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Bolko von Rodern
National Center for Photovoltaics
National Renewable Energy Laboratory
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RE: Quarterly Report IX (February - April 2007)
"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, much of the work summarized below was presented at the Spring Materials Research Society (MRS) meeting in San Francisco. In addition, I gave a talk on thin-film solar cells to a fairly large group at Ball Aerospace in Boulder and a poster presentation at the Solar Energy Technical Program Review in Denver.

CIGS Nonuniformities. Ana Kanevce's MRS talk was entitled, "Impact of nonuniformities on thin $Cu(In,Ga)Se_2$ solar cell performance." She showed the extent to which submicron CIGS devices should be more sensitive to thickness fluctuations than thick ones. Roughness of 100-nm, for example, should lower the efficiency of a 250-nm cell more than 2%, but a 1-μm cell less than 0.2%. Although thinner cells generally have lower lifetimes, they are less sensitive to lifetime variations then the thicker ones. Ana also reported Pspice calculations of current-voltage curves when the CIGS cell is divided into a two-dimensional array of small cells. In this configuration, one small cell is replaced by a "weak diode" of reduced V_{OC}, or in other cases, a local shunt resistance is added. The impact of the weak diode on the device performance is linear in its voltage deficit to a first approximation, and the impact of the low-voltage area is logarithmic. Areas less than 10% of the total device area with voltage deficits less than 100 mV decrease the device efficiency less than 1%. A decrease of 100 mV in V_{OC} can result

equally well from 0.1-eV band-gap fluctuations for any device thickness, a 50% thickness fluctuation for a 250-nm thick device, or two orders of magnitude decrease in lifetime. Although the sheet resistance in the TCO can isolate the weak areas and prevent them from dominating the entire device, it also reduces the fill-factor, and the net result is a reduction in efficiency.

CdTe Efficiency. Alan Fahrenbruch's talk at MRS was "Exploring back-contact technology to increase CdS/CdTe solar cell efficiency," which as the title suggests, focused on modifications to the CdTe back-contact to mitigate its role in limiting efficiency. The paper reviews measurements of the back-contact barrier and explains why it is often less than that predicted by the electron-affinity model. It also calculates the effect of back-contact recombination and applies the results to various choices of back contacts. My poster at the Solar Energy Technologies Program review and the paper with Jun Pan, discussed in earlier reports and recently published in Thin Solid Films [Vol 515, pp 6099-6102 (2007)], are more general. They explore two different strategies, referred to as "n-p" and "n-i-p" that each allow the possibility of moving CdTe voltages above 1 volt and efficiencies above 20%.

Light-Bias QE. Tim Nagle's MRS poster presentation, co-authored by Alan Davies and myself, was "Quantum-efficiency measurements to deduce non-ideal solar-cell features." It examined the effects of bias light on both CdTe and CIGS thin-film solar cells with CdS window layers of varying thickness. In general, for QE measurements taken at zero voltage, bias light had only a small effect, which was to photodope the CdS layer and increase the space-charge width in the absorber. The result was slight improvement in collection at long wavelengths. In CdTe with thin CdS, this effect was minimal since the maximum change in the space-charge volume was limited by the volume of the CdS layer. With thick CdS, however, the space-charge width increased appreciably with bias illumination and allowed for improved collection of carriers generated deep in the absorber. In CIGS where the p-type doping in the absorber was high compared with CdTe, the space-charge width was less susceptible to modification by the photodoping effect, even for thick CdS layers.

The QE light-bias measurements and numerical simulation of expected results showed a general trend of improved collection at all wavelengths under white-light illumination compared with collection in the dark. The conclusions were: (1) QE taken in the dark generally underestimates the values under operating conditions, though often by only a small amount. (2) When barriers exist in the conduction band that distort the current-voltage curve, the difference between dark and light-biased QE can be substantial. (3) The band-profile during a QE measurement should be the same as that in an operating device, which may require light absorption in the CdS layer. (4) As a rule-of-thumb, illumination with 5-10% of solar intensity and a solar-like spectrum was generally sufficient for QE measurements that correspond to full-sun illumination.

We have decided that light-bias QE is sufficiently important that we have now added a user-friendly variable-intensity bias light to the QE system. This addition, designed an built by a visiting German undergraduate student Simon Kocur, allows bias illumination from 2 to 40% of full sun in nine steps, plus a neutral-density filter to reduce any of the intensities by a factor of eight.

CdS Thickness Variation. Alan Davies' MRS poster presentation, "All-CSS processing of thin-film CdS/CdTe solar cells with thin CdS layers," was done with with cells fabricated at CSU by Enzenroth, Barth, and Sampath by the in-line, close-space-sublimation (CSS) process. The source temperature control was used to reduce the deposited CdS thickness. QE measurements implied CdS thicknesses that varied over a range from 10 to 250 nm. J-V measurements showed increased J_{sc} as the CdS was thinned. However, the thinnest-CdS cells had a significantly reduced voltage (800 mV with thicker CdS down to 350 mV at 10 nm) and FF, which more than offset gains in J_{sc} and caused efficiencies to drop from 12.6% for thick CdS layers to 4.5% for devices with the thinnest CdS. These performance trends are consistent with calculations that assumed parallel junctions of CdS/CdTe and SnO_2/CdTe. Localized weak-junction formation was characterized by high-resolution laser-beam-induced current (LBIC) mapping. The general LBIC result was that thinner CdS led to larger spatial non-uniformities in photocurrent response. The 638-nm response had a spread of 4.5% for the thin CdS cells compared to variations of less than 1% for devices with thicker CdS. Additionally, the non-uniformities in cells with thin CdS were highly sensitive to voltage biasing, which gave additional evidence for the assumption that the CdS was not participating in the junction formation in all areas.

Collaborative Work. During the past quarter, we made QE, capacitance, and LBIC measurements on several CIGS cells fabricated at FSEC, and we did various characterization measurements on improved-efficiency CIGS cells made by Heliovolt. We have also begun a collaboration with the University of Toledo to study the variations in CdTe cell performance with CdS thickness, similar to the study with CSU cells discussed above.

Sincerely,

James R. Sites
Professor

Cc: NREL Subcontracts
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