

Manufacturing Process Optimization to Improve Stability, Yield, and Efficiency of CdS/CdTe PV Devices

Phase II, Annual Technical Report
January 2006 – February 2007

W.S. Sampath, A. Enzenroth, and K. Barth
Colorado State University
Fort Collins, Colorado

Subcontract Report
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May 2007

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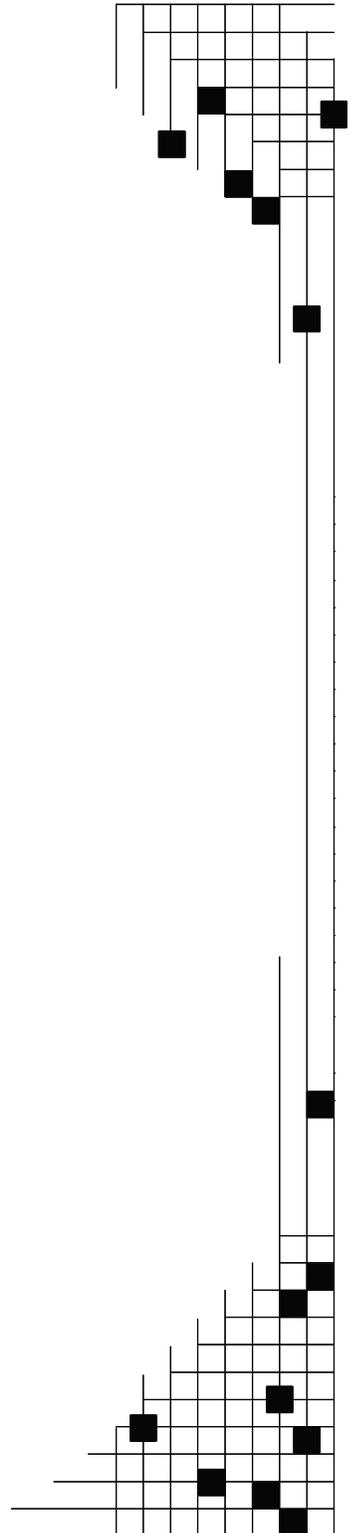
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1. SUMMARY

Under Phase II of the Thin Film Partnership Program, we have made significant progress. A fixture for automated cooling of the substrate in vacuum has been designed, fabricated, installed and tested. This is needed for optimum processing of the back contact. Device efficiencies of 11.83 % have been made in "all forward" process. Large area devices (~ 4 sq. cm.) in the form of strips have been fabricated and tested at NREL. Efficiency of 10.9% has been measured on these large area devices. The air-to-vacuum-to-air seals in the pilot system have a glass filled Teflon liner. These liners have experienced wear and this results in scraping of the glass substrates in the seal. Improved liners have been designed and fabricated, installed and tested in the system. Efforts to improve device efficiency and advance device characterization are underway. Desiccant containing materials for the edge seal and sealing materials for the holes in the back glass have subjected to damp heat tests at NREL with very promising results. Significant progress has been made in characterizing films with ellipsometry and the use of ellipsometry for quality control is being investigated. An additional patent was issued on this technology during the last phase.

A prototype production system to process 16.5x16.5 inch substrates continues to be advanced. This activity is supported by another program from DOE-EERE and cost shared by National Starch and Chemicals (NSC). An advanced encapsulation method has been tested by NSC with promising results.

2. INTRODUCTION

The aim of this Thin Film PV Partnership Program (TFPP) effort is to advance the understanding of device stability, efficiency and process yield for CdTe PV devices. Methodologies for reliably processing larger areas and increasing device efficiencies are being developed. Our ongoing collaborations with the PV Testing Lab at CSU, NREL, Pacific Northwest Natl. Lab and other CdTe Team Members are resulting in further advances. Successful completion of the three phases of this project will be a significant step towards realizing the full potential of CdTe PV.

3. RESEARCH RESULTS

3.1. Cooling Substrates in Vacuum:

The pilot system for processing 3.6 x 3.1 inch substrates has been modified to more closely simulate the back contact processing suitable for actual industrial manufacturing. With the old configuration of the pilot system, the Cu back contact process head is located immediately after the CdCl₂ treatment heads. If the substrate enters the copper process at too high a temperature, the resulting devices have a high series resistance. To avoid this, a pause to cool the substrate was introduced in the old configuration of the pilot system. After a nominal 3 hour wait, the substrate motion direction is reversed and the now cool samples are exposed to a vapor flux of the Cu compound followed by annealing. This completed the formation of the Cu containing back contact in the old configuration. The old configuration is not suitable for large volume manufacturing.

To simulate the Cu back contact process for actual production the pilot system has been lengthened to allow fabrication of devices without the pause and change in substrate motion ("all forward" process). The modified pilot system would also allow processing of devices in a manner which emulates a continuous production system. An automated system for cooling substrates in vacuum has been designed, fabricated, installed and tested. The cooling fixture was tested with automated substrate movement. The substrates were heated to 200 C and after 4 minutes of radiation cooling were cooled with the fixture to 26 C in two minutes. The results indicate that an adequate cooling rate can be obtained to maintain a cycle time of 2 minutes. The measurements of substrate temperatures were performed with infrared sensors. The cooling of the substrates during processing was measured by IR detectors. A journal article has been drafted on the in-situ cooling approach and has been accepted for publication to Journal of Vacuum Science and Technology. A patent application has also been filed. Device efficiencies of 11.83% have been obtained with an "all forward" process. **It is noted that the total time for processing the 11.83% device is only 22 minutes.** This includes glass heating, CdS deposition, CdTe deposition, CdCl₂ treatment and back contact processing.

The modified pilot system will enable precise definition of conditions for all the semiconductor processing steps (including the back contact) needed to fabricate high efficiency, stable CdTe devices. This process definition will be implemented in the 2 MW/yr. production prototype system for 16.5 x 16.5 inch substrates.

3.2. Modification of the Seals:

The pilot system for processing 3.1 x 3.6 inch substrates has a differentially pumped air-to-vacuum-to-air seal that has a glass filled Teflon liner for supporting the belt. This system has been operational since 1997. This system has been used to process nearly 10,000 substrates. The wear in the liner is causing the substrate to contact the seal leading to pinholes in the films. In addition, the adhesive bond between the Teflon liner and the aluminum support plate had also degraded. A new Teflon liner with improved attachment to the aluminum support plate has been designed, fabricated and tested.

3.3. Large Area Devices:

Many large area devices in the form of strips of ~0.7 cm. wide and 4 sq. cm. total area were processed to study the performance of these devices. The widths are representative of cells in modules. Devices were tested at NREL and the efficiency of 10.88% was measured and efficiency of 11.1% was also measured independently at IEC. These measurements indicate that module efficiency of 10% based on active area is feasible with our technology. The 10% module efficiency was utilized in the cost calculations developed for our technology. These calculations show module manufacturing costs less than \$1/Watt and have been presented at CdTe R&D Team Meetings.

3.4 Advanced Encapsulation Method:

During the course of our interactions with NSC, we have expressed the need for simpler and more effective encapsulation methods to lower manufacturing costs. Based on our input and their past expertise, NSC has developed a promising approach for encapsulation. The new

method involves screen printing a polymer based material (developed by NSC for OLED applications) at the edges on the back side of the front glass and then pressing the back glass to the front glass. Subsequently, the polymer is cured by UV exposure for fraction of a second. One glass/glass package with 0.25" wide seal has been tested in the damp heat test (85/85) for 1300 hours. A small quantity of moisture indicating material placed in the middle between the two glass plates has not changed color. This result is very promising and NSC has applied for a patent on this technology.

3.5 Higher Efficiency:

We have demonstrated NREL verified efficiencies of 12.44% on unmodified Pilkington TEC 15 glass. In order to obtain higher efficiencies, low iron sodalime (white glass) glass plates have been obtained and cut to size suitable for our pilot system. Fifty substrates have been sent to Sierratherm for atmospheric pressure CVD coating with TO:F. Coated samples have also been received from Solaronix. Deposition experiments with these substrates will be performed soon. The APCVD process is suitable for low cost high volume processing. The use of barrier layer deposited by APCVD and other methods will be investigated. A number of studies on improved substrates have been performed.

- A. The optical transmission of low iron glass in the visible spectrum is comparable to 7059 borosilicate glass (nearly 92% without AR coating). 7059 glass has been used in many high efficiency devices.
- B. MgF_2 AR coating has been used in many high efficiency devices. MgF_2 is slightly soluble in water and may not be suitable for outdoor applications. The MgF_2 could be replaced with an oxide AR coating made by a pyrolytic process. Oxide AR coated substrates were obtained from Denglass and these substrates have very similar transmission to MgF_2 coated glass.
- C. Significant decrease in the transmission (~ 3 mA/sq. cm.) has been observed due to the TO:F coating. Efforts to reduce the transmission losses in the transparent conducting oxide are currently underway.

Devices have been fabricated on the substrates from Sierratherm. In one run the average efficiency of devices with the Pilkington TEC 15 substrates was 10.8%. The efficiency with white glass substrates was 12%. Cross-sectional SEM studies showed that the white glass had a higher thickness for CdS (nearly 1800 angstroms). This indicates that optimization of CdS thickness would result in higher efficiency. These efforts are currently underway. The results on devices processed with these substrates are shown in Figure 1 below.

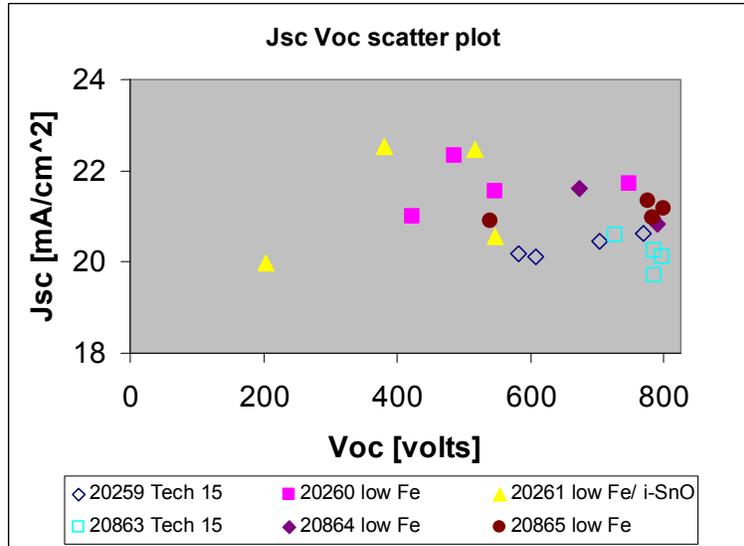


Figure 1: Jsc Voc scatter plot of devices with thinner CdS on three different substrates

To date, three different substrates have been investigated for higher efficiency. These are: TEC 15, Low Fe, and Low Fe with i-SnOx coating. A few substrates with intrinsic tin oxide barrier coating have been obtained from Chris Ferekides. Our current standard process produces Jsc of 20 mA/sq. cm. at ~800 mV. Figure 1 shows the current and voltage performance of devices fabricated on the different substrates. When the CdS thickness was reduced, an increase in Jsc was observed, but the Voc decreased. The open blue squares represent devices on the standard Pilkington glass which have slightly smaller CdS thickness compared to the standard. Nearly 100 substrates and 24 devices were part of the thin CdS study. Six devices have been provided to Prof. Sites' group for LBIC and QE studies.

Further optimization of the TCO and CdS will be needed for obtaining higher efficiencies. To aid in this effort, Xuanzhi Wu of NREL has supplied four 3.6x3.1 inch LOF TEC 15 substrates with a ZTO buffer layer. These substrates will be used for future efforts to increase device efficiency. Additionally, PPG Industries is providing advanced substrates and film characterization. Discussions have been held with Pilkington and PPG and both have indicated that they may produce white glass with "TEC" type tin oxide coating in the future.

3.6 Device Characterization Studies:

A summary of the preliminary work on the transient ion drift (TID) method of characterizing mobile Cu ions was presented in the poster session on May 8th at the 2006 WCPEC 4 in Kona Hawaii. The WCPEC presentation was an extension of the results presented in the talk, "Observations of Cu Diffusion in CdTe PV Devices" at the 2006 CdTe R&D Team at NREL. The TID method is well known as a means of characterizing the drift of Cu ions in c-Si material. Using TID it is possible to obtain the density and the diffusion coefficient of Cu ions. The work in our lab is an attempt to adapt the TID method to thin (2 μm) polycrystalline CdS/CdTe devices. An initial study of CdS/CdTe devices using TID indicates that increasing the quantity of Cu applied during the back contact formation process increases the Cu_i⁺ density. However, for devices with an optimum CdCl₂ treatment the Cu_i⁺ density is on the order of 2E13 cm⁻³. Also a preliminary estimate of the Cu ion diffusion coefficient is $D(\text{Cu}_i) = 1.3\text{E-}6 [\text{cm}^2/\text{sec}] * \exp(-0.29 \text{ eV}/\text{KB} * \text{T})$ which closely matches the value found by others for Cu_i

diffusion in c-CdTe. The WCPEC 4 paper qualitatively discusses the possible effects of grain boundaries, a thin neutral region and a non-uniform doping profile on TID measurements. In order to use TID as a practical method for characterizing Cu diffusion in CdTe PV devices more work is needed to quantitatively address these issues. Al Enzenroth met with Xuanzhi Wu and Su-Huai Wei at NREL on June 29th to discuss Cu diffusion mechanisms in CdTe.

Some of the preliminary work on the photocapacitance (PHCAP) method of characterizing deep states or traps was presented at the 2006 EMRS in Nice France. The EMRS presentation was an extension of the results presented at the 2005 CdTe R&D Team at NREL, in the talk, “Steady State Photocapacitance (PHCAP) Study of CdS/CdTe PV Devices”.

The introduction to the EMRS paper discusses problems in using deep level transient spectroscopy (DLTS) and thermal admittance spectroscopy (TAS) to characterize thin CdTe PV cells that have nearly depleted absorbers. Photocapacitance and optical DLTS with sub-bandgap light are shown to be promising techniques for characterization of deep levels in thin CdTe devices. Both steady state and transient PHCAP were used to characterize deep states related to the CdCl₂ treatment in thin CdTe PV devices. In the study it was found that a non-optimum CdCl₂ treatment increased the density of deep states while an optimum treatment decreased the density of deep states over an untreated sample. Three distinct deep levels were found in the upper half of the band gap in all devices surveyed.

A collaboration has been initiated with Anura Samantilleke of the Department of Chemistry at the University of Bath in the UK to characterize our CdTe devices using modulated electroreflectance (ER). The ER technique was described in a presentation by Ramesh Dhere entitled “Study of CdS/CdTe Junction by Modulated Reflectance”, at the 2006 CdTe R&D Team meeting. Initial ER results from the University of Bath are promising. An example ER spectrum is shown in Figure 2 where two critical points are shown at 1.482 eV and 1.525 eV. These values would indicate that there is little or no intermixing of S into the CdTe layer. The fit to the ER data also indicates that the crystalline quality of the CdTe is very good. Also there is a “lift off” of the ER spectrum at ~ 2.4 eV near the band edge energy of CdS. Since the spectrum continues to increase towards higher energies this is an indication of intermixing of the SnO:F TCO and the CdS layer.

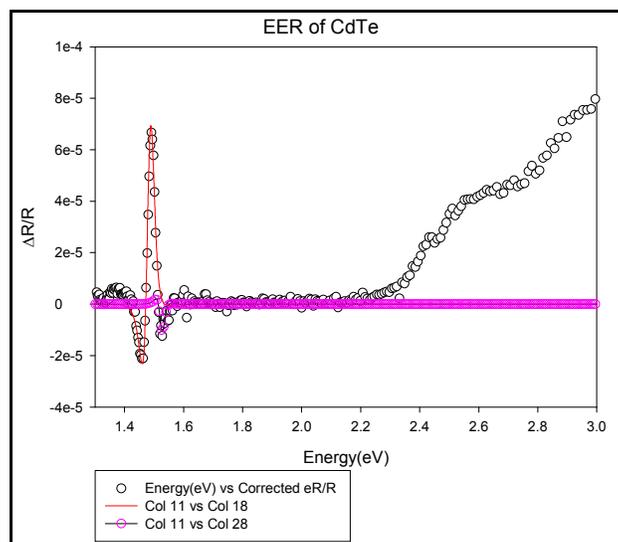


Figure 2: Electrorreflectance spectrum of fully processed CdS/CdTe PV cell. Colored traces are fits to the ER data (black)

3.7. Ellipsometry:

Spectroscopic ellipsometry is being investigated as a quality control tool. It is hoped that ellipsometry would provide a nondestructive means of measuring thickness uniformity of CdS/CdTe films on large areas. It is also possible that by tracking optical constants measured by ellipsometry it would be possible to correlate this data to process variation. Efforts are underway to qualify the technique and verify its usefulness.

In order for ellipsometry to predict layer thicknesses and optical constants for a multi-film stack an analytical model must be developed. Sandeep Kohli of the CSU central instrumentation facility has used a J. A. Woollam Vase ellipsometer to collect experimental spectrums from several samples processed in our laboratory. Working in collaboration with the Woollam Co. Kohli constructed an analytical model to predict the optical constants and layer thicknesses for the measured samples. The model fit to the experimental data for a representative sample is shown in Figure 3. The model has 14 layers and the mean squared error for this fit is 24.22, which is considered to be a good fit.

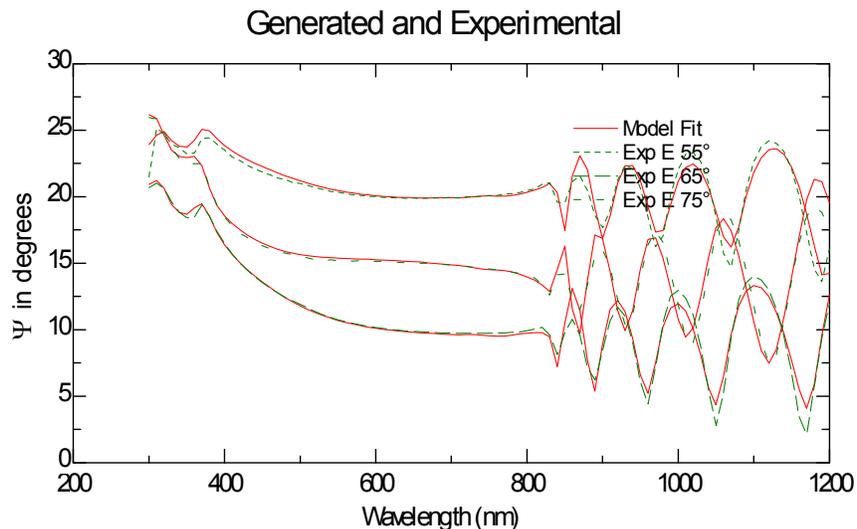


Figure 3: Spectroscopic ellipsometry data and model fit for a LOF Tec 15 substrate with SnO:F/CdS/CdTe:Cu which had received CdCl₂ treatment.

The most difficult part of developing the analytical model was to obtain a good fit to the glass/SnOx substrate. Sandeep eventually used 6 layers including one layer with graded optical constants to fit the measured data. Initial profilometry measurements of the CdS/CdTe layer thickness match the CdS/CdTe thickness predicted by the model. Cross sectional SEM characterization of the samples is also underway to verify the ellipsometry data.

At this point a reasonable model has been obtained and now the predictive capability of the model must be further verified. Optimization and further development of the model will also be pursued. Al Enzenroth of the CSU Materials Engineering Laboratory attended a four day spectroscopic ellipsometry short course on data analysis presented by the Woolam Co. at Arizona State University. In order to exercise the model more samples with varied film thicknesses will be fabricated. Ellipsometry data will be obtained from these samples and the model predictions will be checked. Multiple ellipsometry measurements on 3 x 3 in. samples will also be performed to measure uniformity.

Fred Seymour (currently with Primestar Solar) performed admittance spectroscopy measurements on several cells fabricated at the CSU MEL. These included devices with poor CdCl₂ treatment without Cu and with good CdCl₂ treatment both with and without Cu. For poor CdCl₂ treatment without Cu, there was a uniform spatial distribution of deep states with an activation energy of 0.320 eV. For a cell with good CdCl₂ treatment there was a uniform spatial distribution of deep states with an activation energy of 0.130 eV. This deep state may be assigned to the Cl A-center complex or other states related to Cl. The addition of Cu to a cell with a good CdCl₂ treatment introduces a deep state at 0.350 eV. This deep state has a relatively high density and a non-uniform spatial distribution. The decrease in capacitance signal with increasing temperature indicates a steep concentration gradient near the back contact. This deep state may be assigned to Cu_{Cd}. In all three cells there was evidence of deep states with a continuous energy band with activation energies deep in the band gap. The concentration of this distributed band was lowest for the cell with good CdCl₂ with Cu.

3.8 Production Prototype Development:

A system for processing 16.5 x 16.5 inch substrates is been developed by our group. When completed and run in production mode, the throughput of this semiconductor processing system will be 2 MW/year. Recent advancements include the completion of the vacuum system and testing of the load lock substrate transport system and the installation and operation of two complete process stations. The design of the other process stations have been completed and are being fabricated. Thermal uniformity of +/- 1.5 °C over the deposition area within the vapor source was measured for a temperature of 400 °C. The process stations are designed for continuous running for 40 hours or more without reloading. The system has been tested for a continuous 78 hour thermal run (without source charge). Many 16.5 x 16.5 inch substrates including tempered substrates have been transported with the load lock system and heated to 500 °C in 2 minutes.

3.9 Design of Module:

Initially the design of the packaging for our modules will utilize glass/EVA/glass packaging. In order to reduce moisture ingress into the device, polymers with desiccants will be used for sealing the edges and other specialized materials will be used for the holes in the back glass. Fixtures simulating the package design with the desiccant containing materials have been fabricated and are being tested at NREL under damp heat (85/85). A small quantity of moisture indicating material placed inside the fixture has not changed color after 3000+ hours of testing for the fixtures simulating the edge seal. The fixtures without the desiccant containing materials have failed (the moisture indicating material inside the fixture has changed color). The tests are continuing. This result is very promising. An advanced method for encapsulation is also being developed by National Starch and Chemicals (NSC) with our input.

3.10 Update on Outdoor Testing:

Eleven optimally processed devices are being tested outdoors under open circuit conditions. These devices were recently measured and the results are shown below in Figure 4. It is noted that most of the devices have maintained an efficiency of 10% after nearly 5 years

outdoors at open circuit conditions. Accelerations factors of 7 to 100 have been reported in the literature for CdTe devices between open circuit and max. power condition.

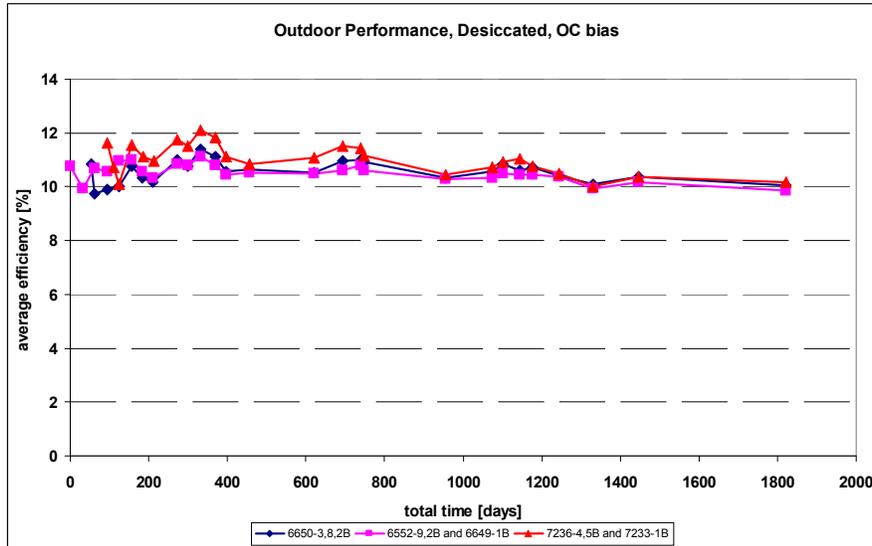


Figure 4: Average efficiency versus time for groups of cells in outdoor test conditions

4. PHASE III PLANS

As in Phase I and II, we will advance the tasks outlined in the statement of work during Phase III. The focus of the efforts will be to further develop the understanding of stability, yield and efficiency of CdS/CdTe devices. We anticipate that further progress will be made towards processing 16.5x16.5 inch substrates into modules. We will continue our collaborative activities with other research groups and provide assistance to industries as in Phase I and Phase II.

5. REFERENCES

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6. APPENDICES

6.1 Collaborative Studies and Other Activities:

During this phase, the following collaborative activities were conducted:

- 1) 19 cells were provided to Alan Davies (Prof. Sites' group) and these cells were stress tested and it was shown that at optimum processing, good stability can be obtained. This was presented at the CdTe Team Meeting.
- 2) Many interactions with Larry Olsen of PNNL regarding the application of CdTe devices for another application have occurred.
- 3) Graduate student Tushar Shimpi graduated with a MS degree and Jim Sites served on his committee.
- 4) Two presentations (one by CSU and one by AVA Tech.) were given at the CdTe Team meeting.
- 5) Twenty slides on our research were provided to Ramesh Dhere of NREL for his tutorial at the IEEE PV Conference.
- 6) Marc Landry and Ramesh Dhere (both of NREL) and visitors from Ziyax Corp. were given a tour of our laboratory and possibilities of collaboration were discussed. Other visitors include: Steve Johnson and researchers from PPG Industries. John Bleem from the local utility, Platte River Power Authority, was given a facility tour.
- 7) Our group has developed a technique for defining CdTe cell areas on glass substrates. The technique consists of applying a contact mask and removal of unmasked areas with an abrasive blast. Xuanzhi Wu supplied four CdTe substrates for initial testing of the abrasive blast technique on NREL devices. Circular areas of $\sim 0.69 \text{ cm}^2$ were defined and the cells were returned to NREL for evaluation.
- 8) Al Enzenroth from our group presented papers at the IEEE meeting and E-MRS meeting (discussed above). He also attended the CdTe workshop in France.
- 9) As described above, collaborations continued with CSM, X. Wu of NREL and a new collaboration with Anura Samantilleke of the Department of Chemistry at the University of Bath in the UK has been initiated.
- 10) Brian Murphy, Fred Seymour and Russell Black of Primestar Solar were given a detailed tour of the lab. and many insights on the effect of processing on device stability were discussed.

- 11) Our laboratory was part of an organized self guided tour of the American Solar Energy Society. Nearly 100 visitors visited the laboratory over a six hour period.
- 12) Mani Manivannan from the Global Research Center of GE has joined our department and is continuing his research on CdTe photovoltaics. He visited NREL with Al Enzenroth from our group to discuss collaboration.

6.2. Description of Interactions with Industry

Our CSU organization has a ongoing relationship with AVA Technologies LLC of Fort Collins to advance CdTe manufacturing. The members of AVA Technologies are also faculty at Colorado State University. AVA Technolgies has been awarded a DOE Inventions and Innovation (I&I) grant. A subcontract to CSU was part of this I & I grant. The close relationship that AVA Tech has with a major research university is very beneficial for both parties. This I & I grant then dovetails with the CSU activities. Recently AVA Technologies has been reorganized into AVA Solar Inc.

Specialty electronic coatings are used as an electrode for our PV devices. These materials are supplied by Acheson Industries which is a part of National Starch and Chemical (NSC is the US subsidiary of the approximately \$10 Billion/yr, ICI Group). NSC manufactures critical products for the semiconductor, electronics and photonic industries. Our group has a continuing involvement with NSC to advance CdTe PV under the I and I program. During this last year, many samples were provided to NSC for metallization studies.

During the last year, a large corporation capable of very large scale manufacturing has expressed interest in pursuing a potential partnership for PV manufacturing with our technology. Numerous teleconferences and site visits have been conducted with high level representatives of the company.

6.3. Student Activities:

Graduate students, Tushar Shimpi, Mark Armijo and Rick Lueb were supported through this project. They have assisted in the activities described in this report. Tushar Shimpi completed his MS thesis and the objective of Tushar Shimpi's thesis was to develop an understanding of the hail impact test. Hershel Shelly is conducting his Ph. D. research on this project. His research is to study our process from an industrial engineering perspective. Chetan Malhotra of CU Boulder completed his Ph.D. His Ph.D dissertation was thermal and deposition modeling of our process. Marh Armijo has made significant progress towards completing his MS thesis and his study is to understand the mechanics of the composite module.

6.4 Presentation to Senator Salazar:

A detailed presentation was made to Senator Salazar and the presentation was well received. The presentation was attended by Harin Ullal and Bolko von Roedern of NREL and many senior administrators from CSU, City of Fort Collins and Larimer County.

6.5. The Refereed Journal Publications that were Completed in this Phase are Listed Below:

Enzenroth, R. A.T. Takamiya, K. L. Barth, and W. S. Sampath, "Photocapacitance Study of Deep Levels in Thin CdTe PV Devices", accepted in Thin Solid Films (2006)

Robert A. Enzenroth, Kurt L. Barth, W. S. Sampath and V. Manivannan, "Measurement of cooling rates of a superstrate cooling apparatus for an integrated in-line manufacturing process for thin-film photovoltaic devices", Accepted to the Journal of Vacuum Science and Technology, 2006

R.A. Enzenroth, K.L. Barth, W.S. Sampath and V. Manivannan, " In-line manufacturing of CdTe thin film photovoltaic devices", Submitted to Journal of Manufacturing Science and Engineering, under review.

R.A. Enzenroth, K.L. Barth, W.S. Sampath and V. Manivannan, " Performance of in-line manufactured CdTe Thin Film Photovoltaic devices", Submitted to Journal of Solar Energy Engineering, Under review.

V. Manivannan, Robert A. Enzenroth, Kurt L. Barth, Sandeep Kohli, Patrick McCurdy and W. S. Sampath, " Microstructural features of CdTe Photovoltaic thin film devices", Submitted to Thin Solid Films, Under review.

6.6. The Conference Publications that were Completed in This Phase are Listed Below:

Enzenroth, R. A., K. L. Barth, and W. S. Sampath, "Transient Ion Drift Measurements of Polycrystalline CdTe PV Devices", presented 2006 IEEE 4th World Conference on Photovoltaic Energy Conversion-4, (2006).

Enzenroth, R. A.T. Takamiya, K. L. Barth, and W. S. Sampath, "Photocapacitance Study of Deep Levels in Thin CdTe PV Devices", presented European Materials Research Society (EMRS) Spring meeting, Strasbourg France (2006)

Barth, Kurt L., R. Albert Enzenroth and W. S. Sampath, "Brief update of progress at AVA Technologies LLC" National CdTe Team Meeting, Sponsored by the DOE through the National Renewable Energy Laboratory, Golden, CO, March 2006. Can be got from: http://www.nrel.gov/pv/thin_film/docs/cdte_team_march_2006.pdf

Enzenroth, R. A., K. L. Barth, and W. S. Sampath, " Observation of Copper Diffusion in CdTe PV DEvices", National CdTe Team Meeting, Sponsored by the DOE through the National Renewable Energy Laboratory, Golden, CO, March 2006. http://www.nrel.gov/pv/thin_film/docs/cdte_team_march_2006.pdf

6.7 Other Publications

Barth, K, R. Enzenroth, and W. S. Sampath, "Advancing Thin Film CdTe PV Manufacturing", Thin Film PV Kickoff Meeting, Given to reputed members of industry, April 4, 2006.

W. S. Sampath, "Mass Production of CdTe Solar Photovoltaics" Presentation for the Northern Colorado chapter of IEEE January 17, 2007.

Sampath, W. S., Robert. A. Enzenroth and Kurt L. Barth, "Mass Production of Thin Film Solar Photovoltaics", Presentation, Discussion and Facility Tour for numerous groups including Reliance Industries, NEA, Sequel, Murphy and Durier, Blackstone, Barings, local investment group, Primestar Solar, Nanosolar and many others.

Barth, K. L, R. A. Enzenroth, and W. S. Sampath, US patent application, 20050158891 Apparatus and processes for the mass production of photovoltaic modules.

REPORT DOCUMENTATION PAGE

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4. TITLE AND SUBTITLE Manufacturing Process Optimization to Improve Stability, Yield, and Efficiency of CdS/CdTe PV Devices: Phase II, Annual Technical Report, January 2006 – February 2007			5a. CONTRACT NUMBER DE-AC36-99-GO10337		
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14. ABSTRACT (Maximum 200 Words): This report describes a fixture for automated cooling of the substrate in vacuum that has been designed, fabricated, installed, and tested. This is needed for optimum processing of the back contact. Device efficiencies of 11.83% have been made in an "all forward" process. Large-area devices (~4 cm ²) in the form of strips were fabricated and tested at NREL. Efficiency of 10.9% were measured on these large-area devices. The air-to-vacuum-to-air seals in the pilot system have a glass-filled Teflon liner. These liners have experienced wear, resulting in scraping the glass substrates in the seal. Improved liners were designed, fabricated, installed, and tested in the system. Efforts to improve device efficiency and advance device characterization are under way. Desiccant-containing materials for the edge seal and sealing materials for the holes in the back glass were subjected to damp-heat tests at NREL with very promising results. Significant progress was made in characterizing films with ellipsometry, and the use of ellipsometry for quality control is being investigated. An additional patent was issued on this technology during the last phase.					
15. SUBJECT TERMS PV; optimum process; large-area; devices; back contact; glass substrate; ellipsometry; automated cooling; liner; damp-heat testing; characterization;					
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