NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Advanced CdTe Photovoltaic Technology

September 2007 — March 2009

Kurt Barth
Abound Solar
Fort Collins, Colorado

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Subcontract Report
NREL/SR-5200-51517
May 2011

Contract No. DE-AC36-08GO28308

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NREL Technical Monitor: Harin S. Ullal
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Acknowledgments

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Colorado State University

Colorado State University was a subcontractor on this project and contributed significantly to the results described here. The CSU contributors include Venkatesan Manivannan, W. S. Sampath and James Sites. Abound Solar greatly appreciates their assistance.

1 Summary

During the last eighteen months, Abound Solar (formerly AVA Solar) has enjoyed significant success under this SAI program. During this time, a fully automated manufacturing line has been developed, fabricated and commissioned in Longmont, Colorado. The facility is fully integrated, converting glass and semiconductor materials into complete modules beneath its roof. At capacity, a glass panel will enter the factory every 10 seconds and emerge as a completed module two hours later. This facility is currently undergoing trials in preparation for large volume production of 120 x 60 cm thin film CdTe modules.

Preceding the development of the large volume manufacturing capability, Abound Solar demonstrated long duration processing with excellent materials utilization for the manufacture of high efficiency 42 cm square modules. Abound Solar prototype modules have been measured with over 9% aperture area efficiency by NREL. Abound Solar demonstrated the ability to produce modules at industry leading low costs to NREL representatives. Costing models show manufacturing costs below $1/Watt and capital equipment costs below $1.50 per watt of annual manufacturing capacity.

Under this SAI program, Abound Solar supported a significant research and development program at Colorado State University. The CSU team continues to make progress on device and materials analysis. Modeling for increased device performance and the effects of processing conditions on properties of CdTe PV were investigated.

2 Large Scale, Automated Manufacturing Systems

The first phase of Abound Solar's 200 MW/yr Longmont manufacturing facility is nearing completion. The first of the manufacturing lines have been installed and tested. Production trials are underway.

2.1 Installation & Testing of Manufacturing Systems

The initial 120 x 60 production systems have been constructed and tested. Multiple vacuum chambers with the substrate motion / load lock system have been installed. Glass motion including load lock performance indicates that learning from the 42 cm substrate pilot system has been successfully scaled to the larger production platform. Process heads have been constructed and installed.

2.2 Fabrication of 120 x 60 cm CdTe Plates

Initial plates with CdS and CdTe films had been fabricated on the 120 x 60 cm semiconductor processing systems back in late 2008. Full modules have been fabricated, initially with significant manual intervention. During the last month, the automated production systems have continued to be optimized. Modules can now fabricated "end to end" on the automated lines. Current efforts involve tuning to further improve cycle times, measurement calibration and manufacturing operator training. Abound Solar is also progressing on ISO 9000 certification.

2.3 Demonstration of Low Capital and Manufacturing Costs

In support of this SAI program, a detailed review of the factory construction, manufacturing equipment layout and production capacity was presented to NREL managers. Capital equipment costs for the factory are compiled directly from vendor quotes and Abound Solar purchase orders already placed. Approximately 7% of the equipment costs are for equipment constructed by Abound Solar, such as the semiconductor processing chambers. The NREL representatives were also given a complete tour of the facility. Abound Solar's proprietary semiconductor processing technology was shown and automated manufacturing equipment was demonstrated.

During this review, Abound Solar demonstrated capital equipment costs below $1.50 including equipment installation, facility improvements and building costs. This is among the lowest capital equipment costs reported for any PV manufacturing technology.

Abound Solar also developed a detailed costing model to calculate module manufacturing costs. This model was reviewed by NREL managers in a separate visit. Module manufacturing costs are the total manufacturing cost of sales of the modules produced in a given period divided by the total cumulative wattage output of the module produced in that same period. Abound Solar's module manufacturing cost of sales was broken down into 4 main categories, each of which include multiple line items. These categories are, 1. Direct material costs, 2. Other variable costs including direct labor, yield losses, glass recycling and freight costs, 3. Overhead and 4. Manufacturing equipment depreciation. Estimates for yield and factory uptime used in this model are considered conservative. Using this model, Abound Solar demonstrated to NREL representatives the capability of the achieving very low manufacturing costs, below $1/Watt. These manufacturing costs are also among the lowest reported for the PV industry.

Figures 1 and 2 are picture showing the some of the tool after the semiconductor processing ("backend") 9 of the manufacturing facility and modules in shipping containers. The facility is designed to be fully automated with no manual intervention in module manufacturing other then the essentially stacking pallets of glass at the front of the line and placing modules in crates at the end. It is believed that this is one of the most highly automated PV manufacturing facilities in the world.

Figure 1. Automated "backend" module assembly tools at Abound Solar's Longmont manufacturing facility. These fully automated systems have a throughout of approximately 65 MW/yr.

Figure 2. Abound Solar Longmont manufacturing line end point and a shipping crate with completed modules.

3 Development of Prototype Manufacturing Systems

During Phase 1 of this SAI Incubator program, Abound Solar completed the development of prototype manufacturing systems for processing 42 cm squared modules. The learning that resulted from the prototype system development was of significant benefit in the design of the large scale manufacturing systems for 120 x 60 cm substrates now in operation.

3.1 Development and Operation of 42 cm Substrate Prototype Systems

The semiconductor processing tool forms the backbone of Abound Solar's manufacturing technologies. These were the focus of significant effort during the first phase of this project. The prototype semiconductor systems was commissioned in 2007 and has produced many devices with over ~12% with NREL verified performance around 11.5%. Even the initial process fabrication runs on the prototype semiconductor system showed quite good initial device efficiencies with a satisfactory statistical variation.

Early on during this development, Abound Solar submitted process uniformity results to NREL in fulfillment of the first deliverable under this program. Panels were taken from a processing run. Twenty small area devices were cut from these panels and measured for light current/voltage performance. The total variation of the five samples was 7.6, 10.1, 8.4, 8.3, 7.7 percent. Within error of measurement, 10% uniformity of device performance was demonstrated. The prototype system has continued to be developed and improved, since these early results were reported. With the commissioning of the Longmont manufacturing lines, the prototype system is now utilized for R&D and advanced process development.

3.2 Installation of Prototype Equipment for Non-Semiconductor Process and Module Fabrication

All equipment needed to fabricate fully encapsulated 42 cm square modules was specified/designed, obtained and commissioned early during this project. Laser scribing, substrate washing, back electrode application, buss bar wiring, lamination and back hole sealing processes were all included. An engineer and technician team then worked optimize each piece of equipment using statistical techniques. Hundreds of interconnected modules have been fabricated and tested. Examples of these modules have passed significant (<1000 hrs) of 85 C / 85% relative humidity exposure and have undergone hundreds of hours of light soak. Further results are reported in Section 4.

3.3 Monitoring of Cd Levels

Abound Solar maintains has an occupational health and safety functional team, active in the company. Cadmium concentration in processing areas is frequently monitored. Surface and air sampling show that Cd concentration is significantly less than the OSHA allowable number. Safety training classes for key employees are conducted

For occupational safety, both the prototype and manufacturing semiconductor processing are isolated in specialized "regulated" rooms, separate from the all other processing areas. Exposure to potentially harmful materials is closely monitored. During the course of this project, experiments were conducted where between 1000 and 1500 plates were processed. The regulated room the room was cleaned and the concentration of Cd in the air was measured. Tests were performed by the local EHS company, Stewart Environmental. All air quality measurements show Cd concentration less than one tenth the OSHA allowable number.

4 Module Efficiency and Certification

4.1 Module Efficiency

Under this SAI program, Abound Solar has fabricated a series of prototype modules with increasing performance. These modules were processed through the semiconductor processing system, scribed and received the metallization/electrode. Buss bars were applied and the modules encapsulated. Modules were submitted to NREL's Photovoltaic Cell and Module Measurement Group and tested at the "SOMS" outdoors facility. The data was collected, normalized and spectrally corrected. Abound Solar achieved two significant performance milestones under the SAI program. Modules with 8% aperture area were demonstrated in July 2008 and modules with equal or greater than 9% aperture area efficiency were demonstrated in October 2008. Module performance and repeatability has continued to increase. Recently, early 120 x 60 cm modules from the manufacturing line have been measured at nearly 9% efficiency by NREL. It is anticipated that higher module performance will be demonstrated as the manufacturing process optimization progresses.

Table 1. NREL Measurements of Selected Abound Solar Prototype Modules, fall 2008. Data from the SOMS facility, normalized and spectrally corrected, NREL estimated total measurement uncertainty +/- 5%

Cell ID	Corrected Max power (W)	Aperture area (cm^2)	Corrected efficiency (%)
C34-55	10.68	1128.7	9.5
C34-60	9.915	1128.7	8.8
C34-62	9.886	1128.7	8.8

4.2 Module Reliability and Certification Testing

During the course of this project, a number of different encapsulation and back hole sealing materials were exposed to accelerated stress conditions to evaluate the module package performance. Testing has included 85 C, 85% relative humidity exposure, temperature cycling and a heat / water spray / UV light test. The preferred encapsulation has passed over 3000 hrs at 85 C / 85% RH with no failures.

Abound Solar's prototype modules are undergoing testing described in the Underwriters Laboratories (UL) 1703, IEC 61646 and 61730 standards. Modules and PV devices are also tested internally for durability in methods that exceed those specified in the certification standards. These methods include long duration accelerated stress light soaking.

In order to further ensure reliability, Abound Solar has constructed a reliability lab which can perform nearly all the testing described by IEC 61646 and 61730 standards needed to issue the CE mark. Only a few specialized tests such as the "fire tests" cannot be performed in-house. Large modules are currently under test at the lab. Modules have also been mounted in a 600V array at the Abound Solar facilities to evaluate module performance and reliability. Voltage output and weather conditions are monitored. Modules were also demounted and individually tested for JV performance to closely track performance.

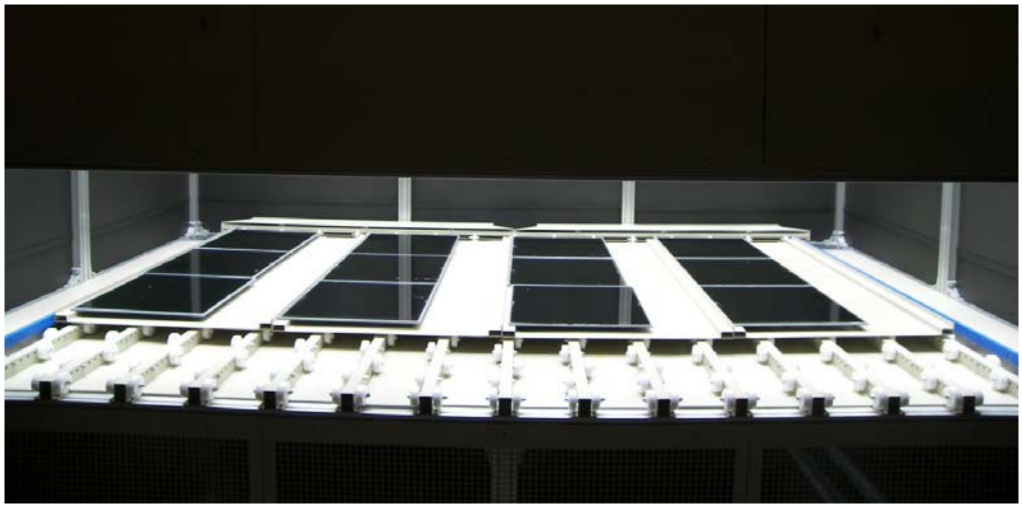


Figure 3. Modules being tested for reliability under one sun light soak.

5 Finite Element, Thermal Modeling and Advanced Designs

Under this program studies using the finite element method (FEM) among others have been conducted to develop a quantitative understanding of the Abound's semiconductor process and fabrication hardware. Many of these models utilize non-linear radiation boundary conditions and body to body radiation. These studies have led to improvements in the design of the manufacturing hardware for processing 120 x 60 cm substrates. During the course of the development of the manufacturing systems, a number of different design iterations and modeling cases were investigated. Good correlation between the models and experimental results has been observed. Optimized designs demonstrate that critical processing chambers can achieve close to +/- 2 C temperature uniformity over the entire 120 x 60 cm surface. A brief summary of the some of the key studies conducted is given below.

5.1 Mechanical Modeling of the Substrate Conveyor

Abound's semiconductor processing systems utilize a conveyor that transports the substrates through the different processing stations. In one design iteration, metal conveyors were found to have variable properties including the camber. A FEM modeling analysis was performed to understand the effect of the tension on the conveyor properties including the camber. Findings include:

1. The camber "corrects" under proper tension
2. For a specific geometry, the camber corrects even with tension less than 10 lbs. The typical tension in the conveyor is significantly greater.
3. It takes only 0.25 lbf. to move the conveyor in the middle by 0.5 inch

5.2 Thermal Modeling of the Substrate and Semiconductor Vapor Source

One of the main attributes that is critical for Abound's technology is the thermal uniformity of the vapor sources. Our vapor sources typically employ crucibles that are heated by IR radiation. Significant FEM modeling of the vapor source for processing 120 x 60 cm substrates has been performed. These analyses include transient thermal modeling of the vapor sources and the radiation shields and estimating the time to reach steady state.

Thermal uniformity perpendicular to the conveyor (midsection) is uniformity within 3° C in a horizontal plane. The CdTe, CdS and substrate heaters were all reviewed in detail and a FEM study was done for the optimum heater spacing. The nominal heater spacing was planned to be 4 inches. Additional configurations were modeled. In one study the two heaters at the farthest edge of the process heat were brought varied and the remaining heaters were spaced equally. A plot of the temperatures at the bottom of the CdTe source indicated the optimum heater spacing for thermal uniformity.

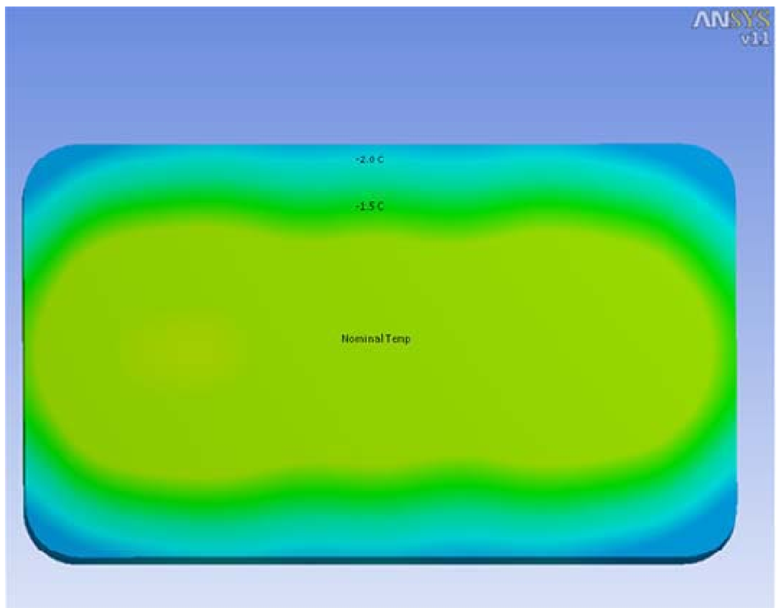


Figure 4. Thermal analysis modeling results for an experiemental 120x60 cm process head. Areas where processing occurs has better than +/-2 C uniformity.

Thermal stress analysis was also performed using the FEM method. The conveyor was modeled as radiation coupled radiation coupled to the vapor source and the glass substrate, based on past experience. It was found that the largest thermal stress occurs in the first heating station in the semiconductor manufacturing process. The glass is hotter at the top and colder at the bottom. The substrate edges are slightly hotter due radiation shielding facing theses regions. The magnitude of the stresses induced is relatively small at ~100 psi in the x direction and a von mises stress of 400 psi.

The FEM analysis was extended to the deflection of 120 x 60 cm glass substrate during processing. The model includes all thermal and mechanical effects. All the processing stations present in the semiconductor tool were modeled in the analysis. The maximum vertical deflection of the substrate was found to be on the order of 1 mm during processing. The temperature calculations were performed as "lumped mass calculations" and used a lower value of specific heat. Distortions related to tempering were not included. Abound Solar designs were developed to easily account for this relatively small deflection.

5.3 Transient Thermal Analysis of Vapor Source

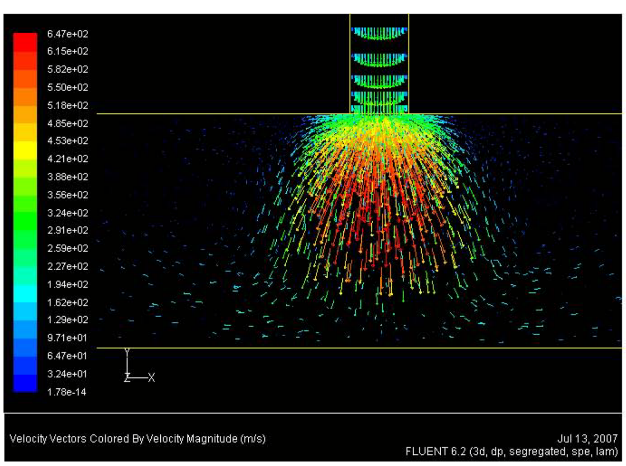
A series of FEM transient heat transfer analyses were performed on the vapor sources. The time for the vapor source to come to temperature is dependent on a number of variables including heater power, operating temp and geometry. For one configuration of the CdS process head, the source takes approximately one hour to come to temperature. Twenty minutes after the source reaches the set temperature at the measuring point, some radiation shielding the source is still in the transient state.

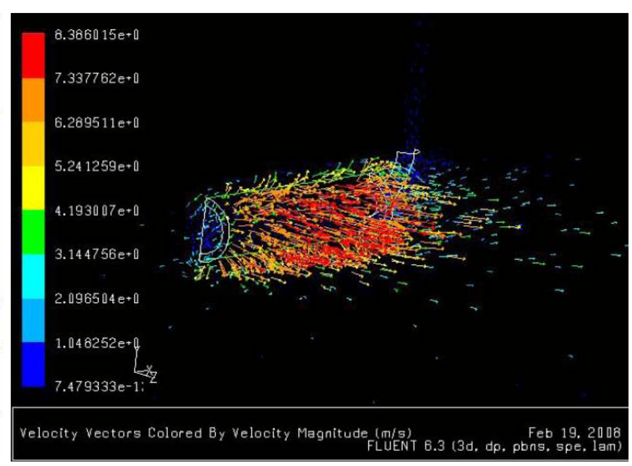
In this analysis, the boundary condition was to keep the radiation flux constant at the bottom to keep the temperature in the middle at the set point. Additional analyses were performed with the other boundary conditions which also showed positive results.

5.4 Oxygen Diffusion and Gas Flow in the Semiconductor Tool

It is well known that the $CdCl_2$ treatment has a significant effect on the CdTe PV device performance and that oxygen assists in the $CdCl_2$ treatment. A FEM diffusion analysis was performed to calculate the diffusion of oxygen into the processing heads performing the $CdCl_2$ treatment. It was found that oxygen concentration was uniform. A similar analysis was performed for the out-diffusion of $TeCl_2$ (a potential by-product of the $CdCl_2$ treatment). The initial source design had nearly 2 times higher concentration in the center than edges which could affect devices performance. Since this analysis was performed, the source was redesigned to better optimize the $CdCl_2$ treatment for larger substrates.

Computational fluid dynamics modeling of gas flows and pressure distribution inside the prototype semiconductor process chamber was performed. It was found that diffusers were required to significantly reduce the inlet gas velocities. The gas streams were also significant. However, these streamlines could be used to direct the flows of specific gases where needed. The CFD modeling was done in collaboration with Prof. Hiroshi Sakurai of the Mechanical Engineering Dept. of Colorado State University.





Figures 5 and 6. Examples of inlet gas velocity modeling.

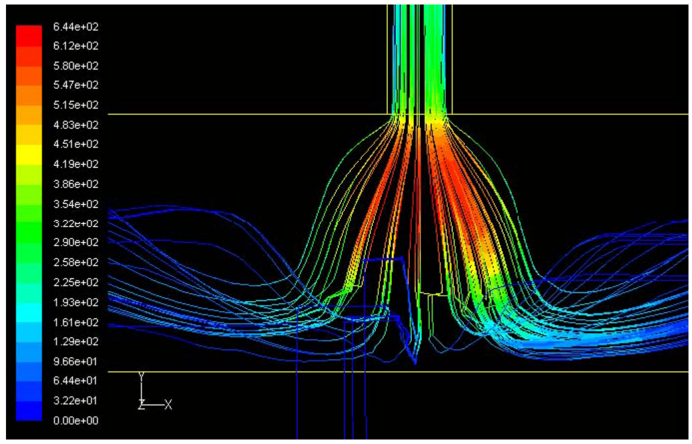


Figure 7. Modeling of gas streamlines through a diffuser into a vacuum chamber. The lines are colored by velocity.

5.5 Additional Studies

A Monte Carlo calculation of the vapor atoms within the vapor source pocket was performed in collaboration with Prof. Pat Burns of CSU. In this effort, the walls were treated as specular and diffuse. The specular reflection assumes that the molecules obey the laws of reflection at the source walls. The diffuse reflection assumes that the molecules are absorbed and reemitted. The diffuse reflection model more closely approximates the real behavior of surfaces. Understanding this "absorb and reemit" behavior of the real surfaces, enabled more optimal source geometries to be developed.

Addition studies include:

1. Additional mechanical, thermal and thermomechanical modeling of the substrate conveyor
2. Modeling of the vapor sticking coefficient using kinetic theory of gases
3. Modeling and design of a shell and tube heat exchanger utilizing computational fluid

dynamics to calculate the heat transfer coefficient (Figure 8). The shell and tube heat exchange is being designed to cool a plate that is being used to control the substrate temperature in the process.

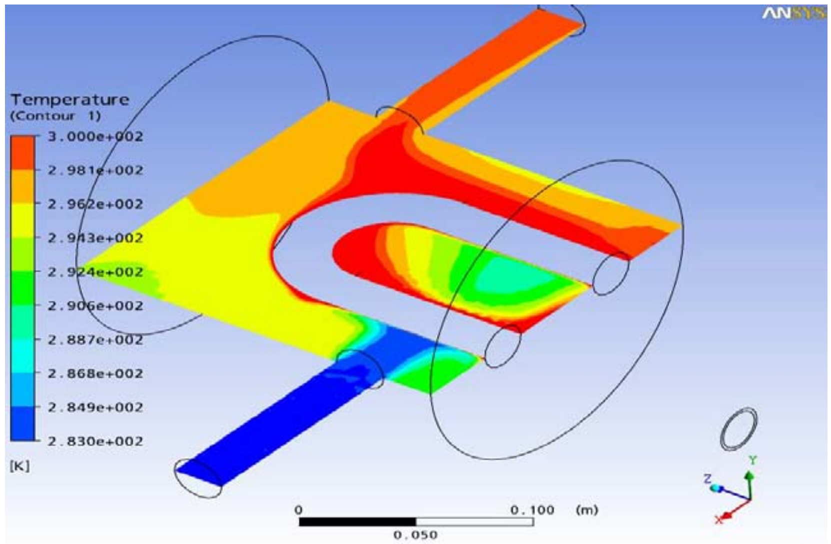


Figure 8. Temperature contours in the cooling water of a shell and tube heat exchanger.

6 Device Performance, Process Optimization, Modeling and Testing

The following are activities that were performed at CSU under this program. The CSU team includes Professors Manivannan, Sampath and Sites with grad student assistance. In addition to the modeling and characterization efforts described below, facilities to perform device accelerated stress testing in the dark and light have been provided to Abound Solar. These tests are performed with close loop temperature control

6.1 Materials Analysis Studies

Effects of the $CdCl_2$ treatment on the microstructure properties of CdTe photovoltaic devices are analyzed by applying many of experimental techniques including X-ray diffraction (XRD), scanning electron microscopy (SEM), photoluminescence (PL), atomic force microscopy, and current-voltage (IV) measurements. The observed changes are correlated to the performance of the devices. It was found that the minority carrier lifetime increased with the increased $CdCl_2$ treatment of both 4 min and 6 min. However, the efficiency of the PV devices decreased. This loss of efficiency was attributed to possible creation of defects like voids, cracks and pinholes in the CdS/CdTe interface during increased (4 min and 6 min) $CdCl_2$ treatment, as compared to the baseline treatment duration (2 min). The results shows that further theoretical and experimental analyses are needed to fully understand the effect of $CdCl_2$ treatments.

Early in this program, a reliable spectroscopic ellipsometry (SE) model has been developed for the TCO layer which consists of 3 layers (un-doped SnO, barrier SiO_2 and conducting doped SnO) by collecting the data in transmission mode and having 50:50 each for void and surface roughness. This model produced results where the thickness of the layers obtain matched with thickness obtained from characterization techniques. The MSE obtained was <10 indicating good fit of the experimental data to the model developed. Additional models are under development.

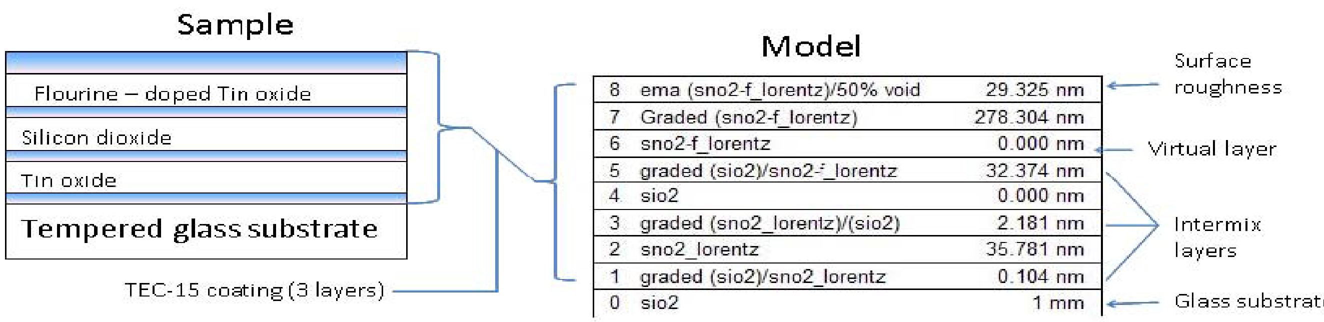


Figure 9: Spectroscopic ellipsometry TCO model construction

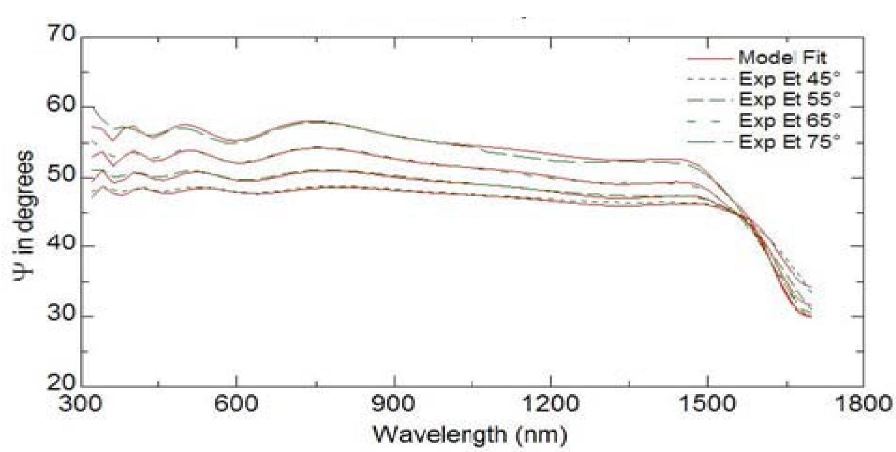
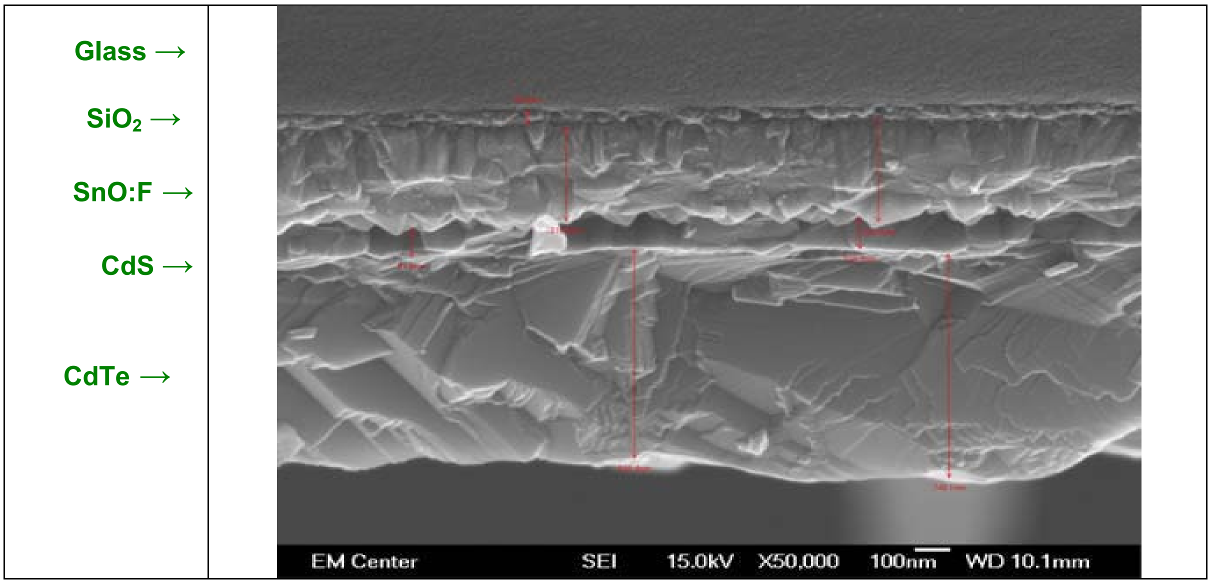


Figure 10: Experimental and model results for Spectroscopic ellipsometry analysis of TCO

The feasibility of applying SE technique to non-destructively characterize micro structural details of CdTe solar cells is demonstrated. To ensure that the SE data is accurate, additional methods of measuring the film thicknesses can be made with other instruments, including X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM).



Brief summary of sample results – SAMPLE. CdS, CdTe, TCO layer thickness are measured by SEM

Figure 11. Cross section SEM image of CdTe device and layer thickness

As the program progressed, more sophisticated SE models were developed. Spectroscopic ellipsometry analysis were performed on $CdCl_2$ treated CdTe devices. The effect of the copper treatment on the optical properties of the PV device was of particular interest. Spectroscopic ellipsometry results showed that no changes in either the band gaps or critical points of CdTe layer were noticed as a result of copper treatment. The copper treated CdTe layer exhibited a higher refractive index in the visible and longer wavelengths (< 3 eV) as compared to the untreated layer. This was attributed to the increased disorder in the case of copper treated layer. It was found that technique is dependent on the model developed. More information is available in Kohli et. al.[1] Analysis of the metallic constituents in the films has been performed by inductively coupled plasma (ICP) spectroscopy. Detailed reports on the effect of process conditions on efficiency and stability; the effect of chamber pressure on the deposition rate and the rate of oxidation of CdTe as a function of temperature were developed and provided to Abound Solar by CSU.

6.2 Modeling and Electrical Analysis

Studies were performed to understand the effects of partial-shunting of a module. Experimental measurements with different numbers of module cells shaded by varying amounts were compared to simulations where the breakdown voltage as a free parameter was determined. This work also includes the comparison of simulations with experimental data before and after the isolation of a shunt. Further investigation finds that a single shunt, no matter how severe, has only minor impact on a full module, since any reasonable TCO resistivity will isolate it. In general the module power loss can be well-approximated as a function of the number of shunts, the average severity of the shunts, and to a lesser extent, the distribution of the shunts. More detailed information of this research is presented by Koishiyev and Sites[2].

1. Kohli, S, Manivannan, V, Hilfiker, J., McCurdy, P., Enzenroth R. Barth, K. Smith, W., Luebs, R. Sampath, W., Effect of Chemical Treatment on the Optical Properties of a Cadmium Telluride Photovoltaic Device Investigated by Spectroscopic Ellipsometry, Journal of Solar Energy Engineering, 2009 by ASME May 2009, Vol. 131 / 021009-1

Simulations were performed on the expected J-V curves when an electron reflector is added. In addition to the increased voltage predicted by previous work, we find a kink in the J-V curve when the absorber is not fully depleted. According to the calculations, CdTe that is fully depleted under bias (2 microns and 10^{13} cm^{-2}), with a 0.2-eV electron barrier ($Cd_{0.75}Zn_{0.25}Te$ is suggested), should increased voltage by 200 mV and efficiency by 3%. A near-equivalent strategy is a lower-band-gap alloy of CdTe for most of the absorber with thin CdTe at the back to form the barrier. Additional details are presented in Sites[3].

7 Additional Activities

The following activities were completed during the last quarter:

- The respected engineering firm R. W. Beck, Inc performed detailed assessment on the technical and environmental aspects of Abound Solar's manufacturing process and Longmont facility. Key findings from the resulting validate Abound Solar's approach, plant construction, environmental permitting, costing methodologies and production methods. This report was submitted to the DOE.

- Abound Solar hosted Senator Udall and Representative Markey at the Longmont manufacturing plant. The visit of Senator Udall was well covered in the media.

- Abound Solar received additional media coverage recently. Additional coverage is listed in section 9

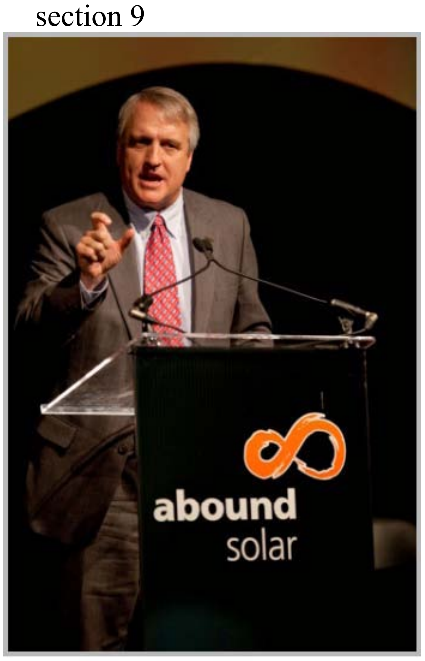


Figure 12: Governor Ritter at Abound Solar's Factory Opening.

http://www.cnn.com/2009/POLITICS/02/17/stimulus.solar.company/
http://www.publicbroadcasting.net/kunc/news.newsmain?action=article&ARTICLE_ID=1471067

- Colorado's Governor Ritter, NREL's director Arvizu and others addressed Abound Solar's Longmont manufacturing plant ribbon cutting.

- Jim Sites and students have made progress on their major projects, and abstracts have been accepted for poster presentation at the upcoming Materials Research Society (MRS) and Photovoltaics Specialists (PVSC) meetings.

- K. Barth, Project director on this SAI program, has accepted an invitation to give a talk on Abound Solar's progress at the 34th IEEE PVSC conference.

[2] Effect of Shunts on Thin-Film CdTe Module Performance, G. Koishiyev, and J. Sites, 2009 MRS Spring Meeting, presented April 2009.
[3] The electron reflector strategy for CdTe Solar Cells, J. Sites, 34 IEEE PVSC Philadelphia, PA, to be presented June 2009.

8 Publications and Presentations

1. Abound Solar's CdTe Module Manufacturing and Product Introduction, K. L. Barth, Invited talk 34 IEEE PVSC Philadelphia, PA, to be presented June 2009.

2. The electron reflector strategy for CdTe Solar Cells, J. Sites, 34 IEEE PVSC Philadelphia, PA, to be presented June 2009.

3. Effect of Shunts on Thin-Film CdTe Module Performance, G. Koishiyev, and J. Sites, 2009 MRS Spring Meeting, presented April 2009.

4. Effect of chemical treatment on the optical properties of cadmium telluride photovoltaic devices investigated by spectroscopic ellipsometry, S. Kohli, V. Manivannan, J. N. Hilfiker, Patrick R. McCurdy, R.A. Enzenroth, K. L. Barth, W. P. Smith, R. Luebs and W. S. Sampath, J. Solar Energy and Engineering, May 2009, Vol. 131 / 021009-1.

5. Stable Cu-based back contacts for CdTe thin film photovoltaic devices, R. A. Enzenroth, K. L. Barth, W. S. Sampath, V. Manivannan, A. T. Kirkpatrick and P. Noronha, J. Solar Energy and Engineering, (in press) (2008).

6. Advances In Continuous, In-Line Processing Of Stable CdS/CdTe Devices, W. S. Sampath, S. Kohli, R. A. Enzenroth, K. L. Barth, V. Manivannan , James Hilfiker, Patrick R. McCurdy, K. Barricklow and P. Naronha, 33 IEEE PVSC May 2008

7. Measurement of cooling rates of a superstrate cooling apparatus for an integrated in-line manufacturing process for thin-film photovoltaic devices, R.A. Enzenroth, K. L. Barth, W. S. Sampath and V. Manivannan, /J. Vac Sci Tech./ A 25 (2) Mar/Apr 2007, L9-L11.

8. Performance of In-line manufactured CdTe thin film photovoltaic technology, R.A. Enzenroth, K. L. Barth, W. S. Sampath and V. Manivannan, Journal of Solar Energy Engineering, Vol. 129, 2007, 327-330.

9. Microstructural features of cadmium telluride photovoltaic thin film devices, V. Manivannan, R. A. Enzenroth, K. L. Barth, S. Kohli, P. R. McCurdy and W. S. Sampath, /Thin Solid Films/, 516 (6) (2008) 1209-1213.

10. Effect of hail impact on thermally tempered glass substrates used for processing CdTe PV modules, T. M. Shimpi, K. L. Barth, R. A. Enzenroth, W. S. Sampath and V. Manivannan, Journal of Testing and Evaluation, Vol 36, No. 2 (2008) 1-6.

11. Thermal model for a superstrate cooling apparatus for an integrated in-line manufacturing process for thin film photovoltaic devices, R. A. Enzenroth, K. L. Barth, W. S. Sampath and V. Manivannan, Journal of Vac. Sci. Technol. B, Vol 25, No. 6 (2007) 1-4.

9 Recent Press Coverage of Abound Solar's Factory Opening

NREL and DOE involvement was emphasized.

OutOutlet	Story Link	Circulation
National		
Reuters	http://www.reuters.com/article/rbssSemiconductors/idUSN1334527120090414	Syndicate
Dow Jones	N/A: Subscription-based newsletter	N/A
CNBC	http://www.cnbc.com/id/30200952	2,907,475
Forbes.com	http://www.forbes.com/feeds/afx/2009/04/14/afx6286076	12,246,445
MarketWatch.com	http://www.marketwatch.com/news/story/abound-solar-opens-first-production/story.aspx?guid=%7B47AF1504-92B2-4CE1-A4DB-CDE7F82F75FB%7D&dist=msr_4	4,370,566
Local/Regional		
Denver Post	http://www.denverpost.com/business/ci_12139570	210,585
Denver Business Journal	http://denver.bizjournals.com/denver/stories/2009/04/13/daily25.html?surround=lfn	14,684
Coloradoan	http://www.coloradoan.com/article/20090415/BUSINESS/904150335	25,000
Northern Colorado Business Report	http://www.ncbr.com/article.asp?id=99635	7,092
Denver Post	http://www.denverpost.com/headlines/ci_12143297	210,585
Longmont Times Call	http://www.timescall.com/news_story.asp?ID=15600	20,000
KUSA-TV (NBC Affiliate)	http://www.9news.com/rss/article.aspx?storyid=113766	N/A
Northern Colorado 5 (CBS Affiliate)	http://www.noco5.com/story.aspx?ID=638&Cat=2	N/A
KDVR-TV (Fox Affiliate)	N/A	N/A
KGMH – TV (ABC Affiliate)	N/A	N/A
Trades		
Greentech Media	http://www.greentechmedia.com/articles/aboundsolar-opens-factory-claims-under-1/watt-cost6032.html	50,814 (per month)
Earth2Tech	http://earth2tech.com/2009/04/14/new-name-same-ambition-abound-solar-hot-on-first-solars-heels/	66,307 (per month)
Inside Business Green Sheet	http://www.businessinsider.com/solar-startup-abound-says-it-will-crush-first-solar-2009-4	N/A
PV Tech	http://www.pv-tech.org/news/_a/abound_solar_to_challenge_first_solar_with_low-cost_plant/	12,565 (per month)
Semiconductor Today	http://www.semiconductor-today.com/news_items/2009/APRIL/AVASOLAR_150409.htm	1,800 (per month)
Earth Times	http://www.earthtimes.org/articles/show/abound-solar-opens-first-production-facility,784564.shtml	283,340 (per month)
EcoFriendly Magazine	http://www.ecofriendlymag.com/sustainable-transporation-and-alternative-fuel/abound-solaropens-first-production-facility/	6,000 (per month)
Energy Current	http://www.energycurrent.com/index.php?id=3&storyid=17402	11,615 (per month)
RenewableEnergyWorld.com	http://www.renewableenergyworld.com/rea/news/article/2009/04/abound-solar-opens-thin-film-production-facility?src=rss	72,129 (per month)
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14. ABSTRACT *(Maximum 200 Words)*

During the last eighteen months, Abound Solar (formerly AVA Solar) has enjoyed significant success under the SAI program. During this time, a fully automated manufacturing line has been developed, fabricated and commissioned in Longmont, Colorado. The facility is fully integrated, converting glass and semiconductor materials into complete modules beneath its roof. At capacity, a glass panel will enter the factory every 10 seconds and emerge as a completed module two hours later. This facility is currently undergoing trials in preparation for large volume production of 120 x 60 cm thin film CdTe modules. Preceding the development of the large volume manufacturing capability, Abound Solar demonstrated long duration processing with excellent materials utilization for the manufacture of high efficiency 42 cm square modules. Abound Solar prototype modules have been measured with over 9% aperture area efficiency by NREL. Abound Solar demonstrated the ability to produce modules at industry leading low costs to NREL representatives. Costing models show manufacturing costs below $1/Watt and capital equipment costs below $1.50 per watt of annual manufacturing capacity. Under this SAI program, Abound Solar supported a significant research and development program at Colorado State University. The CSU team continues to make progress on device and materials analysis. Modeling for increased device performance and the effects of processing conditions on properties of CdTe PV were investigated.

15. SUBJECT TERMS
solar cells; CdTe; thin film; SAI

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