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Bolko von Rodern
National Center for Photovoltaics
National Renewable Energy Laboratory
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RE: Quarterly Report VII (August - October 2006)
"Characterization and Analysis of CIS and CdTe Cells"
Subcontract XXL-5-44205-03

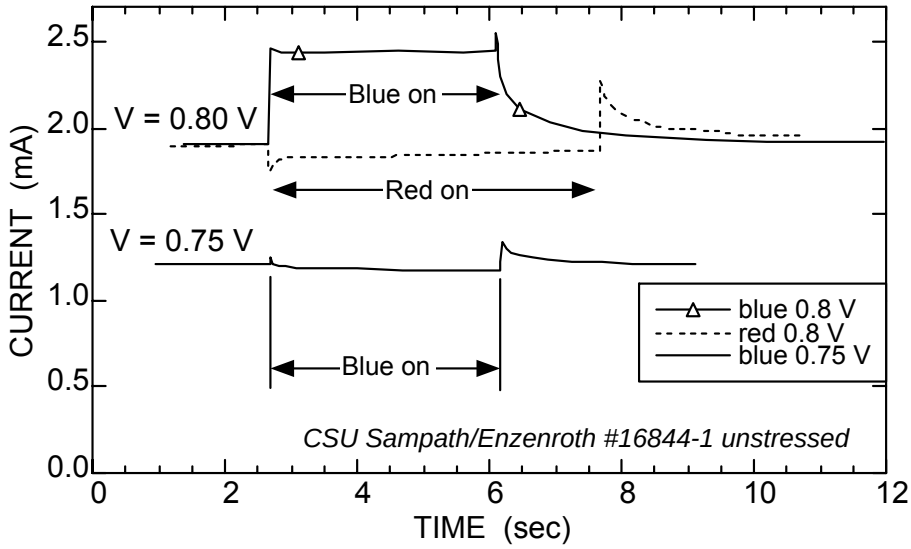
For additional information: www.physics.colostate.edu/groups/photovoltaic

Dear Bolko,

During the past quarter, we made progress in several areas as described below. Also during this period, several submissions, mostly from results given in earlier reports, were either published or were accepted for publication. These are listed in the final section. Samuel Demtsu's work at NREL with Dave Albin was particularly productive. In September, Caroline Corwine began work at Advent Solar in Albuquerque, and like other recent PhD graduates, she has been assembling and testing characterization facilities. In October, Ana Kanevce presented a talk on thin CIGS cells at the regional American Physical Society meeting in Logan, Utah, and received the best-presentation award for her session.

CdTe Cells with Thinner CdS. Alan Davies has been working closely with Sampath's group, Al Enzenroth in particular, to explore buffer layers that would allow the CSU cells to be made with thinner CdS without compromising performance in other ways. Several sets of cells, with and without resistive ITO and ZTO layers between the CdS and the conductive TCO layers, are being fabricated with several CdS thicknesses in each case. Comparisons among the sets include both the J-V and C-V-f responses and the LBIC profiles. The goal is to how best to reduce the CdS thickness, without introducing electronic weak spots, in an industrial process.

CdTe Transient Effects. Alan Fahrenbruch, also using CdTe cells fabricated by Sampath's group, has examined transient effects related to photoconductivity and has related these to anomalous AQE effects. The experiment was to measure the response of cells held at constant forward bias to pulses of blue (470 nm) or red (630 nm) light. At zero and low forward biases, the result was a simple J_L step as expected, but at higher biases ($\geq V_{max}$), the response showed growth and decay curves with time constants of seconds as shown below:



Forward-bias current response to blue and red illumination.

The decay curves following both red and blue illumination showed a similar time constant. The existence of the red decay curves suggests that at least part of the photoconductivity occurs in the CdTe. In addition, Alan, like others, found that the apparent QE was negative at high forward biases.

CdTe Voltage. In his WCPEC-4 paper, Alan Fahrenbruch discussed two extreme band profiles: the n/p junction, where the built-in junction voltage V_{bi} is supported by charge in the bulk CdTe, and the n/i/p junction, where the CdTe is insulating and V_{bi} is primarily supported by charge at the contacts. The n/p results suggest that increasing p-type doping density in the CdTe does increase V_{OC}, but decreases efficiency (albeit not strongly) due to decreasing current collection. The n/i/p model, which is closer to existing technology, suggests that, if it were possible to decrease the back-contact barrier height $Ø_{bc}$, the resulting increase in V_{bi} would increase V_{OC} while maintaining current collection. A conservative projection for the n/i/p structure is Eff = 18% and V_{OC} = 0.96 V with $Ø_{bc}$ = 0.1 eV. Jun Pan took the n/i/p structure a step further by considering the possibility of a back layer that not only eliminated the hole barrier, but also added an electron reflector. In this case, voltages above a volt and efficiencies above 20% should be possible. It

would be necessary, however, for the interface between the CdTe and the electron reflector to have a very low interfacial recombination velocity.

CdS Dipole Barrier. Jun Pan has also followed up on the possibility on a pressure-induced CdS dipole that was suggested as an explanation for the experimental results of Shvydka et al. Jun's simulations show:

(1) The size of a dipole barrier would need to be approximately 0.5 V to have a significant impact on solar-cell performance. The key parameter is the maximum energy difference between the conduction band and the quasi-Fermi level for electrons, and it makes only a small difference whether the barrier results from a dipole across the CdS, an interfacial charge sheet, or a band offset at an interface.

(2) The onset of performance degradation should be abrupt, as was seen in the pressure measurements. In contrast to the large voltage drop seen experimentally, however, the primary J-V effect should be in the fill factor, similar to observed problems with CIGS when there is a large band-offset spike.

CIGS Nonuniformities. Ana Kanevce has added nonuniformities in diode voltage to her simulations of CIGS cells with submicron absorber layers. Several physical conditions (reduced local Ga concentration, reduced local thickness, reduced back electron reflector) can be well approximated by a weak diode with a lower value of V_{OC} in the midst of an array of normal diodes. Key parameters are the amount of voltage reduction, the area of the reduction, the density and distribution of reduced voltage regions, and the sheet resistance of the TCO. All of these parameters are amenable to analysis with Pspice, and the resulting J-V curves can also be approximated analytically The basic results are that for a diode with V_{OC} only weakened by the order of AkT, there is little change in J-V, but for weaker diodes, the overall efficiency drops linearly with the weak-diode V_{OC} and logarithmically with its area.

High-Effiency CdZnS/CIGS. Ana also worked with Raghu Bhattacharya of NREL on the analysis of CIGS cells that that were fabricated with a solution-grown CdZnS buffer layer. The best of these cells achieved 19.5% efficiency, equal to that achieved with NREL's standard CdS buffer. At short wavelengths, the CdZnS buffer did achieve about 2 mA/cm^2 higher current than the CdS buffer, but it also had slightly less collection in the longer wavelength region. The CdZnS buffer also produced a slightly higher A-factor (1.5 vs. 1.3) both light and dark, and is C-V curve was slightly less well behaved and indicated a smaller CIGS carrier density near the junction.

Work with Companies. We have continued to assist Heliovolt with J-V and QE measurements and with the interpretation of the results. We have also supplied the CurVA software to Solyndra for analysis of their cell measurments, and I have offered modest assistance to two other companies for their SAI proposals. In all

cases, I continue to insist that my relationship with one company does not preclude working with others.

Publications:

(1) "Stability Study of CdS/CdTe Solar Cells Made with Ag and Ni Back-Contacts," S.H. Demtsu, D.S. Albin, J.W. Pankow, and A. Davies, Solar Energy Materials and Solar Cells **90**, 2934-2943 (2006).
(2) "The Relationship of CdS/CdTe Cell Band Profiles to J-V Characteristics and Bias-Dependent Quantum Efficiency," A.L. Fahrenbruch, Proc. WCPEC **4**, 376-379 (2006).
(3) "Role of Copper in the Performance of CdS/CdTe Solar Cells," S. Demtsu, D. Albin, and J. Sites, Proc. WCPEC **4**, 523-526 (2006).
(4) "Performance Assessment of PV Modules – Relationship Between STC Rating and Field Performance," M. Topič, K. Brecl, and J. Sites, Proc. WCPEC **4**, 2141-2144 (2006).
(5) "Film Thickness and Chemical Processing Effects on the Stability of CdTe Solar Cells," D.S. Albin, S.H. Demtsu, and T.J. McMahon, Thin Solid Films **515**, 2659-2668 (2006).
(6) "Effective Efficiency and Performance Ratio as Energy Rating System for PV Modules," M. Topič, K. Brecl, J. Kurnik, and J. Sites, Proc. E-PVSEC **21**, 2507-2510 (2006). [Also received best poster award in the PV Modules and Components of PV Systems area].
(7) "Hole Current Impedance and Electron Current Enhancement by Back Barriers in CdTe Thin-Film Solar Cells," J. Pan, M. Gloeckler, and J.R. Sites, J. Appl. Phys. **100** (2006).
(8) "High Efficiency Thin-Film CIGS Photovoltaic Cells Using a CdZnS Buffer Layer," R.N. Bhattacharya, M.A. Contreras, B. Egaas, R.N. Noufi, A. Kanevce, and J.R. Sites, Appl. Phys. Lett., in press.
(9) "Strategies to Increase CdTe Solar-Cell Voltage," James Sites and Jun Pan, Thin Solid Films, in press.

Sincerely,

James R. Sites
Professor

Cc: NREL Subcontracts
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