Effects of non-uniformity on rollover phenomena in CdS/CdTe solar cells

A. R. Davies and J. R. Sites
Colorado State University, Fort Collins, Colorado 80523

ABSTRACT

The behavior of CdS/CdTe devices with very little Cu in the back-contact was investigated. Though the devices maintain decent voltage (V_{oc} ~760-780 mV), the fill factor suffers (FF ~ 45-50%) due to a secondary curvature in the power quadrant of the J-V plane. Capacitance results indicate full depletion, and laser-beam-induced-photocurrent mapping indicates spatial QE variations of several percent at voltage-bias near that of the initial diode turn-on. Guided by the LBIC results, we have developed an expanded equivalent circuit model to approximate effects of non-uniform back-contact barrier not explained by the traditional two-diode model [1]. PSpice modeling of the new circuit model successfully accounts for the non-standard rollover in the experimental J-V behavior.

INTRODUCTION

The back contact to CdS/CdTe thin-film solar cells continues to be a central issue in device and module processing. The twin goals are reduction of the Schottky barrier height at the CdTe/metal interface and minimal introduction of extraneous impurities into the absorber layer. CdTe is a moderately wide band-gap semiconductor ($E_g \approx$ 1.5 eV) with a large electron affinity (χ = 4.4 eV). Therefore, only a metal with work-function of 5.9 eV or greater should form a purely ohmic contact to CdTe. Due to the lack of such metals, a Schottky barrier is formed when applying a metallic contact directly to CdTe. Several back contact structures have been proposed, most involving an etch of the $CdCl_2$-treated CdTe layer and the introduction of Cu to minimize the distortion in the current-voltage relationship. Post-processing annealing and environmental degradation tend to induce a diffusion of the Cu away from the back contact and into the absorber layer, which may result in a return of the Schottky barrier and a concurrent reduction of V_{oc} [2].

Earlier work [1,3] showed that the back barrier height may often be determined from an experimental J-V curve by ascertaining the current at which the rollover curvature reaches a maximum and assigning this value as the back-contact reverse saturation current. The barrier height is then related to this current by

$$J_{ob} = A^{*}T^{2}\exp(-q\varphi_{b}/kT)\,, \qquad (1)$$

where A^* is the Richardson coefficient, a parameter of the semiconductor material, T is the absolute temperature, and φ_b is the barrier height. The device is then modeled as a series connection of two diodes having opposite polarity, one to represent the main junction, and the other representing the back contact. (referred to below as the "two-diode" model)

EXPERIMENTAL DETAILS

For this study, devices were fabricated in the pilot-scale deposition system in the Mechanical Engineering Laboratory at Colorado State University. Details of the deposition system are given elsewhere [4]. The relevant feature for this study is the two-stage method of Cu inclusion for the back-contact. With one of the Cu sources removed, the deposition of Cu is expected to be significantly less than optimum for mitigation of the contact-barrier effect [5]. We have characterized CdS/CdTe devices with reduced Cu using capacitance, current-voltage, and laser-beam-induced-current (LBIC) measurements.

The behavior of the Cu-deficient device is compared and contrasted with equivalent circuit results generated from a two-diode model as described above.

RESULTS AND DISCUSSION

Capacitance-voltage results are given in Fig. 1. The nearly constant capacitance in reverse and moderate forward bias is common in MIS structures. A typical interpretation of this result is that the weakly doped absorber layer becomes fully depleted of free carriers, and thus behaves as an insulator with essentially constant built-in electric field between the metal back contact and strongly doped n-type window layer.

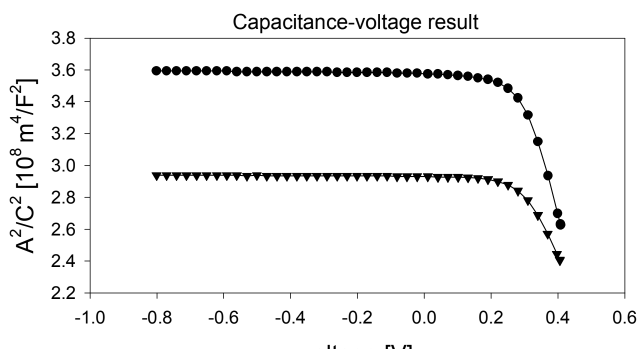

Figure 1. Capacitance results indicate that the experimental device is fully-depleted even under moderate forward bias conditions.

A comparison of J-V data from a simulation of the two-diode model and an experimental result of a Cu-deficient CdTe device is given in figure 2.

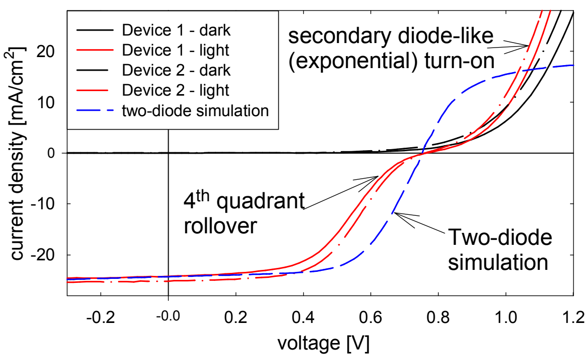

Figure 2. J-V data for a simulated high-barrier device (blue curve) and experimental cases with non-standard rollover (red).

As indicated in the plots, there are two prominent differences in the light curves. The simulated J-V curve shows rollover at about 13 mA/cm^2 ($\varphi_b \approx$ 0.45 eV) and the forward current behavior is dominated by the parallel shunt conductance of the back contact. Both of these behaviors are consistent with the model presented in [2] and investigated in detail in [3]. However, for the experimental data, the rollover occurs in the power quadrant, implying an unphysical negative saturation current if the theory of Eq. 1 is applied. In addition, at higher voltages, there is a second region of exponential current growth. According to the two-diode model, voltage bias beyond the point where the forward current is limited drops across the back-contact as reverse bias [6]. Further growth of forward current greater than that allowed by the shunt conductance of the back contact is therefore prohibited.

Figure 3 shows the results from LBIC characterization of the experimental device from figure 1. At the zero-bias point the photocurrent collection is uniform. This implies that for the penetration depth of the laser light, the junction field is strong enough to effectively collect all the absorbed carriers. However, in the voltage range of the rollover onset, the LBIC response has developed substantial variation, particularly near the edges. In forward bias, the depth of the space charge region is reduced, and for the scan shown, the reduction is enough to reduce collection. One explanation is that the areas of reduced collection arise from regions where the main junction has been weakened such that its V_{oc} is lower than that of the overall device and especially of the center area of the cell.

NON-UNIFORMITY MODEL

From the characterization results and the details of the device fabrication, two likely sources of non-uniform collection are identified. Both hinge on the condition of full-depletion as was observed from capacitance. First, if the incorporation of Cu varies from position to position, then the effective height of the contact barrier varies accordingly.

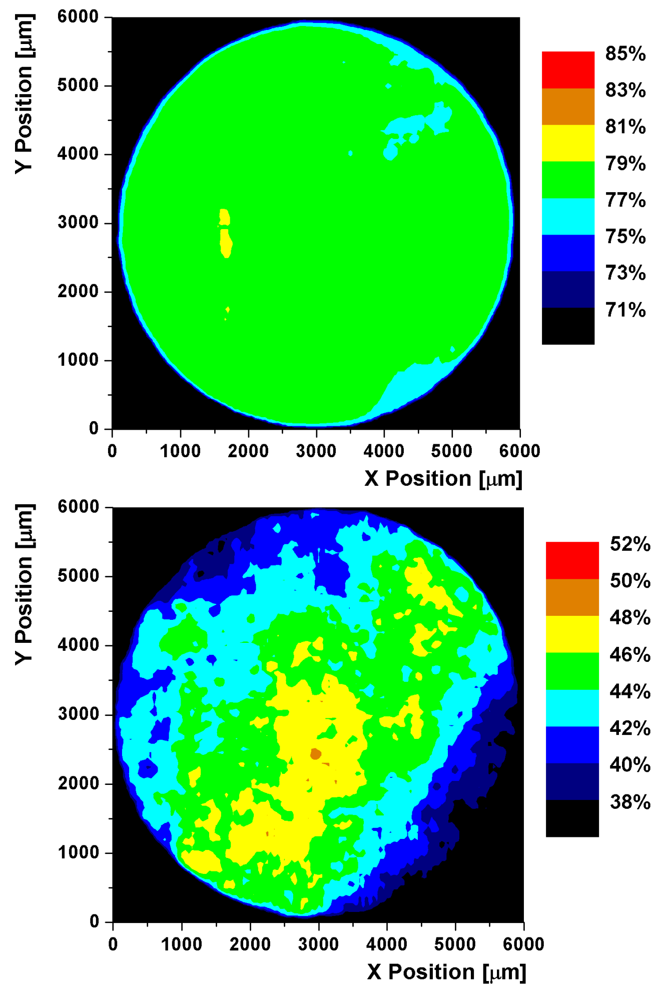

Figure 3. LBIC data for the device of figure 1 at zero-bias (top) and +535 mV (bottom).

A locally high contact barrier is expected to result in locally reduced voltage and fill-factor due to the reduction in potential difference from front to back of the absorber layer and consequent earlier onset of the flat-band condition. Furthermore if variations in absorber thickness arise because of the layer roughness, V_{oc} is reduced due to an enhancement in the minority electron current, encouraging earlier diode turn-on as explained in [7]. In the device under consideration here, a combination of both effects is likely.

We propose that the unexplained rollover feature in the J-V behavior from figure 2 is related to the non-uniformities observed in figure 3. The likely sources of those non-uniformities originating with the back-contact were summarized above. We model the solar cell with a four-diode network as indicated in figure 4. The “strong branch” consists of a high-voltage diode and a DC current source to represent the light-generated current, in series with a low-barrier back contact. This portion of the circuit taken alone generates a well-behaved J-V curve. The “weak branch” consists of a low-voltage main-junction diode and a high barrier reverse-polarity diode to represent the blocking contact. By itself, this portion of the circuit has a low voltage, and first-quadrant rollover.

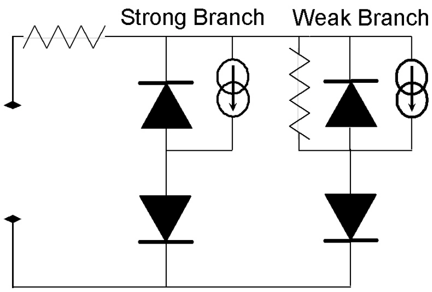

Figure 4. Equivalent circuit schematic of a non-uniform device with a non-uniform back contact barrier.

The total circuit current is the sum of the current from the two branches and the simulation result is shown in fig. 5.

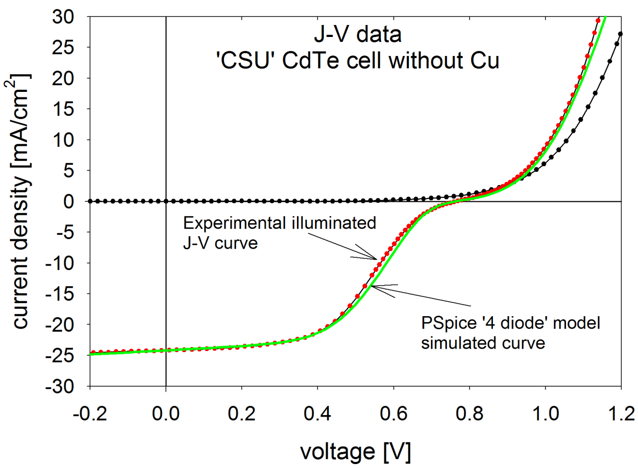

Figure 5. J-V characteristic and non-uniform equivalent circuit fit for a CdTe device with variable back-barrier influence.

The equivalent circuit model gives a good fit to the experimental J-V assuming 40% of the cell area having $V_{oc(weak)}$ = 450 mV, and barrier height of 0.425 eV in the weak branch.

Physically, it is quite plausible that the edge areas seen in LBIC to have weak collection correspond to areas where environmental stresses—the mechanical process of defining the cell, and moisture ingress at the exposed edge, for example—have induced partial degradation of the back contact layer. The diffusion of Cu away from the back contact has a two-fold effect. First, it leaves behind an insufficient Cu or Cu_xTe layer to mitigate the Schottky barrier. Secondly, interstitial Cu provides a deep donor level in CdTe which, by compensating the absorber material, may locally reduce the built-in potential and hence, V_{oc}. This, in combination with the voltage lowering effects of thickness variations in the depleted absorber, may be sufficient to induce the variations observed in bias-dependent LBIC data, and to induce the non-standard distortion observed in the J-V curve.

CONCLUSIONS

Two aspects of experimental J-V curves for some CdTe cells are attributed to non-uniformities in the back-barrier and the main diode junction. Current blocking in the power quadrant of the J-V curve and a secondary exponential “turn-on” in the first quadrant are postulated to be due to the shared influence of defective areas of the cell—which exhibit both a low main-junction voltage, and a high contact barrier—with well-behaved areas. A new solar cell equivalent-circuit model is proposed which reproduces the experimental J-V curves by assuming non-uniformity, consistent with that observed in LBIC data.

Acknowledgement:
The research reported here was supported by the National Renewable Energy Laboratory. The authors are grateful for the samples provided by Prof. W. Sampath’s research group.

References:

[1] G. Stollwerck and J. Sites, “Analysis of CdTe back-contact barriers”, *Proc. 13th European Photovoltaic Sol. Energy Conf.*, 1995, pp. 2020-2022.

[2] C. Corwine, A. O. Pudov, M. Gloeckler, S. H. Demtsu and J. R. Sites, *Solar Energy Matierials and Solar Cells*, **82**, 481-489 (2004).

[3] S. H. Demtsu, PhD thesis, Colorado State University, 2006.

[4] K. Barth et al., “Advances in continuous, in-line processing of stable CdS/CdTe devices”, *Twenty-ninth IEEE PVSC*, 2002, pp. 551-554.

[5] A. O. Pudov et al., “Effect of back-contact copper concentration on CdTe cell operation”, *Twenty-ninth IEEE PVSC*, 2002, pp. 760-763.

[6] A. Niemegeers and M. Burgelman, *Journal of Appied Physics* **81**, 1997, pp. 2881.

[7] J. Pan et al., “Hole-current impedance and electron-current enhancement by back-contact barriers in CdTe thin film solar cells”, *Journal of Applied Physics* **100**, 2006, pp. 124505 (6 pp).