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Overview and Challenges of Thin Film Solar Electric Technologies

Conference Paper
NREL/CP-520-43355
December 2008

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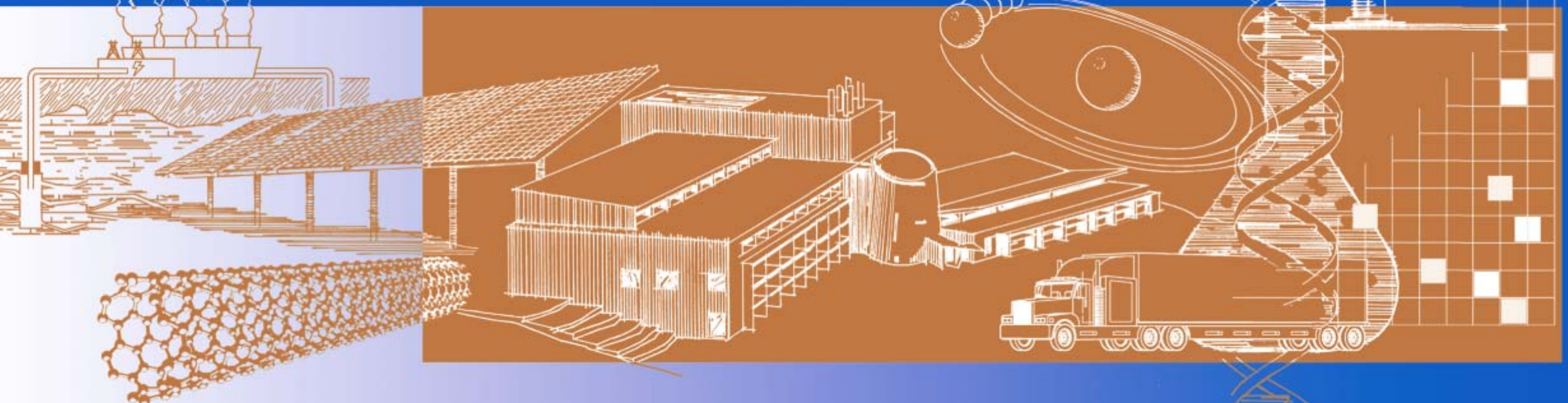
Presented at the World Renewable Energy Congress X and Exhibition 2008
Glasgow, Scotland, United Kingdom
July 19–25, 2008

NREL is operated for DOE by the Alliance for Sustainable Energy, LLC Contract No. DE-AC36-08-GO28308



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Overview and Challenges of Thin Film Solar Electric Technologies*

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1 Introduction

In this paper, we report on the significant progress made worldwide by thin-film solar cells, namely, amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). Thin-film PV technology status is also discussed in details. In addition, R&D and technology challenges in all three areas are elucidated in this paper. The worldwide estimated projection for thin-film PV technology production capacity announcements are estimated at more than 5000 MW by 2010.

2 Thin-Film Amorphous Silicon Solar Cell Technologies

Amorphous (a-Si) solar cells were fabricated at RCA laboratory in 1976. The initial conversion efficiency was 2.7%. Since then, considerable progress has been made to improve the stabilized total-area, conversion efficiency of a-Si in the range of 12% to 13% for small-area laboratory solar cells. This section describes the family of a-Si solar cells that include microcrystalline, nanocrystalline and micromorph solar cells. a-Si solar cells can be either a single junction, dual junction or multijunction devices. The highest total-area, stabilized efficiency of 12% to13% has been demonstrated using tandem and multijunction devices.

a-Si solar cells are fabricated on substrates such as low-cost, sodalime glass, stainless steel and polyimide. All manufacturing plants use the plasma-enhanced chemical vapor deposition (PECVD) for the deposition process. The typical superstrate structure is p-i-n on glass or substrate structure of n-i-p on foil with a TCO as a top contact and Al along with ZnO as the bottom contact. The ZnO/Al serves as a back reflector to enhance the short-circuit current (Jsc) by approximately 15%. Ag has been tried as a back metal contact instead of Al, but has been found to be problematic in terms of product reliability in module fabrication. However, with the recent developments in the tandem (micromorph) devices, the performance of ZnO/Ag or ZnO/Ag/Al have been quite reliable for stable back contacts.

Although much of the a-Si commercial production has been single junction modules fabricated on low-cost, sodalime glass and multijunction devices on stainless steel substrates, there is a great deal of effort worldwide to introduce tandem devices using a-Si as the top cell and microcystalline absorbers as the bottom cells. This is also sometimes referred to as micromorph devices. The typical intrinsic layer thickness in a single junction device is about 0.3 micrometer, since this has demonstrated the best stabalized device efficiency [2]. In the case of multijunction devices, the total thickness of the 3 devices is about 0.7 micrometer. This poses a major challenge for the micromorph tandem device, since the typical thickness is about 2.0 mircometer for the bottom cell and it is an indirect semiconductor. This needs higher thicknesses to absorb the photons in the solar spectrum. Thus some of the major challenge for scientists is to develop i) higher efficiency solar cells, ii) reduce the light induce changes in the devices, iii) develop higher deposition rates for the

* Employees of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Dept. of Energy have authored this work.

microcrystalline bottom cell without compromising on the opto-electronic properties of the a-Si tandem devices, which could potentially have detrimental effect on the solar cell performance, and iv) reduce the manufacturing cost of the a-Si power modules.

The market share for a-Si modules is several percent of the worldwide PV sales. The major players are Uni-Solar, USA, Energy Photovoltaics (EPV), USA, Power Film Solar, USA, OptiSolar , USA, Kaneka, Japan, Mitsubishi, Japan, Sharp Solar, Japan, Schott Solar, Germany and many more. There are also five equipment suppliers for turnkey a-Si factories, namely, Applied Materials, USA, Anwell Technologies, Singapore, Hind High Vac, India, Oerlikon Solar, Switzerland, and Ulvac, Japan. Most recently, Applied Material, USA announced the sale of a turnkey manufacturing plant worth $ 1.9 Billion, presumably to the LDK Investor Group in China. This potentially could translate to a production capacity of 1000 MW per year of a-Si power modules. The new company is called Best Solar and is based in China.

3 Thin-Film Cadmium Telluride Solar Cell Technologies

Thin-film CdTe solar cells are one of the most promising thin-film PV devices. With a bandgap of 1.45 eV it has an excellent match with the solar spectrum. Since these are direct bangap semiconductors with high absorption coefficient, very thin absorber layer are needed to absorb the photons. Theoretical efficiencies for these devices are about 26%. Laboratory efficiencies of 16.5% for thin-film CdTe solar cell has been demonstrated by NREL scientists [3]. Historically, thin-film CdTe solar cells were referred to as the “dark horse” for thin-film PV devices. Subsequent concerted research effort by several groups worldwide has resulted in developing several deposition processes for the growth of the absorber layer. The processes are close-space sublimation, electrodeposition, vapor transport deposition, spray, screen-printing, sputtering, physical vapor deposition, laser ablation, metal organic chemical vapor deposition, molecular beam epitaxy, and atomic layer epitaxy [4]. Many of these processes has resulted in thin-film CdTe solar efficiency of 10% or higher. Five of these processes have demonstrated prototype power modules, namely, close-space sublimation, electrodeposition, spray, screen printing and vapor transport deposition.

For thin film CdTe technology, five key research, development, and technology challenges include: (1) standardization of equipment for deposition of the absorber layer, (2) higher module conversion efficiency, (3) back-contact stability, (4) reduced absorber layer thickness to less than 1 micrometer and (5) control of film and junction uniformity over large area for power modules.

The current status of the manufacturing technology is power modules with a conversion efficiency of 10.5% made by First Solar (FS). Their manufacturing cost is $ 1.14 per watt and installed system price is in the range of $ 4-5 per watt, the lowest in the industry for any PV system. Clearly, FS is the world leader in all thin-film PV manufacturing technology. They have an installed capacity of more than 132-MW in Perrysburg, Ohio. They have also installed a 176-MW manufacturing plant in Germany in 2007. In addition, they are installing a 704-MW thin-film CdTe manufacturing line in Malaysia, which will be commissioned in phases in 2009. Thus FS’s target is to have a worldwide installed manufacturing capacity of 1000-MW by December 2009. To date, FS has sold a few 100 MW of thin-film CdTe power modules to six installers in Germany for commercial roof-top and utility-scale applications. They are also working very closely with a system integrator -- Juwi Solar to install a 40-MW solar farm in Saxony, Germany to be completed in December 2008. Like for all PV companies, the German feed-in-tariff law has clearly helped in the market acceptance of the thin-film CdTe power modules. A few more emerging companies are AVA Solar, Colorado, USA, Primestar Solar, Colorado, USA, Calyxo, Ohio, USA, Calyxo, Germany, and Avendi, Italy.

4 Thin-Film Copper Indium Gallium Diselenide Solar Cell Technologies

Thin-film PV technology based on copper indium gallium diselenide is another attractive option for fabricating high-efficiency, low-cost, and reliable thin-film power modules. Thin-film CIS is also a direct bandgap semiconductor and has a bandgap of ~0.95 eV. When Ga is added to CIS, the bandgap increases to ~1.2 eV depending on the amount of Ga added to the CIGS film. This material has demonstrated the highest total-area, conversion efficiency for any thin-film solar cells in the range of 19.3% to 19.9%, fabricated by NREL scientists [5,6,7,8].

Several challenges still need to be addressed as emerging and new groups develop CIGS thin-film PV technologies. The following six challenges are critical for developing low-cost and reliable CIGS products: (1) standardization of equipment for the growth of the CIGS absorber films, (2) higher module conversion efficiencies, (3) prevention of moisture ingress for flexible CIGS modules, (4) improved processing for CIGS deposited by alternative process for high efficiency cells and modules, (5) thinner absorber layers of less than 1 micrometer or less and (6) CIGS absorber film stoichiometry, and junction and film uniformity over large areas for power module fabrication.

Worldwide, some 40 companies are actively involved in the technology development of thin-film CIGS products. Towards this end, twelve deposition processes are being used for growing the thin-film absorber layers. In all cases, Mo is used as the back contact deposited by sputtering, while majority of the groups use ZnO as the front contact deposited by sputtering or chemical vapor deposition. Some companies use ITO instead of ZnO for the front contact. Five thin-film CIGS companies: Wurth Solar, Germany, Global Solar Energy (GSE), USA, Showa-Shell, Japan, Honda, Japan, and Sulfurcell, Germany are in commercial production. The production capacity varies between 5 to 40 MW per year. GSE has recently installed a 40 MW CIGS manufacturing plant in Tucson, Arizona, USA and are installing a 35 MW manufacturing plant in Germany later in 2008. In addition, GSE is also planning an expansion of 100 MW plant in Tucson, Arizona that will be completed by December 2010. Thus, GSE will have a cumulative production capacity of 175 MW worldwide by December 2010.

The thin film CIGS absorber layers vary in thickness from 1.5 to 2.5 micrometer and are deposited by coevaporation or the two-stage process in which the first step is the growth of the precursors, Cu, In, Ga by sputtering followed by selenization in H_2Se gas for CIGS film formation.

5 Summary

Rapid progress is being made by a-Si, CdTe, and CIGS-based thin-film PV technologies in entering the commercial markets. In the United States, market share for thin-film was about 65% in 2007 compared to less than 10% in 2003, and has surpassed Si shipments in the year 2007 [8]. Several critical research, development, and technology issues need to be addressed by emerging thin-film PV companies as they plan to enter the market. The projections for worldwide production capacity announcements for all thin-film PV are estimated at more than 5000 MW in 2010, with First Solar's global target at 1000 MW by 2009 and Sharp's target of 1000 MW by 2010. These economies-of-scale production capacity should substantially reduce the manufacturing price of the thin-film PV products and potentially make solar electricity price-competitive with grid-parity electricity by the year 2015.

6 Acknowledgment

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-99G010337. The authors would like to thank the numerous managers, engineers, scientists, and technicians whose data are included in this paper.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
December 2008

2. REPORT TYPE
Conference Paper

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Overview and Challenges of Thin Film Solar Electric Technologies

5a. CONTRACT NUMBER
DE-AC36-08-GO28308

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
H.S. Ullal

5d. PROJECT NUMBER
NREL/CP-520-43355

5e. TASK NUMBER
PVB75401

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

8. PERFORMING ORGANIZATION REPORT NUMBER
NREL/CP-520-43355

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)
NREL

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*
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15. SUBJECT TERMS
PV; thin film; solar cells; amorphous silicon; cadmium telluride; copper indium gallium diselenide; solar electricity; research and development; technology challenges;

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(10/2008)