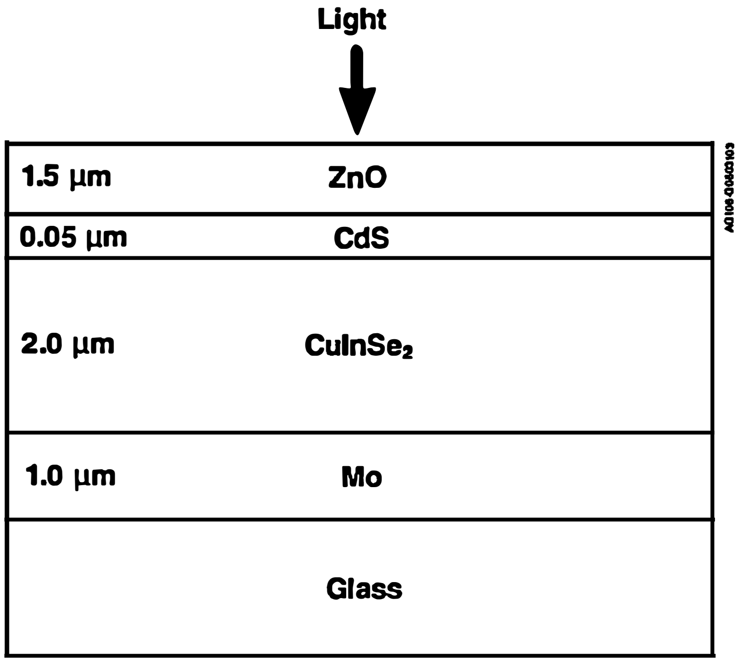

Figure 2 Device structure of a Glass/Mo/$CuInSe_2$/CdS/ZnO polycrystalline thin film solar cell

International Solar Electric Technology (ISET), a spin-off from ARCO Solar, was also successful in making 10.9% (active area) devices by a low-cost two-stage process [12]. Mo coated on glass is used as a substrate, on which Cu and then In are deposited by E-beam. The Cu-In sandwich is thermally reacted with H_2Se gas, forming high quality $CuInSe_2$. To complete the cell fabrication, a thin layer of dip-coated CdS is deposited on the $CuInSe_2$ to form the heterojunction. Using a similar approach, the Institute of Energy Conversion has demonstrated J_{SC} of 42 mA/cm^2 [13].

During the 1980s, ARCO Solar developed proprietary processes for manufacturing $CuInSe_2$ modules using a potentially low-cost approach [14,15]. This success in the manufacturability was a significant step for the $CuInSe_2$ technology and subsequently led to ARCO Solar's scale-up of large-area modules.

Ermer and co-workers reported on the major advances of the performance of large-area $CuInSe_2$ modules [16]. They reported achieving an 11.1% efficient 1000 cm^2 module, the most efficient at its size among the various thin films. For even larger areas of about 4000 cm^2, efficiency in excess of 9% with a power output of 35.8 watts (Fig. 3) for unencapsulated modules was also reported. These modules have now been tested at SERI under natural sunlight for 240 days under both load and open-circuit conditions and have been found to be very stable [17].

CADMIUM TELLURIDE

Cadmium telluride (CdTe), normally referred to as the "dark horse" of thin film solar cells, has shown improved performance in the past few years. Based on a bandgap of 1.45 eV, which is an optimum match with the solar spectrum, practical CdTe devices could potentially achieve efficiency up to 18%. Theoretical efficiencies are as high as 27.5% [18%].

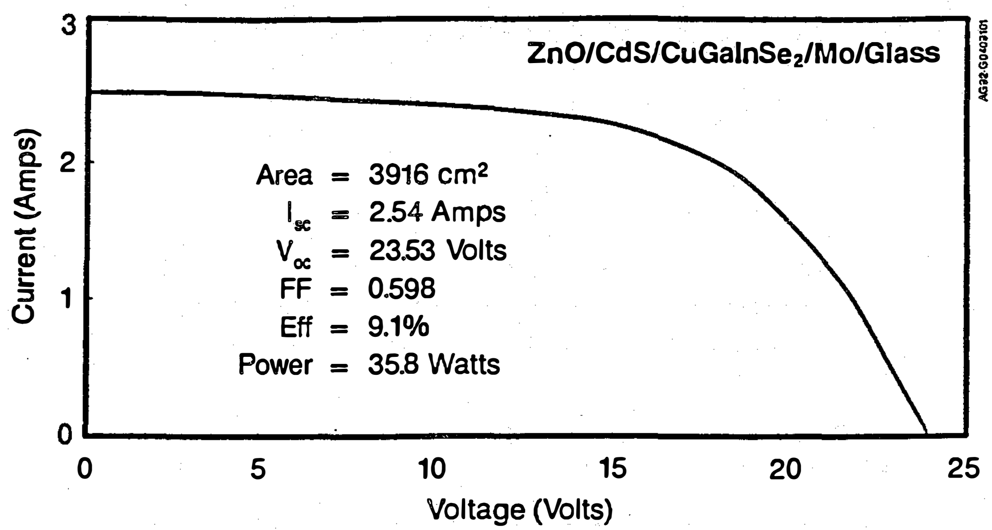

Figure 3 Light I-V characteristics of a large-area 3916 cm² polycrystalline thin film $CuInSe_2$ module

One of the key problems encountered in fabricating thin-film CdTe devices is its contact stability. To circumvent this problem, a research group at Ametek has developed a novel n-i-p cell design, which is shown in Fig.4. The undoped CdTe acts as an intrinsic layer sandwiched between the n-type CdS and p-type ZnTe layers that induce a drift field across the CdTe. Figure 5 shows the Auger depth profile for this cell structure. One of the key processing steps is a heat-treatment at 400°C for about 20 minutes. This step causes significant change in the morphology [19,20] and is the key to high process yields. During the heat treatment, the polycrystalline grains at the CdS-CdTe interface are believed to coalesce or fuse, thus greatly reducing the density of grain boundary states. Recrystallization occurs over the entire thickness of the CdTe film. Using this cell design, Ametek has fabricated 11% cells by electrodeposition [21]. Ametek has also tested their cells and submodules and have reported stability of their devices for 3000 hours.

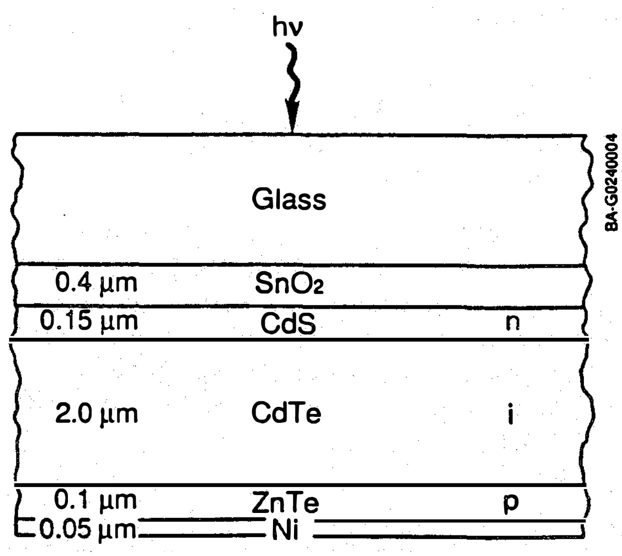

Figure 4 Device structure of a n-i-p n-CdS/i-CdTe/p-ZnTe polycrystalline thin film CdTe solar cell

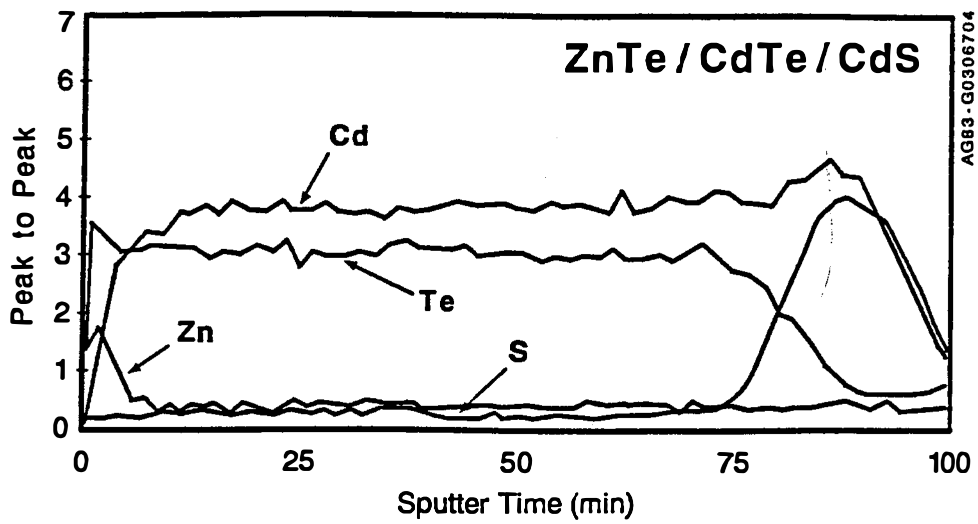

Figure 5 Auger depth profile of a n-i-p n-CdS/i-CdTe/p-ZnTe polycrystalline thin film solar cell

Photon Energy is another successful CdTe group. Their primary focus of research is to fabricate thin film CdTe solar power modules by a potentially low-cost spraying method. To date they have achieved 12.3% efficient small area cells, and 7.3% efficient square-foot module [22]. They have also made prototype four-square-foot CdTe modules for production.

SERI IN HOUSE RESEARCH

Active investigation is underway at the Solar Energy Research Institute to study the materials growth, characterization and device fabrication of thin film $CuInSe_2$ and related alloy materials. SERI makes state-of-the-art $CuInSe_2$ devices [23]. Also, extensive support is given to the photovoltaic industry in terms of material characterization such as Auger Electron Spectroscopy, Electron Beam Induced Current, Electron Spectroscopy for Chemical Analysis, Photoluminescence, Scanning Electron Microscopy, Secondary Ion Mass Spectroscopy, Spectroscopic Scanning Tunneling Microscopy, Wavelength Dispersive Spectroscopy, defect chemistry, chemical and heat treatments, stability testing, etc.

CONCLUSIONS

Polycrystalline thin-film $CuInSe_2$ and CdTe solar cells and modules have made rapid advances and are now the leading thin films for PV in terms of efficiency and stability. They have attained the highest cell efficiencies (14.1% for $CuInSe_2$ and 12.3% for CdTe), the highest module efficiencies (11.1% for $CuInSe_2$ and 7.3% for CdTe on a square-foot; 9.1% for 4 square feet for $CuInSe_2$); the best stabilities ($CuInSe_2$ 240 days without degradation), are made by the lowest cost processes (spraying, electrodeposition, sputtering and selenization). The U.S. Department of Energy has increased its funding through an initiative through the Solar Energy Research Institute in $CuInSe_2$ and CdTe with subcontracts to start in Spring 1990. The level of federal support for $CuInSe_2$ and CdTe is doubling to about $2.4M for each material. Both $CuInSe_2$ and CdTe are now moving out of the lab and into demonstration projects through the Photovoltaics for Utility Sale Applications (PVUSA) proposals. 20 kW systems of $CuInSe_2$ supplied by ARCO Solar and 20 KW of CdTe supplied by Photon Energy will be installed in Davis, California, next year for field testing and evaluation.

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