Research and progress in high-throughput manufacture of efficient, thin-film photovoltaics

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ABSTRACT

This paper reports progress in high-throughput manufacture of thin-film, CdTe-absorber PV modules. The achievement of 3 m^2/min CdS/CdTe deposition throughput and ~9% efficiency highlight the potential of the technology.

This paper also reports on research efforts to translate that potential into high-volume manufacture. Handling of large volumes of hot glass through a vacuum deposition system presents a challenge, and efforts to improve glass flatness and strength are described. Efforts to improve the uniformity of the semiconductor films while maintaining high throughput are also described. Diagnostics, research on cell operation and alternative processes, and safety and environmental issues are also discussed.

1. Introduction

In order to radically change the power-generation paradigm of the world, a PV technology must be capable of achieving < $1/W costs and multi-GW/yr volumes. Thin-film CdTe-absorber photovoltaics is recognized as a technology compatible with these goals because of the characteristics and availability of the materials involved [1].

A brief description of the cell structure and production approach employed at First Solar is as follows: SnO_2-coated, soda-lime glass is edge seamed, cleaned, and placed in a low-pressure deposition system with high-speed load locks. CdS and CdTe are deposited at ~ 1 µm/sec to thicknesses of ~ 0.3 µm and 3 µm, respectively [1]. A $CdCl_2$-anneal is performed, followed by back contact processes, laser scribing for monolithic integration, and encapsulation.

2. High-throughput manufacture

High-speed manufacturing has been demonstrated with high-throughput stations and automation of station transitions. The vapor-transport semiconductor-deposition system has been run successfully with throughput as high as 3 m^2/min. Extended runs have been done at a slower speed, e.g., 1220 plates (each 0.72 m^2) were deposited in 10 h.

Module processing with in-line equipment has been demonstrated, with a portion of the results shown below.

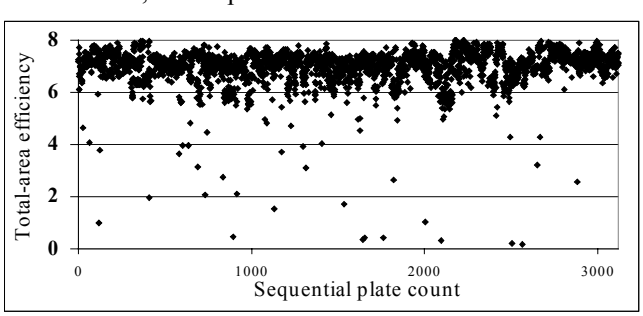

Figure 1. Total-area efficiencies for 3128 sequentially-deposited modules (unencapsulated, 0.72 m^2 each).

Figure 1 shows the total-area efficiency results from 3128 sequentially-coated plates (from 8 sequential deposition runs). The data has not been filtered to remove experiments or non-standard processing.

3. Module efficiency

As reported previously, one of the known methods of increasing the conversion efficiency of modules over that produced from the current process is to reduce CdS thickness to < 0.1 µm to reduce optical absorption in the CdS and thus increase short-circuit current [1]. In order to prevent loss of cell voltage, a buffer layer is required between the front contact (the conductive SnO_2:F) and the CdS. Progress has been made with the deposition of buffer layers and with thin-CdS modules.

In-house development of buffer layers has been done with an atmospheric-pressure chemical vapor deposition (APCVD) system with a throughput rate of ~ 1 m^2/min. New precursor chemistry, nozzle design, and mass-flow control has improved film deposition. Additionally, runs were conducted with a glass company to test the feasibility of producing a SnO_2:F/buffer film stack on a float line.

Modules produced with high-speed deposited SnO_2 buffer layers (by APCVD on a float line) and thin CdS (by vapor-transport on the production coater) were processed with unconfirmed aperture efficiencies of > 9%. Figure 2 provides an IV of a finished, encapsulated 0.72 m^2 module.

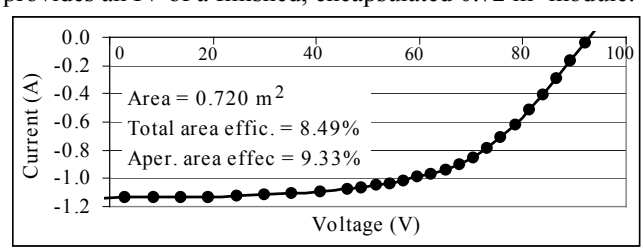

Figure 2. IV of module with thin-CdS/buffer layer

4. Glass properties

Glass is an inexpensive material well-suited as a substrate for large-volume, low-cost PV. However, with the process temperatures used (> 500°C), careful temperature control during cooling is required to control residual stress, flatness, and breakage. Moreover, due to large thermal mass of the entire system, significant start-up transients must be taken into account. Heating and quenching conditions were modified in an effort to reach a target of 2000 psi surface compression to provide protection against breakage in subsequent processing or in the field.

5. Semiconductor uniformity

Consistent deposition of uniform CdS and CdTe are vital to reaching the potential for the material system. Layer thickness is one of the parameters that has been used to

improve uniformity. In-situ laser sensing of CdS thickness [2] and off-line X-Y mapping of CdS and CdTe thicknesses have been used to achieve standard deviations in thickness within runs and within plates of < 10%.

Surface photo-voltage (SPV, as measured by using a high-impedance meter with a graphite pad in contact with the CdTe side while illuminating from the glass side) has been used to provide rapid characterization of the electrical properties on coated plates. Post-deposition processes ($CdCl_2$ treatment and back contact processes) greatly improve the uniformity of SPV, but mapping plates immediately after CdTe deposition shows that considerable non-uniformity can be present in the cross-web direction (down-web standard deviation is essentially zero). Figure 3 shows an SPV map of a plate showing lower voltage at the edges of the plate prior to $CdCl_2$ treatment and contact processing.

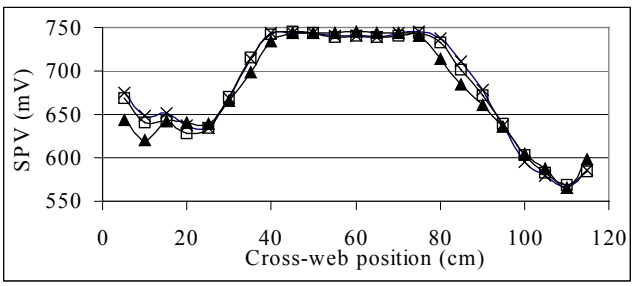

Figure 3. SPV from glass/SnO_2/CdS/CdTe plate (3 different down-web positions on one plate)

Uniformity of microstructure (grain size, orientation, and roughness) is also found to be excellent in the down-web direction, but there is opportunity for improvement in the cross-web direction. Research on deposition conditions and vapor-distributor design is ongoing to improve cross-web uniformity of SPV and semiconductor microstructure.

6. Diagnostics

Tools that provide information for improved control or understanding are essential for high-volume manufacture. In addition to those mentioned above, full-module mapping systems have been developed for four-point probe resistance, photoluminescence, and V_{oc}. Semi-automation of cell IV measurement was done to improve research efficiency, with over 190,000 IVs taken in the past year.

7. Research on cell operation and alternative processes

Improved understanding of cell operation is also vital to reaching the potential for the material system. For example, it has been found that back contact variables can have a strong influence on cell open-circuit voltage. Figure 4 provides an extreme example of this influence whereby the omission of an interfacial layer (IFL) normally included in the contact suppresses cell V_{oc} by 500 mV. However, stripping the back-contact metal layers from the low-V_{oc} cell reveals it has ~ normal SPV (~780mV). Finite difference and closed-form analysis [2 and references therein] show that micro-nonuniformity could explain this behavior, and LBIC mapping [3] found that high micro-nonuniformity correlated with low efficiency for the set studied.

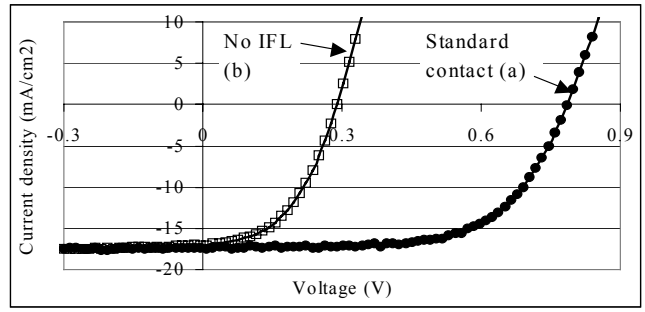

Figure 4. IV of two cells. (a) cell with standard contact, (b) cell with interfacial layer of back contact omitted.

Other efforts to improve understanding have included the use of admittance spectroscopy, electron-beam-induced current, compositional analysis, spectral response, and stress studies [2, and references therein].

While the majority of effort has been on refinement of existing processes and improving understanding, some effort was dedicated to exploring alternative processes. Alternative contact treatments remain an area of interest for their potential to improve product reproducibility, efficiency, and robustness, while potentially lowering costs.

9. Worker safety and environmental protection

Despite increased research and production activities, a safe working environment has been maintained [4]. A new hazard recognition program and internal audit program has been put in place to ensure continued success.

Environmental issues have also been successfully addressed. Recycling of off-spec and end-of-life modules is done on site, and a program for recovery of materials from deposition system components has been instituted. A change from a methanol-$CdCl_2$ process to an aqueous-$CdCl_2$ process enabled the retention of a *de minimus* rating of emissions for the facilities, so no permitting is required.

10. Acknowledgements

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