# R & D OF CdTe-ABSORBER PHOTOVOLTAIC CELLS, MODULES, AND MANUFACTURING EQUIPMENT: PLAN AND PROGRESS TO 100 MW/YR

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## ABSTRACT

As part of a long-term vision of multi-GW production of photovoltaic (PV) panels per year, First Solar is implementing a plan for 17 KW/hour (~100 MW/year for 3 shifts) production. The research and development of the cells, modules, and manufacturing equipment necessary for this level of production are discussed. A component of this plan is to raise module efficiencies to 10%, with the majority of improvement coming from i) improvement of thin-film uniformity, and ii) reduction of CdS layer thickness while protecting open-circuit voltage with the inclusion of a high-resistivity layer between the TCO and CdS layers. The operation of a new semiconductor deposition system at 2.9 $m^2$/min, production throughput, and product quality are also discussed.

## Introduction

The production of multi-GW of photovoltaics (PV) per year has long been the vision of many researchers and industrialists. CdTe is a candidate material to fulfill that vision because i) Cd and Te are readily available in the quantities required [1], ii) CdTe has a direct bandgap of about 1.5 eV, which is ideal for PV conversion of sunlight [2], iii) high efficiency and stability have been demonstrated with high-speed processes [3, 4], iv) projected costs are sufficiently low [5], and v) CdTe modules can be manufactured, used, and recycled in a safe and environmentally responsible manner [6, 7].

It is because of these attributes that Solar Cells, Inc. (SCI) performed research, development, and pilot-production of CdTe modules for 8 years. In 1999, First Solar, LLC was formed as a joint venture between SCI and True North Partners, LLC of Scottsdale, AZ with the intent of accelerating the development and production of CdTe-based PV.

In July 1999, ground was broken for a new 75,000 $ft^2$ manufacturing facility in Perrysburg, OH. The building was completed in January 2000 with new high-speed manufacturing equipment being constructed and sited in the building. This paper provides highlights of the plan and progress for the R&D of the product and equipment needed to reach a production level of 17 KW/hr (~100 MW/year with 3 shifts of production).

Our path to 100 MW/year production involves the following tasks that are being pursued concurrently:

1) design and construct a CdS/CdTe deposition system with a throughput of four 0.72 $m^2$ (120 cm x 60 cm) plates per minute,
2) design and construct a module finishing line with a throughput of one plate per minute which can be rapidly replicated later on location or at other sites,
3) redesign modules for lower manufacturing costs and higher quality,
4) increase module efficiency to 10%, and
5) scale-up to large production volumes without a loss in product quality

First Solar currently uses $SnO_2$-coated soda-lime glass [8] substrates. After washing, ~3000 Å CdS and then ~3 μm CdTe are deposited on the $SnO_2$ in less than 10 seconds using vapor-transport deposition (VTD) [9]. After a $CdCl_2$ anneal and CdTe surface modification, the contact metals are sputter-deposited then annealed. At this time, small cells (1.1 $cm^2$) from production plates have efficiencies of ~10%, which generally result in 0.72 $m^2$ modules with total-area efficiencies of approximately 7%.

### Semiconductor deposition system

A new CdS/CdTe deposition system (Fig. 1) has been designed and constructed. The system has a throughput of four 0.72 $m^2$ modules/minute. This high throughput (~100 MW/yr for 10% efficient modules) is made possible by the extremely high growth rate (~1 μm/sec) of First Solar's patented VTD process.

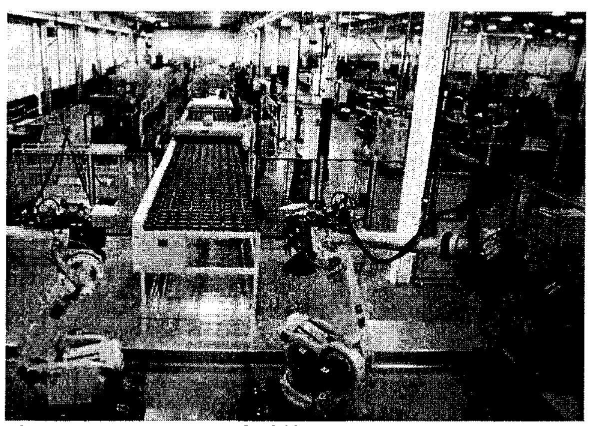

**Figure 1.** High-speed CdS/CdTe deposition system with 2.9 $m^2$/min throughput.

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The first CdS/CdTe coatings were made with the system in February. The first CdS/CdTe-coated plate from the system yielded cells of up to 11% efficiency after light soaking. The system has a 1.2 m web width and can coat 1.2 m x 2.4 m plates. Figure 2 shows the uniformity of the CdS coating from the system. For the plate shown, the standard deviation was 0.004 and 0.023 µm in the down-web and cross-web directions, respectively.

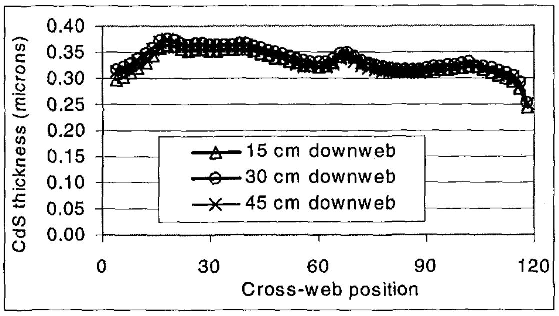


**Figure 2.** CdS thickness as a function of cross-web position for three different down-web positions.

Figure 3 shows the thickness uniformity of the CdTe coating for two different deposition conditions. As with the CdS, the CdTe thickness is very uniform in the down-web direction, but has a standard deviation in the cross-web direction of 11% and 6% for deposition conditions 1 and 2 shown in the figure, respectively.

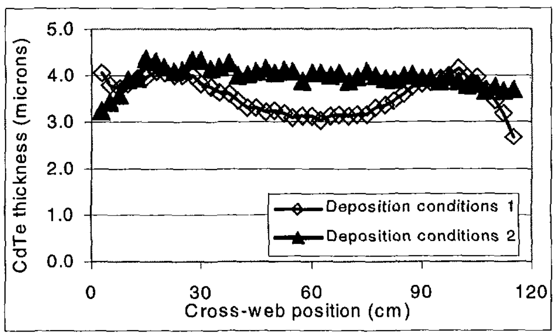


**Figure 3.** CdTe thickness as a function of cross-web position for two different deposition conditions.

## Module finishing equipment

New equipment has been designed and constructed to handle the post-CdTe deposition processes at 1 plate /min. The plan is to establish production at this level (20 MW/yr for 8% modules) with the ability to add finishing capacity in increments on site or at other locations.

The first step after CdTe deposition is a $CdCl_2$-anneal, which serves to increase device efficiency. There are two parallel efforts with $CdCl_2$ systems. The first is to run the current production line that uses a spray/roll $CdCl_2$-in-water system followed by a conveyor-line anneal. This system has a 1.2 m wide web and 1 plate/min throughput. The second effort is to refine vapor-$CdCl_2$ processing on the module scale. A pilot-production system with a 0.6 m web has been constructed to determine the characteristics needed. Since vapor-$CdCl_2$ results in a more uniform treatment and pristine CdTe surface, it is expected to be superior for high-volume production and is thus being considered for future capacity additions.

Sputtering is currently used for the back-contact metals. A sputter system and an in-line anneal oven have been installed for the 1 plate/min line.

To make a monolithically-connected module, laser scribing is used to turn the filmed-plate into 116 series-connected cells. As shown in Figure 4, scribe-1 isolates the front contact of the cells, scribe-2 enables the series connection to the next cell, and scribe-3 isolates the back contact of the cells.

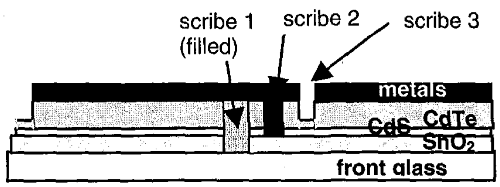


**Figure 4.** Monolithic integration with laser scribing.

In pilot-production, laser scribing of modules was done with two multi-beam laser systems at ~5 min/module. A recent breakthrough (patent application in process) in laser scribing allows us to do a scribe set on a module with one system in less than a minute. Linear scribing speeds of 3 m/s have been achieved with the new approach, which uses only one laser. The approach resulted in an order of magnitude increase in scribe speed and accuracy, with a 50% reduction of capital costs. A previous concept for high-throughput laser scribing was to use a large number of fixed lasers; the use of just one laser has the advantages of lower initial cost and higher system up-time.

The module encapsulation line, which uses a new semi-automated EVA laminating system, was also designed and built for a rate of 1 plate/min.

## Module design

In addition to the scale-up of production with the EVA encapsulation line, there is a parallel effort to further reduce material costs and improve manufacturability. One approach is to replace the back glass with a film/foil [10], which would reduce module weight by about 30%. If this effort succeeds prior to the addition of extra finishing capacity, it could be used instead of the current approach. Work is also being done to reduce the materials and labor costs of panel mounting in the field.

## Cell and module efficiency

While production scale-up will continue with the current module efficiencies, increasing module efficiency to 10% is a part of the near-term plan to reach 17 kW/hr production. Since the $J_{sc}$ for an ideal solar cell with a direct bandgap of 1.45 eV is ~30.6 mA/cm$^2$, the typical $J_{sc}$ of a production cell of ~18 mA/cm$^2$ stands out as an opportunity for significant improvement in cell efficiency.

The low $J_{sc}$ is the result of absorption of photons with energy greater than 2.4 eV in the CdS, with no collection of these photogenerated carriers. Thinning of the VTD CdS results in increased $J_{sc}$, but low $V_{oc}$. The incorporation of a thin high-resistivity layer, commonly called a buffer layer, between the conductive front contact ($SnO_2$:F) and the CdS has been shown to allow thinning of CdS without loss of $V_{oc}$ [11] [12].

While we have had some success with a sputtered buffer layer in devices with thin CdS, the very low cost of atmospheric-pressure chemical vapor deposition (APCVD) makes it more attractive for high-volume production if the necessary properties of the layer can be obtained.

Figure 4 shows the spectral response of a standard production cell and a cell with an APCVD-deposited buffer layer with thin CdS. As can be seen in Figure 5, the buffer/thin-CdS cell has significant response in the wavelengths that would normally be lost in absorption in the CdS (350-500 nm). A cell with an NREL-confirmed efficiency of 13.2% ($V_{oc}$ of 0.821V, $J_{sc}$ of 23.0 mA/cm$^2$, FF of 70.06%) after 7 days of light soak (~800 W/m$^2$, 65°C) was achieved using an APCVD buffer layer.

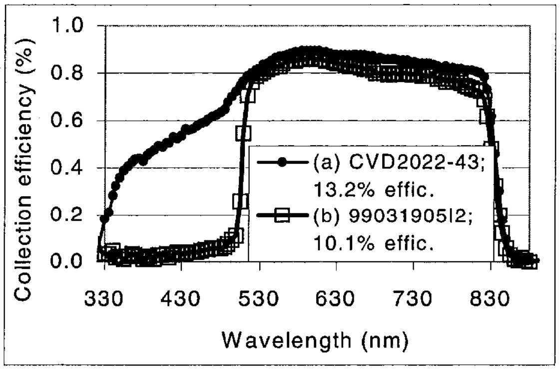


**Figure 5.** Spectral response of (a) standard production cell and (b) cell with APCVD buffer layer and thin CdS.

In parallel with the effort to develop new deposition chemistry and process parameters for the APCVD of buffer layers, we have proceeded with the development of a pilot-production system capable of depositing the buffer layer on a 60 cm wide web (Fig. 6). While this system is limited to a speed of 1.8 m/min, the process is suitable for a glass line speed of 12 m/min. The system has resulted in cells with unconfirmed efficiencies as high as 13.8%.

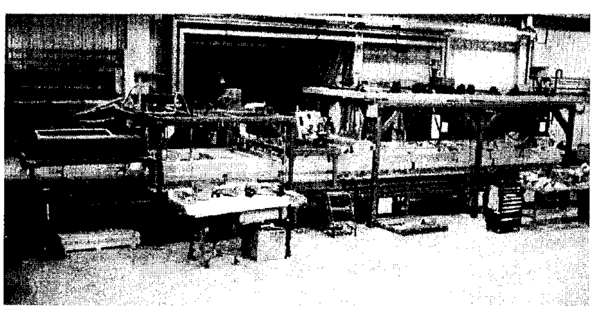

**Figure 6.** APCVD system for buffer-layer deposition.

A few full-size modules have been run on the new production line with thin CdS and an APCVD buffer layer, with some encouraging results.

Another important part of our plan to increase module efficiency to 10% and beyond is an increase in the uniformity of modules. While the incorporation of a buffer layer is expected to improve the uniformity of performance, improvement of deposition and processing uniformity is also important. Mapping layer characteristics (e.g., CdS thickness) and cell efficiencies as a function of cross-web and down-web position has provided feedback to improve module uniformity (see "Semiconductor deposition system" section of this paper and reference 13). Cutting an average-efficiency module into 72 equal-sized minimodules showed that the standard deviation of the $V_{oc}$ was only 1.7% and the $J_{sc}$ only 2.1%, but the standard deviation of the efficiency was 7% (primarily due to spatial variation of FF), showing opportunity for additional improvement.

Additional gains in efficiency, reproducibility, and quality are expected from ongoing research in other areas, such as the effect of cell non-uniformity, deep-level traps, and back-contact formulation on cell open-circuit voltage.

### Product quality and production scale-up

Field stability has been demonstrated with CdS/CdTe modules. A 1 kW array that was made using the SCI pilot-production line and installed at the National Renewable Energy Laboratory (NREL) in 1995 was analyzed in August 2000. Simulator and spectrally-corrected outdoor measurements of the 24 modules in the array showed that the average efficiency of the modules was slightly higher than when the modules were fielded 5 years ago. In March of 1995 the average efficiency of the modules was 6.95% with a standard deviation of 0.47, and in August of 2000 the efficiencies were 7.17+/-0.54. Seven of the 24 modules did measure lower in 2000 than in 1995, with the largest drop being 9% and the average drop of the 7 being 4%. Overall, the efficiency of the modules was 3% higher than when fielded, and mismatch in the array was essentially unchanged from the 5 years of field exposure.

We have previously reported that cells and minimodules have shown variation in stability performance [14]. Some minimodules were higher in efficiency after 35,000 hrs of continuous light soak (at 65°C) than initially, while some cells and minimodules have been found to degrade under light soak. The new manufacturing plant includes extensive automation, including robotic handling of glass and auto-load/unload of workstations. The automation, as well as the designed-for-production systems of the new facility, will improve reproducibility and thus provide a method of ensuring and improving product quality. The changes to new equipment and processes do, however, necessitate experimentation to ensure that this more-reproducible product is high quality. For instance, the behavior of the new cells and modules must be checked for their resistance to light soaking, heat, humidity, etc. Considerable resources have been, and will continue to be, dedicated to testing and verification of product quality and to the understanding and control of mechanisms of change in stress tests and the field.

As part of the product-quality effort, First Solar applied for and passed UL testing [15] and is now authorized to apply UL Recognition marking. Modules are currently in test for IEEE 1262 certification.

### Production results and plans

We are currently ramping production up to a single-shift volume of more than 1000 modules per week by year-end. This scale up is being done concurrently with the introduction of the final pieces of the new production line. For example, the new high-speed laser scribing system was introduced in early September. Considering the experimental work associated with bringing a new plant on-line, surprisingly high yields have been achieved. For example, the September 6th run through sub-module efficiency measurement (pre-encapsulation) resulted in a 92% yield (47 of 51 above lower-efficiency threshold). The histogram of the efficiencies is shown in Figure 7.

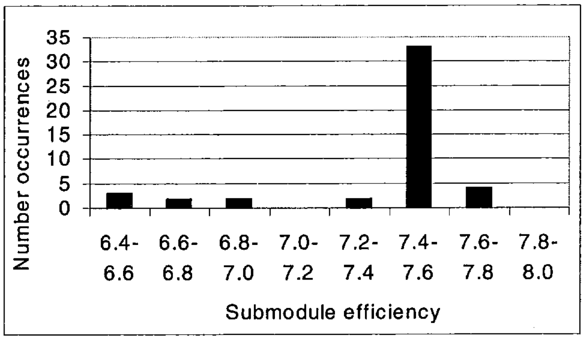


**Figure 7.** Histogram of unencapsulated module efficiencies for 9/6/00 production run.

The modules currently being produced are being supplied to partners and customers as part of a multi-beta-site strategy.

In addition to the R&D and production efforts described in this paper, First Solar has made a commitment to the protection of the environment and the safety of employees [7][16]. The plant is designed to be a zero-emission facility with a closed-loop liquid waste system and module recycling.

## ACKNOWLEDGEMENTS

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