SERI/TP-211-3679
UC Category: 270
DE90000321

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March 1990

Prepared for the World Renewable Energy Congress
Reading, United Kingdom
23-28 September 1990

Prepared under Task No. PV040301

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A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

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RECENT TECHNOLOGICAL ADVANCES IN THIN FILM SOLAR CELLS

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ABSTRACT

High-efficiency, low-cost thin film solar cells are an exciting photovoltaic technology option for generating cost-effective electricity in 1995 and beyond. This paper reviews the substantial advances made by several thin film solar cell technologies, namely, amorphous silicon, copper indium diselenide, cadmium telluride, and polycrystalline silicon. Recent examples of utility demonstration projects of these emerging materials are also discussed.

KEYWORDS

Amorphous silicon, cadmium telluride, copper indium diselenide, polycrystalline silicon, solar cells, thin-films, photovoltaic techology, photovoltaic systems

INTRODUCTION

Thin film solar cells are an integral part of the photovoltaic (PV) technology base, whose main goals are to deliver electricity at 12¢/kWh in the year 1995 and 6¢/kWh by the year 2000. To accomplish these major objectives, intense research and development is underway with the following materials: amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium diselenide ($CuInSe_2$ or CIS), and polycrystalline silicon (p-Si). Other solar cells such as crystalline silicon, sheet or ribbon silicon, gallium arsenide, and concentrator cells are also being investigated (Kazmerski 1989). In this paper, we report on the recent technological advances made by thin film solar cells in the past few years. Several advantages of thin-film solar cells have been reported elsewhere (Ullal et al., 1989).

AMORPHOUS SILICON SOLAR CELLS AND TECHNOLOGY

Ever since the first report of a-Si solar cell with a MIS structure was published by Carlson and Wronski in 1976, there has been many groups that have actively pursued device fabrication. From 1982 to 1990 at least 27 groups worldwide have reported a cell efficiency of over 10%. For small-area devices, Energy Conversion Devices has fabricated a multijunction cell with an active-area efficiency of 13.3%, the highest efficiency a-Si device to date.

Much of the recent technological advances in a-Si have focused on module fabrication. The highest single-junction module efficiency for a-Si to date is 9.84% with a power output of 9.18 W for an aperture area of 933 cm^2 made by Solarex. The light I-V characteristic is shown in Fig. 1. Several advanced module design and processing steps have been incorporated, such as textured tin-oxide front contact, improved doping method for the p-layer, high-reflectivity back metallization, all laser-scribed patterning of modules, and a low-cost, spray-on encapsulant that has replaced the more expensive EVA/Tedlar package. ARCO Solar has fabricated a 9.4% efficient semi-transparent square-foot module with a white back-reflector. Energy Conversion

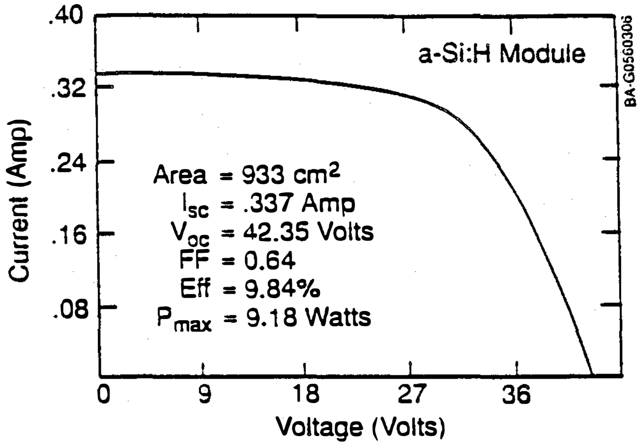

Fig. 1 Light I - V characteristics of a 933 cm² a-Si Solarex module

Devices has produced a 8.4% efficient multijunction square-foot module. The largest a-Si module (2.5 ft x 5 ft) has been fabricated by Chronar with a power output of about 62 W and an aperture area efficiency of 5.2%. In the United States alone, there are at least seven companies, ARCO Solar, Chronar, Energy Conversion Devices, Glasstech Solar, Solarex, Utility Power Group and Iowa Thin Technologies that are actively involved in taking the a-Si technology from the lab to the market place. One of the key issues in this technology is the so-called "Staebler-Wronski" effect, i.e., a reduction in a-Si device efficiency upon exposure to light. To minimize this light-induced effects, two approaches are being pursued. The first is to use thin intrinsic layers of 0.2-0.3 µm, while in the second case, the multijunction device structure represents an attractive engineering solution, with losses expected to be kept below 10%. Research on multijunction on modules is currently underway, which potentially can result in cost-effective thin film a-Si modules.

POLYCRYSTALLINE THIN FILMS

Polycrystalline thin films (PTF) such as copper indium diselenide, cadmium telluride, and polycrystalline silicon have made substantial technical advances during the 1980s. Initially CIS, CdTe, and p-Si were competing for attention along with copper sulfide, gallium arsenide, zinc phosphide and other polycrystalline thin films. Progress at Boeing in CIS, and at Kodak, Matsushita, Ametek, and Monosolar in CdTe led to polycrystalline thin films with efficiencies over 10%. This key proof-of-concept aroused great interest in both CIS and CdTe. ARCO Solar and International Solar Electric Technology (ISET) began work on CIS. Photon Energy and SOHIO/BP Solar started efforts in CdTe, and AstroPower in thin p-Si solar cells.

Copper Indium Diselenide

Following on the early CIS research at Boeing, ARCO Solar improved on the cell design by improving the blue response of the devices. In 1986, Choudary et al. proposed to replace the thick CdS layer which has a bandgap of 2.4 eV with a "thin CdS" layer (<500 Å) and a wide bandgap ZnO (3.2 eV) window layer. This improved the current density by about 6 mA/cm², or about 15%. With this novel design shown in Fig. 2, ARCO Solar was able to report achieving 14.1% efficiency (active area, Mitchell et al., 1988). This latter efficiency was achieved with a CIS layer that included about 7% Ga in place of In. The addition of Ga improves the open-circuit voltage of the CIS devices. Boeing has also done pioneering work in the area of Ga alloying and achieved 12.5% efficiency (total area) that has been verified at SERI.

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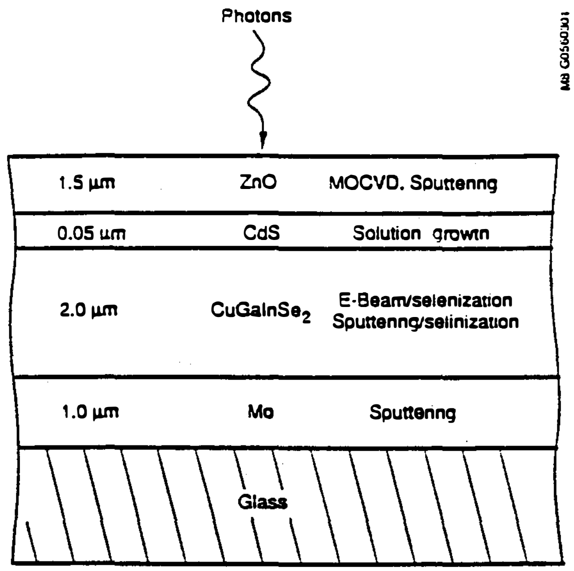

Fig. 2 Solar cell structure of a thin film CIS device

ARCO Solar has successfully scaled up their proprietary process for large-area CIS module fabrication. The sputtering/selenization method has been described in their patents (e.g., Love et al., 1984) and an European patent application (Eberspacher et al., 1988). In this approach, the deposition of Cu and In is sequential. The metals are about 2000 Å of Cu and 4000 Å of In and can be sputtered rapidly. ISET has demonstrated that the metals can also be deposited by E-beam evaporation. Following this step, Se is introduced via H_2Se gas and a carrier gas such as Ar or N_2. Due to interdiffusion, the elements mix and form high quality CIS. ARCO Solar has demonstrated the effectiveness of their innovative device design and processing by making large-area modules. In 1988, they fabricated an 11.1% efficient CIS module with an aperture area of 938 cm^2, and subsequently an even larger 9.1% efficient module with an aperture area of 3900 cm^2 and a power output of 35.8 W before encapsulation was reported (Ermer et al., 1989). This large CIS module is presented in Fig. 3. Square-foot CIS modules have also been tested outdoors at SERI for over a year for their reliability, under both open-circuit and load conditions. No appreciable change in performance has been observed over this extended period of testing.

Fig. 3 A 3900 cm^2 large-area CIS module fabricated by ARCO Solar with a power output of 35.8 W

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Cadmium Telluride

CdTe is another promising thin-film solar cell material. Its primary advantage is that it has the optimum bandgap of 1.5 eV, which is well matched with the solar spectrum. Although several methods are available to deposit thin-film CdTe (Ullal et al., 1989), the most promising ones are eletrodeposition and spraying. Photon Energy has successfully used the spray method to fabricate both high efficiency cells (12.3%) and modules (7.3%) (Albright et al., 1990). They have also fabricated four-square-foot prototype CdTe modules. Photon Energy has very aggressive near-term goals to enter the PV production markets. Their cost estimates suggest that they may potentially be one of the lowest cost module manufacturers. They do not appear to require the same levels of manufacturing scale (i.e. 10 MW/year) to achieve economies-of-scale. Infact, they claim that they will achieve low cost ($1-$2/W modules) at a production level of about 3 MW/year.

Another low-cost, non-vacuum method to deposit thin-film CdTe is electrodeposition. Both Ametek and BP Solar are pursuing this approach. One of the main advantages of this method is the high materials utilization. The key technology issue for CdTe devices is the contact stability. Ametek has circumvented this problem with a novel n-i-p cell design. In this device structure, the undoped CdTe is sandwiched between n-CdS and p-ZnTe. There is no direct metal contact to the high resistivity CdTe. Using this unique cell design, Ametek has fabricated 11.2% efficient cells, while BP Solar has reported fabrication of 9% efficient 900 cm^2 modules. Ametek has also tested their submodules for over 5000 hours, and within experimental error there are no significant changes in the submodule performance. This is shown in Fig. 4.

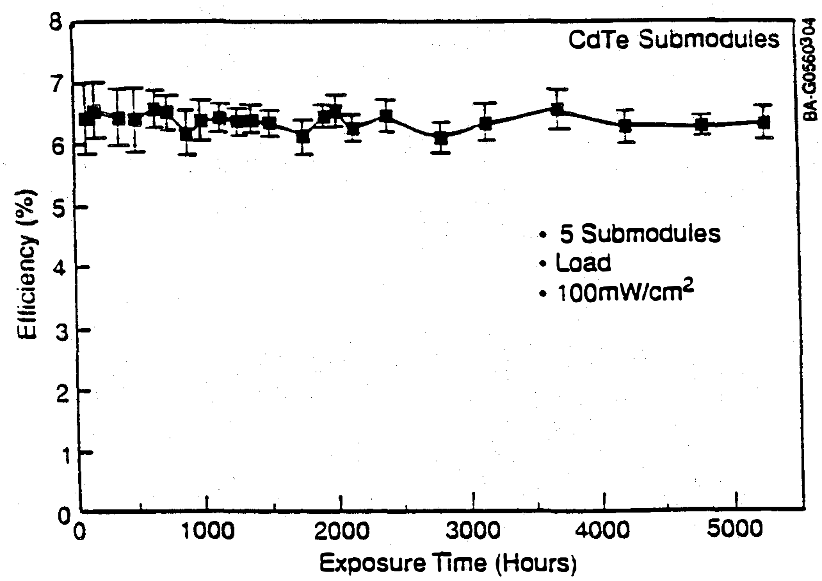

Fig. 4 Reported stability performance of CdTe submodules tested indoors at Ametek

Polycrystalline Silicon

AstroPower is pursuing another attractive method for making low-cost thin-film solar cells. Their approach is to deposit silicon-films (thin p-Si) on a low-cost, ceramic substrate. Currently the Si film thickness is about 80-100 μm and is projected to be reduced to 20-50 μm in the near future. This reduced thickness of the device along with an optical coupler for confining the incident photons via a light trapping mechanism will be used to enhance the performance of the cells. So far AstroPower has fabricated small-area laboratory devices with an efficiencies of 15.7% and commercial-size (78 cm^2) devices of 8.5% (Barnett et al., 1989).

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THIN FILM PV TECHNOLOGY DEMONSTRATION PROJECTS

Due to the rapid progress made by thin film solar cell technologies there is an increasing interest on the part of utilities to test and evaluate the performance of these emerging technologies. The Photovoltaics for Utility Scale Applications (PVUSA) project - a joint project between a utiliy consortium and the U.S. Department of Energy has awarded contracts to thin film groups in a-Si, CIS, CdTe, and thin p-Si as part of their demonstration projects. System sizes varying from 20 kW to 400 kW will be installed in Davis, California in mid to late 1990 to test these thin film PV systems.

SUMMARY

Thin film solar cells are strong candidates to generate cost-effective PV electricity of 12 ¢/kWh in the year 1995 and beyond. Several thin materials are being actively pursed to achieve this major objective; the most promising among them are: amorphous silicon, copper indium diselenide, cadmium telluride, and thin polycrystalline silicon. Advanced module design and manufacturing methods are presently being investigated to lower the cost and develop stable large-area modules. This could potentially have a significant impact on global PV electricity production.

Acknowledgment

This work was supported by the U. S. Department of Energy under contract # DE-AC02-83CH10093.

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