Colorado State University
Knowledge to Go Places
Department of Physics
Fort Collins, Colorado 80523-1875
Telephone: (970) 491-5850
FAX: (970) 491-7947
E-mail: sites@lamar.colostate.edu
www.physics.colostate.edu/groups/photovoltaic

June 2, 2008

Bolko von Rodern
National Center for Photovoltaics
National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, CO 80401

RE: Quarterly Report XIII (Feb 2008 - April 2008)
"Characterization and Analysis of CIS and CdTe Cells"
Subcontract XXL-5-44205-03

For additional information: www.physics.colostate.edu/groups/photovoltaic

Dear Bolko,

During the past quarter, we continued our work on the characterization and analysis of CIGS and CdTe cells. Of particular note, Alan Davies completed his PhD degree, and the last part of his thesis work is included below. Alan, who has now joined AVA Solar, is the eighth student to complete the PhD with funding through Subcontract XXL-5-44205-03. All eight are engaged in photovoltaic research and development, three with CdTe, two with CIGS, two with silicon, and one with dye-sensitized cells. In addition, Lei Chen completed his MS degree during the past quarter, and his thesis work is also included below.

Also during the past quarter, I was invited to speak on CIGS in the US at the annual Japanese Future Directions in Photovoltaics Workshop. After the workshop, I visited Tokio Nakada at the new Aoyama Gakuin campus and gave a talk to the PV group there on grain boundaries in CGS and CdTe.

Barrier Measurement Technique. Galym Koishiyev presented the technique he developed for determination of the back-contact barrier at the recent Photovoltaics Specialists Conference. His paper, "Determination of back contact barrier height for $Cu(In,Ga)(Se,S)_2$ and CdTe solar cells," described a straightforward technique to quantify the energy barrier for holes between absorber and back-contact. The data required are the current-voltage (J-V) curves for the solar cell measured over a range of temperatures. The key parameter is the "turning current" J_t, which he defined as the current at the transition from the positive J-V curvature of a diode to the negative curvature associated with contact-barrier current. The analytical strategy is to calculate a series of J_t vs. T curves for different values of barrier height and then overlay the experimental values of J_t. Specific examples included in his presentation were CIGSeS cells fabricated at the Florida Solar Energy Center and CdTe ones fabricated at NREL Generally the experimental data followed a single barrier-height curve over a wide temperature range. The range of J_t that can be practically identified extends from approximately 0.1 to 80 mA/cm^2. Assuming that temperatures between 220 and 340 K are available, the range of barriers that can be determined is between 0.30 and 0.55 eV. This is also the practical range, since lower barriers do not have a measurable effect on the power quadrant and higher ones effectively kill the performance of a cell. Many CIGSeS and CdTe cells, however, do have a back-contact barrier in the 0.30 to 0.55 eV range, and the ability to determine it can assist both cell analysis and process optimization.

CdTe Internal Photoemission. Alan Fahrenbruch, also at PVSC, presented a complementary paper, "Measuring the barrier height of CdTe barriers by internal photoemission," which described an alternative method for barrier determination. Alan measured the quantum efficiency for sub-band-gap light and interpreted is as the internal photoemission (IPE) response according to the Fowler theory. When plotted appropriately, the extrapolated photon-energy intercept should be equal to the barrier height. Alan made quantum-efficiency measurements on a number of cells from various fabricators, and compared the IPE curves from CdTe cells with good and bad contacts and from electronically thick and thin CdTe cells. His results suggested that two barriers in parallel are relatively common: a larger one (~ 0.9 eV), which agrees well with observed UPS values, and a lower one (~ 0.3 eV) with a much smaller fractional area (1 to 4%), which dominates the contact transport and corresponds more closely to barrier heights observed for high-efficiency CdTe cells. For thick cells, the IPE results also agree well with the determination of the barrier from temperature-dependent J-V measurements.

Non-Uniform CdTe Barriers. A third presentation at PVSC, this one by Alan Davies, was entitled "Effects of non-uniformity on rollover phenomena in CdS/CdTe solar cells." It included parts of Alan's PhD thesis. In this paper, he explored the behavior of CdS/CdTe cells made by Sampath's group at Colorado State with very little Cu in the back-contact. Although these devices maintained a decent V_{OC} (~760-780 mV), their fill factor was low (FF ~ 45-50%) because of non-standard behavior in the power quadrant. In this case, the effect on FF was greater than that which can be explained by a single barrier height. Capacitance results indicated full depletion, and laser-beam-induced photocurrent mapping indicated spatial variations of several percent in quantum efficiency at voltage biases near that of the initial diode turn-on. Guided by the LBIC results, Alan developed an expanded equivalent circuit model to approximate the effects of the non-uniform back-contact barrier which were not explained by the traditional two-diode in series model. He found that a parallel set of two front and back diodes was necessary to produce the non-standard rollover in the experimental J-V curves.

CdTe Cells with Thin CdS. Alan Davies and Lei Chen explored CdTe cells made at different laboratories with a large range of CdS buffers. In general, the QE curves nicely tracked the short-wavelength behavior predicted by the physical CdS thickness. The optical thicknesses, however, were consistently slightly smaller by ~20 nm than the deposited thickness, because of the partial intermixing of CdS with CdTe. In contrast to the predictable changes in QE and current, voltages changed fairly abruptly near 100 nm from voltage values associated with a SnO_2/CdTe junction to those consistent with CdS/CdTe.

The general model proposed by Lei Chen for variations of voltage with CdS thickness assumed that when CdS is deposited on a TCO layer, it first nucleates at preferred sites and then fills in between them. Since only a very small area of direct contact between CdTe and SnO_2 will significantly reduce voltage, the average CdS thickness needs to be somewhat greater than the average spacing between nucleation sites. A rough estimate of that spacing, based on typical CdS crystallite size, is in fact about 100 nm. Alan Davies' approach was more direct: he looked with LBIC at the spatial variations in photocurrent at different CdS thicknesses. He saw a major increase in photocurrent non-uniformity for CdS thicknesses below 100 nm when there is a mix of CdTe contact to CdS and the TCO. He also, however, saw a uniformity improvement at the smallest CdS thicknesses where most of the CdTe was in contact with the TCO.

Sheet Resistance and Fill Factor. A manuscript by Galym Koishiyev and myself entitled, "Impact of series resistance on 2-D modeling of thin-film solar cells," has been prepared for *Solar Energy Materials and Solar Cells.* The basic results were included in last quarter's report. In summary, a comparison of calculated power losses in a TCO layer due to lateral currents for continuous and discrete distributions of TCO sheet resistance showed that ρ_S (Ω/□) ≅ R (Ω) for all practical situations. A self-consistent mathematical formula relating the experimental series resistance R_S (Ω·cm^2) of a solar cell to the physical parameters TCO sheet resistance ρ_S (Ω/□) and semiconductor resistivity ρ (Ω·cm) was derived. It was found that the fractional decrease in fill-factor due to the sheet resistance is determined to a reasonable approximation by the dimensionless variable $x = \rho_S L^2 J_{SC}/V_{OC}$.

Effect of Shunts. An extension of the sheet resistance studies has been to examine how the fill-factor and efficiency are affected when there is are physical shunts. Galym has calculated the effect of local shunts of different magnitudes located at different positions in the cell. It appears that the effect on fill-factor is primarily a function of the local conductance (in mS), and it is affected only to a small extent by the physical size the shunt or its position relative to the contacts. The effect of shunts, however, is smaller when the sheet resistance is higher, and

Galym's current assignment is to quantify the relationship between shunt conductance, sheet resistance, and the fill-factor of the cell.

Contour Plots. Jun Pan has constructed a series of contour plots that show the calculated voltage, current, fill-factor, and efficiency of CdTe cells on a plane with axes chosen in pairs from bulk lifetime, carrier density, absorber thickness, and back-contact barrier. This allows both a visual picture of the likely materials properties and a roadmap of how improvements in materials properties will affect the cell parameters. To date, we have focused on CdTe analysis, but the same approach can be applied to CIGS and other absorbers.

Collaborative Work. In addition to the PVSC presentations from our group, Alan Davies was a co-author with Victor Plotnikov from the University of Toledo on a PVSC paper on measurements and interpretation of CdS/CdTe cells, and Galym was a co-author with the FSEC group on their CIGSeS presentation. We have also applied Jun Pan's contour plots to AVA cells, and that work will be continued under the AVA incubator project. In addition, Jun and I have assisted SoloPower with a series of measurements and analysis on their CIGS cells. And finally, earlier measurements that we made for HelioVolt were included in their invited talk at the recent PVSC.

Sincerely,

James R. Sites
Professor

Cc: NREL Subcontracts
CSU Office of Sponsored Programs