INSTITUTE OF
ENERGY CONVERSION

451 Wyoming Road
Newark, DE 19716-3820
Ph: 302/831-6200
Fax: 302/831-6226
www.udel.edu/iec

UNITED STATES DEPARTMENT OF ENERGY
UNIVERSITY CENTER OF EXCELLENCE
FOR PHOTOVOLTAIC RESEARCH AND EDUCATION

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Bolko von Roedern
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

Re: NREL Subcontract #ADJ-1-30630-12
D.5.32

Dear Bolko,

This report covers research conducted at the Institute of Energy Conversion (IEC) for the period of January 1, 2008 to January 31, 2008, under the subject subcontract. The report highlights progress and results obtained under Task 1 (CdTe-based solar cells). During this period, effort was focused on two sub-tasks: 1.1) deposition and characterization of device structures with thin CdTe absorber layers and 1.2) deposition of CdTe/CdS/ITO onto a temporary supporting superstrate for transfer to a flexible polymer substrate.

Task 1 – CdTe-based solar cells

1.1 Thin CdTe Absorbers

CdTe films were deposited by vapor transport (VT) from a single compound source. This method provides several key control parameters for adjusting growth rate and thickness: 1) translation speed; 2) source temperature; 3) carrier gas flow rate; 4) total system pressure; and 5) substrate temperature. For this work, translation speed was fixed at 2 min per plate, and source temperature was used to adjust the incident flux at the substrate. The total system pressure was 20 Torr, substrate temperature was 550°C, carrier gas flow rate was 20 sccm. CdTe source temperature was varied from 830°C to 800°C to control deposition rate. Thermal loading on the inlet side of the source cools the source by ~20°C, resulting in a thickness gradient perpendicular to the translation direction along a 2 cm wide band of the otherwise uniform substrate. Thus a single 10 x 10 cm plate carries a CdTe film with uniform thickness over a 10 x 8 cm portion, and a narrow band of graded thickness.

VT CdTe films were deposited onto 10 x 10 cm commercial soda-lime glass (SLG) substrates translating beneath the CdTe source as described previously.[1] The superstrate devices consist of SLG/SnO_2/HRT/CdS/CdTe with Cu/C contacts, where the CdTe received post-deposition treatment at 1 atm in Ar/O_2 containing $CdCl_2$ vapor generated from a sublimation source.[2] The

SLG/SnO_2/HRT substrates are Pilkington TEC15, coated with either high resistance Ga_2O_3 or ITO. The 90 nm thick CdS films were deposited by chemical surface deposition and received vapor $CdCl_2$ treatment at 400°C prior to CdTe deposition. Baseline CdTe films ~5 µm thick are routinely deposited using a source temperature of 830°C at a growth rate of 10 µm/min. Thinner films, as thin as 0.3 µm, were obtained by reducing the source temperature to 790°C.

CdTe films were examined for pinholes with lateral size from 1 to 50 µm using white light transmission. Pinhole counts exceeding 5 per plate were only found on depositions run immediately after source ampoule changes, due to dislodged particulates, and such plates were rejected for processing into completed devices. Otherwise, plates exhibited only 1-5 pinholes in the CdTe film over the entire surface, independent of thickness. CdTe film morphology was analyzed by atomic force microscopy (AFM) in tapping mode using a Digital Instruments Nanoscope IIIa Dimension 3100. The grain size distribution was determined from AFM scans covering a 20 x 20 micron region (Figure 1) on each sample by binning grains into size categories. The grain size distributions of thin CdTe films, with thickness from 0.3 µm to 3 µm, are shown in Figure 2 and approximate log-Normal distribution with peaks indicative of height/width ratio ~2X. Films with 0.3 µm to 0.5 µm thickness exhibit nearly-identical frequency distributions and conform to the underlying SnO_2. The r.m.s. roughness on bare SnO_2 and on the CdTe films with thickness from 0.3 µm to 0.8 µm was 35 nm ± 5 nm. CdTe surface roughness increased proportionally with thickness for films from 1 µm (r.m.s. = 50 nm) to 5 µm (r.m.s. = 90 nm).

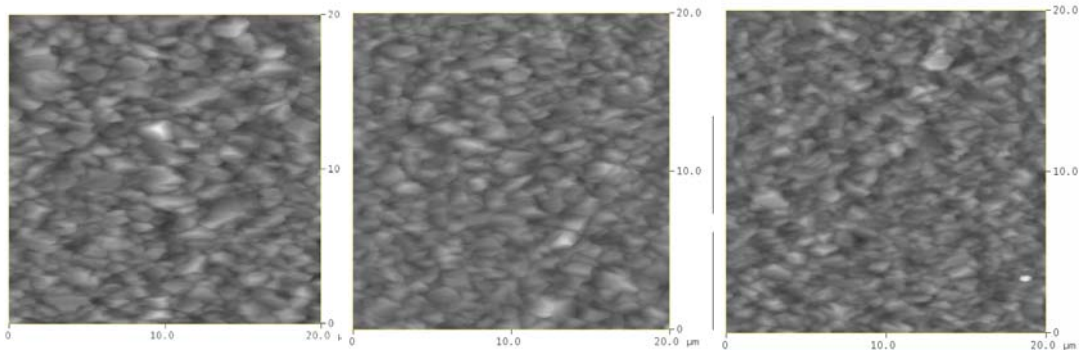

Figure 1. Tapping AFM images of CdTe surface (20 x 20 µm) for thin CdTe films: 1 µm (left), 0.8 µm (center) and 0.5 µm (right) VT films deposited at source T_{sou} = 800°C and substrate T_{sub} = 550°C.

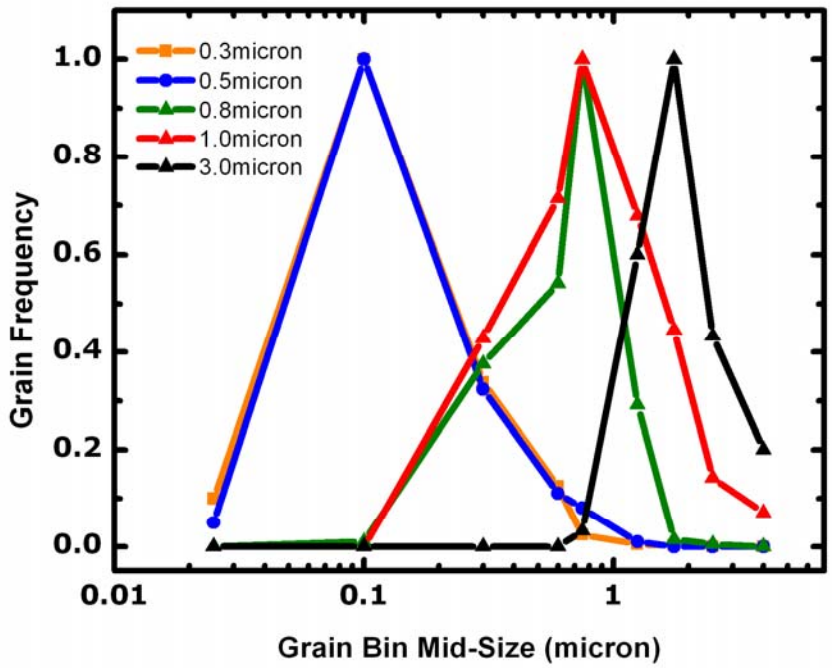

Figure 2. Grain size distribution of VT CdTe films with thickness ranging from 3 to 0.3 µm.

Optical transmission (T) and reflection (R) were measured using a Perkin-Elmer Lambda-9 spectrophotometer from 400 nm to 1000 nm. T/(1-R) is shown in Figure 3 for SLG/SnO_2/ITO/CdS/CdTe structures with CdTe thickness from 0.3 µm to 3 µm. Long wavelength transmission increases with decreasing film thickness. The loss in photocurrent for single-pass absorption is estimated from the transmission data by integrating the transmission with the AM1.5 spectral output. The effect of reducing CdTe on short circuit current (J_{SC}) in cells is listed in Table I for several films of Figure 3. No significant change in photocurrent is expected from baseline thickness down to 1 µm. Photocurrent losses from 1 mA/cm^2 to ~4 mA/cm^2 are expected for films with thickness below 1 µm.

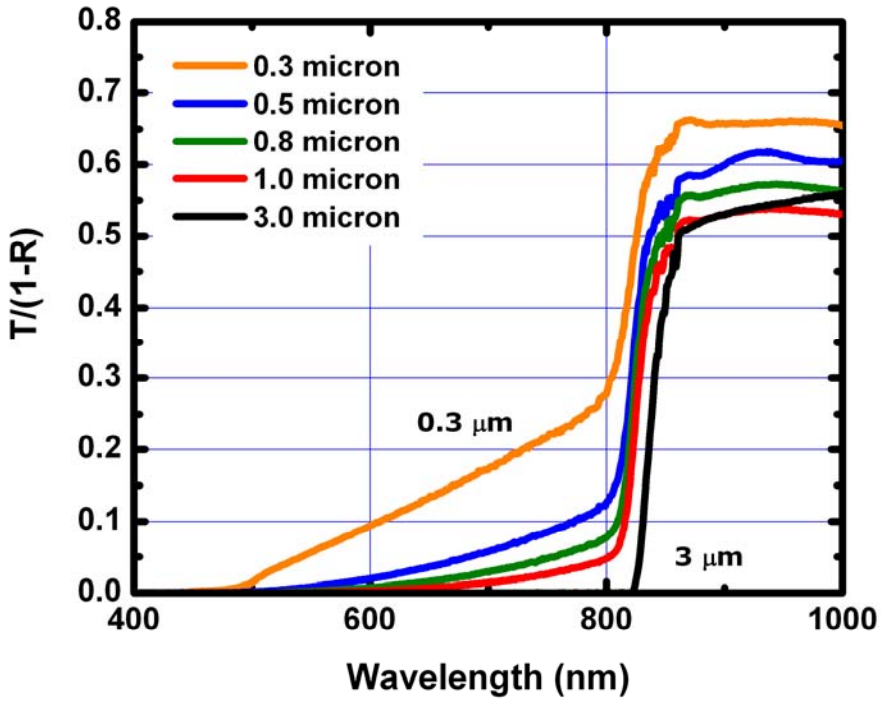

Figure 3. Normalized optical transmission T/(1-R) versus wavelength of SLG/SnO_2/Ga_2O_3/CdS/CdTe structures with CdTe film thickness ranging from 0.3 to 3 µm.

Table I. Calculated AM1.5 J_{SC} loss for data of Figure 3.

CdTe Thickness (µm)	J_{SC} Loss (mA/cm^2)
3.0	0
1.0	0.3
0.8	1.1
0.5	1.8
0.3	3.6

1.2 Flexible CdTe Solar Cell

The goal of this sub-task is development of a process to deposit CdTe films in a superstrate configuration onto CdS/ITO window layers using a temporary Al foil substrate. Both low temperature PVD and high temperature VT deposition methods are considered for the CdTe film growth, allowing comparison of the mechanical and chemical robustness of films deposited at low temperature with those deposited at high temperature. The primary structural effect of deposition temperature is on grain size and structure. The PVD technique, with Ts < 400ºC, does not achieve the grain size and low crystallographic defect density found in films deposited at high temperature (Ts > 450ºC). However, the technique imparts the least thermal stress on the thin film and Al foil system.

A primary objective of this work is transferring the completed CdTe solar cell onto a polymer substrate, and the key challenges are selection of an appropriate bonding agent/substrate combination for mechanical robustness and low contact resistance and a chemical etchant for removing the Al substrate. Initial efforts were focused on single-sided adhesive Kapton tape and lamination directly onto polymer substrates using a conductive epoxy. On-going work is the fabrication and characterization of devices to determine: 1) the effect of the Al substrate on p-n junction behavior; 2) the effect of Al etching and etching on device operation; and 3) the mechanical effects of different adhesion methods on the durability of the transferred solar cell. Backwall J-V analysis of partially-completed devices will be used to monitor the progress of junction quality through the post-deposition and transfer process. We anticipate future analysis of stress-induced effects on device operation, in view of the fact that cells will undergo stresses related to mechanical deployment and thermal cycling. The mechanical robustness of the CdTe solar cell transferred to a polymer substrate is an open question. Adhesion and mechanical strength will be characterized with respect to deformation caused by bending of the substrate. Adhesion will be quantified by standard tape tests. Mechanical strength of the structure will be determined by the minimum radius at which the on-set of cracking is detected. In this context, the issue of fatigue fracture will be also be evaluated.

Figure 4 shows a schematic representation of the transfer process of a CdTe/CdS thin-film device from the temporary Al superstrate to a flexible polymer substrate. The process steps used in preliminary experiments are:

1. Sputter 0.25-0.30 µm thick ITO film on 0.002 cm thick Al foil;
2. Evaporate 0.2 µm thick CdS film at 220ºC and 3 Å/s;
3. Evaporate 4.0 µm thick CdTe film at 340ºC and 30 Å/s;
4. Vapor treat structure in $CdCl_2$:Ar:O_2 ambient at 400ºC for 20 minutes;
5. Vapor treat back surface and deposit Cu to form cuprous telluride;
6. Evaporate Ni contact;
7. Bond cell to polymer substrate;
8. Etch Al foil in 1 molar NaOH at 35ºC.

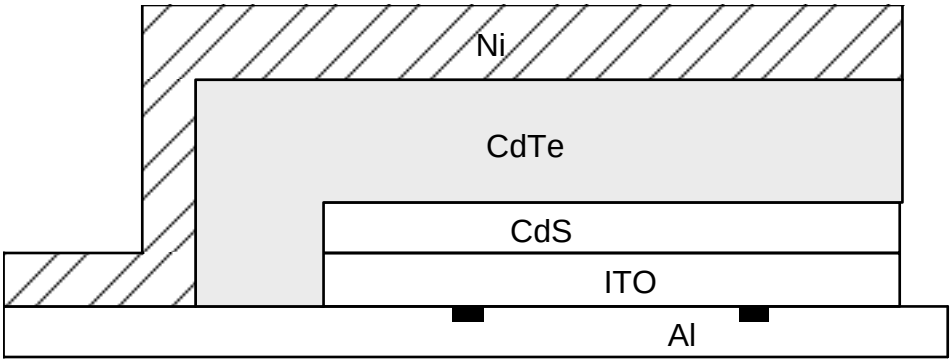

Figure 4a. As-deposited CdTe/CdS superstrate structure on Al foil.

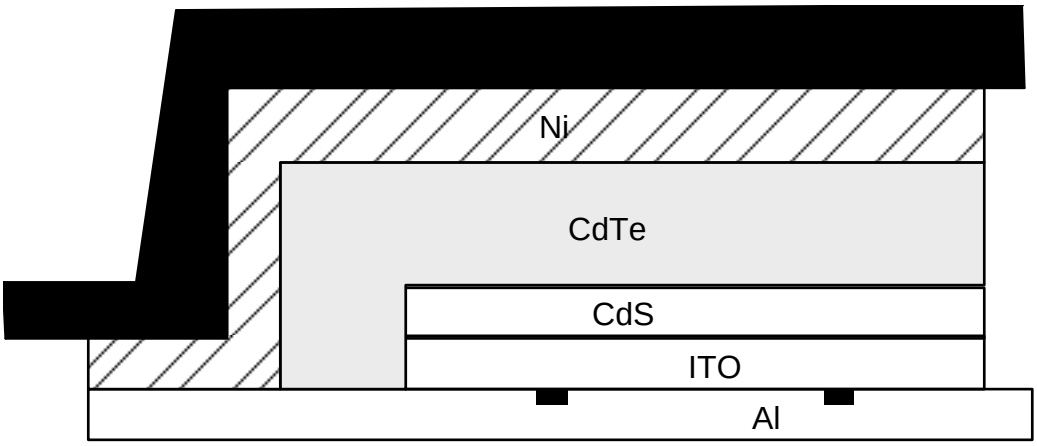

Figure 4b. Intermediate structure bonded to polymer material.

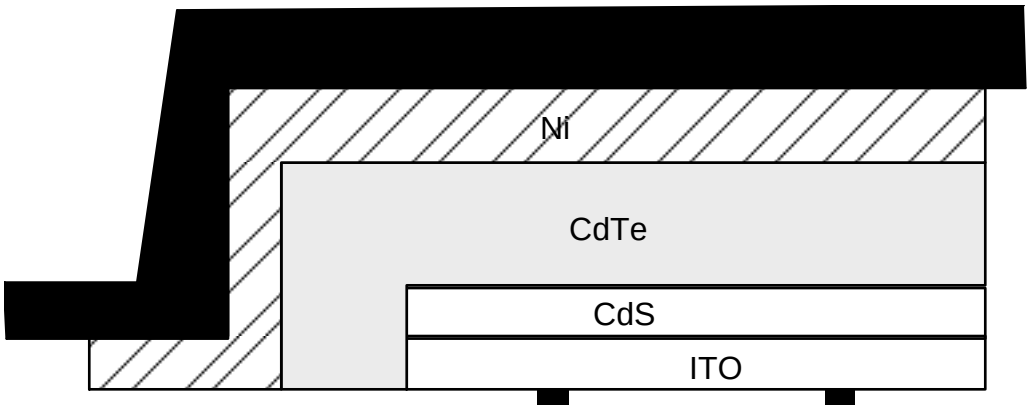

Figure 4c. Final CdTe/CdS device: Al foil temporary substrate etched away.

To support the Al foil throughout the deposition sequence, it was wrapped around a 10 cm x 10 cm stainless steel platen. Initially, soda lime glass was employed but was found to frequently crack during VT CdTe deposition or during cool-down. In all experiments, the CdS was deposited by PVD at 150°C at a growth rate of 5A/s. Figure 5 shows a photograph of the CdS-

coated ITO/Al structure of 1" x 3" sections taken from a PVD and a VT run, each with nominally 4 μm thick CdTe.

Figure 5. As-deposited ITO/Al structure.

Figure 6. As-deposited CdS/ITO/Al structure.

Figure 7. CdTe/CdS/ITO/Al structures with CdTe deposited by PVD (left) and VT (right).

In a preliminary experiment, we transferred a completed 2 cm x 2 cm Ni/CdTe/CdS/ITO device with a 4 µm thick VT CdTe layer from an Al foil superstrate to Mo-coated Upilex polyimide sheet using a conductive silver epoxy. The temporary foil substrate used was 40 µm thick ultra-high vacuum Al foil supplied by All-Foils, Inc. and the epoxy was No. 40-3905RSI04 by Epoxies Etc. Prior to bonding to Upilex, the cell structure was subjected to the same processing conditions used to fabricate baseline 11% efficient (AM 1.5) solar cells. As neither gridding nor TCO area definition was used in the preliminary experiments, photoresponse measurements were made using point contacts. The structure is flexible, exhibits an open circuit photovoltage of 300 mV and exhibits a weak photocurrent. Cracks in the CdTe film were correlated with crease-like distortions in the Al foil superstrate. Techniques for handling the foil will need to be developed and analyzed to determine the influence of superstrate condition on mechanical integrity of the CdTe film.

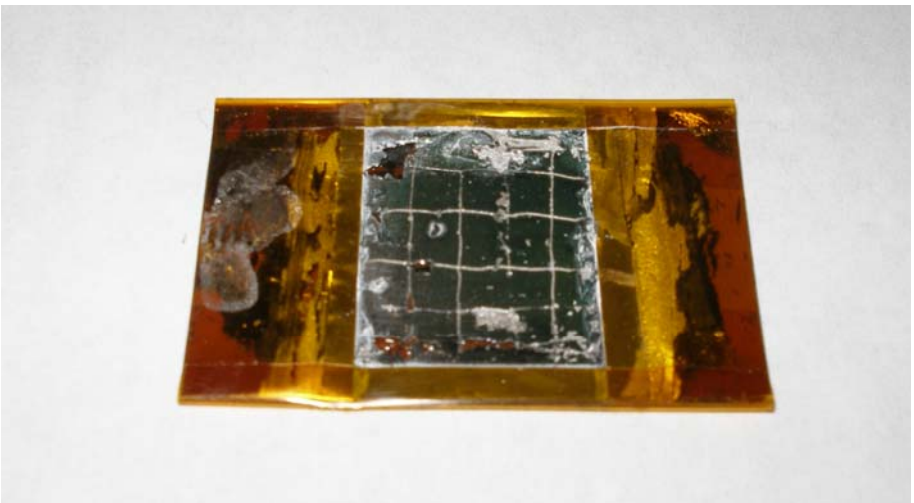

Figure 8. Transferred Ni/CdTe/CdS/ITO solar cell structure (3 cm x 2 cm) showing mechanical scribe lines to isolate smaller regions for electrical probing. Bright areas are regions where the CdTe cell delaminated from the silver epoxy during NaOH etching to remove Al.

References:

[1]G. M Hanket, B. E. McCandless, W. A. Buchanan, S. Fields, R. W. Birkmire, "Design of a vapor transport deposition process for thin film materials," J. Vac. Sci. Tech. A 24(5), (2006), 1695.
[2]B. E. McCandless, H. Hichri, G. Hanket, R. W. Birkmire, "Vapor phase treatment of CdTe/CdS thin films with $CdCl_2$:O_2," Proc. 25th IEEE PVSC, (1996), 781.

Best regards,

Robert W. Birkmire
Director