EFFECT OF BACK-CONTACT COPPER CONCENTRATION ON CdTe CELL OPERATION

A.O. Pudov, M. Gloeckler, S.H. Demtsu, and J.R. Sites, Department of Physics
K.L. Barth, R.A. Enzenroth, and W.S. Sampath, Department of Mechanical Engineering
Colorado State University, Ft. Collins, CO 80523

ABSTRACT

CdTe solar cells were fabricated with five different concentrations of copper, including zero, used in back-contact formation. Room-temperature J-V curves showed progressive deterioration in fill factor with reduced copper. J_{SC} and QE were similar for all Cu-levels. Capacitance measurement suggested enhanced intermixing at the back contact with copper present. Photocurrent mapping was much less uniform for reduced-Cu cells. Elevated-temperature stress induced very little change in J-V when sufficient Cu was used in the contact.

INTRODUCTION

Copper is commonly used to form low-barrier contacts to p-type CdTe absorbers. Copper, however, is a fast diffuser, and there are continuing concerns about the long-term stability of such cells. Previous work with NREL-fabricated CdTe cells showed that both the initial properties and changes with elevated temperatures were a function of the amount of copper used [1].

Five sets of CdTe cells, nominally identical except for the back contact, were fabricated at Colorado State University (CSU) using pilot-scale in-line processing [2]. To form the back contact to the CdTe absorber, a copper-containing material was deposited, followed by an anneal and the application of a carbon paste. The deposition times for the copper material were 0, 0.5, 1, 2, and 4 min. Two minutes, which adds the equivalent of 20 Å of copper, is the standard deposition time for the CSU back contacts. A common $CdCl_2$ treatment was used for all cells. Three cells with each copper concentration were measured in depth.

MEASUREMENTS

Initial

Fig. 1 compares light (100 mW/cm^2) and dark current-voltage (J-V), quantum efficiency (QE), and capacitance-voltage (plotted as $(A/C)^2$ vs. V, where A is the cell area) curves for the five copper concentrations. Except for the zero-copper set of cells, where only the best one is shown, there was good consistency among the three cells from each set. The better cells, 2- and 4-min Cu, have an efficiency just over 11%. The lower-Cu ones are progressively lower in efficiency, primarily suffering in fill-factor. All of the copper-containing cells displayed reasonable superposition. Data trends similar to Fig. 1 are also seen in CdTe cells with ZnTe:Cu contacts of varying thickness [2].

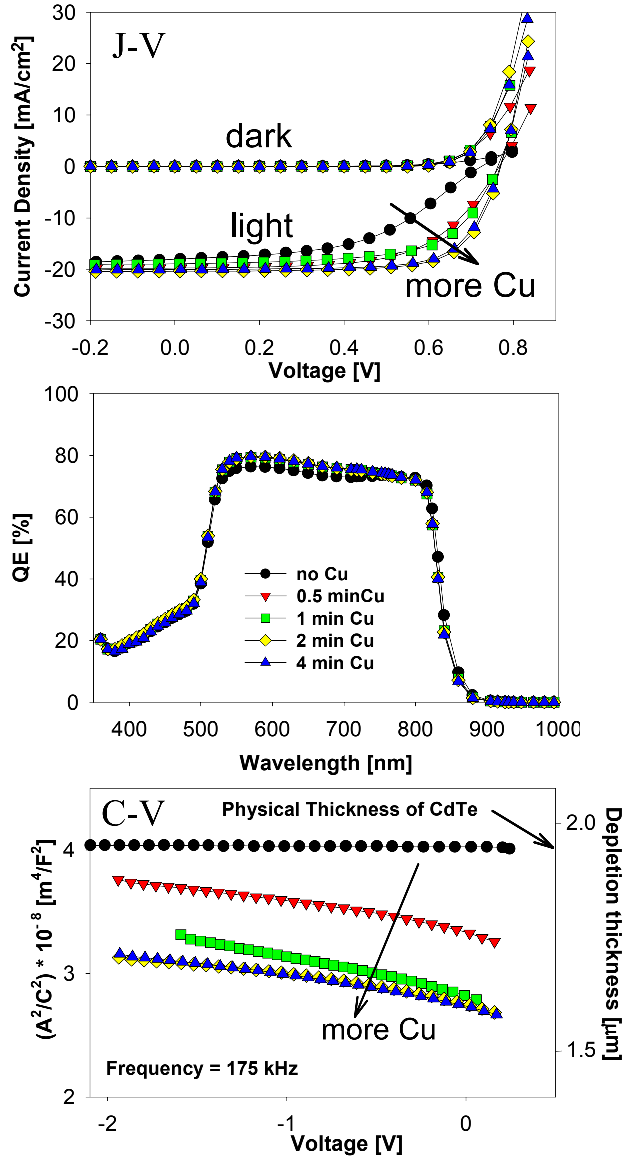

Fig. 1. Initial J-V, QE, and C-V measurements for cells made with five back-contact copper concentrations.

The QE curves in Fig. 1 were nearly identical for all amounts of copper, as one would expect with changes only at the back contact. The capacitance of the zero-Cu cell was independent of voltage, which implies a CdTe layer that is fully depleted (1.9 μm). The variations in capacitance of the cells with finite Cu, for the voltage range shown, are in the CdTe/contact transition region and imply that the transition is less abrupt with Cu present. If the $(A/C)^2$ vs. V curve is extrapolated to zero (infinite capacitance) at a reasonable built-in potential, its slope implies a CdTe hole density in the mid-10^{14} cm^{-3} range, typical of all CdTe cells measured by the CSU group.

Temperature Variations in J-V

Fig. 2 shows the temperature dependence of the J-V curves for the five Cu concentrations. All of the cells display "rollover" as the temperature is reduced and the back-contact barrier becomes larger compared to kT [4]. The impact on the power quadrant is relatively modest for the larger Cu-concentrations. At the shorter Cu deposition times, however, the impact is greater, which is consistent with a larger barrier when less copper is used. The open-circuit voltages for the four finite-Cu cases shown, when plotted against temperature, extrapolate to approximately 1.5 eV, or very near the band gap of CdTe. The zero-Cu cell data had more scatter, and the extrapolation was not reliable.

Local Variations

The whole-cell results shown in Figs. 1 and 2 are not necessarily uniform over the cells. Photocurrent mapping was used therefore to examine nonuniformities, to check whether nonuniformities varied with the amount of back-contact copper, and to determine their role when the cells were subjected to elevated-temperature stress.

Although the mapping system used has 1-micron resolution [5], the features of interest in the current cells are best seen with a lower resolution. Fig. 3 shows the photocurrent maps of initial QE (before any stress) for cells with Cu-deposition times of 0, 0.5, and 4 min on a 500- by 500-micron field with 10-micron resolution. The absolute calibration of QE in this system is ± 3%, so that the difference between the maps for 4- and 0.5-min Cu should not be considered significant.

The 4-min cell map shows a very uniform current response, as does the 1-min cell map (not shown). The 0.5-min map shows a single low-current feature, but the zero-Cu one shows a spread of about 6% in current response and reduced average QE consistent with Fig. 1.

Elevated-Temperature Stress

The cells with the different back-contact-Cu levels were subjected to elevated-temperature stress (100°C in the light) for progressively extended periods of time. One cell from each set was held at short-circuit and a second at open-circuit.

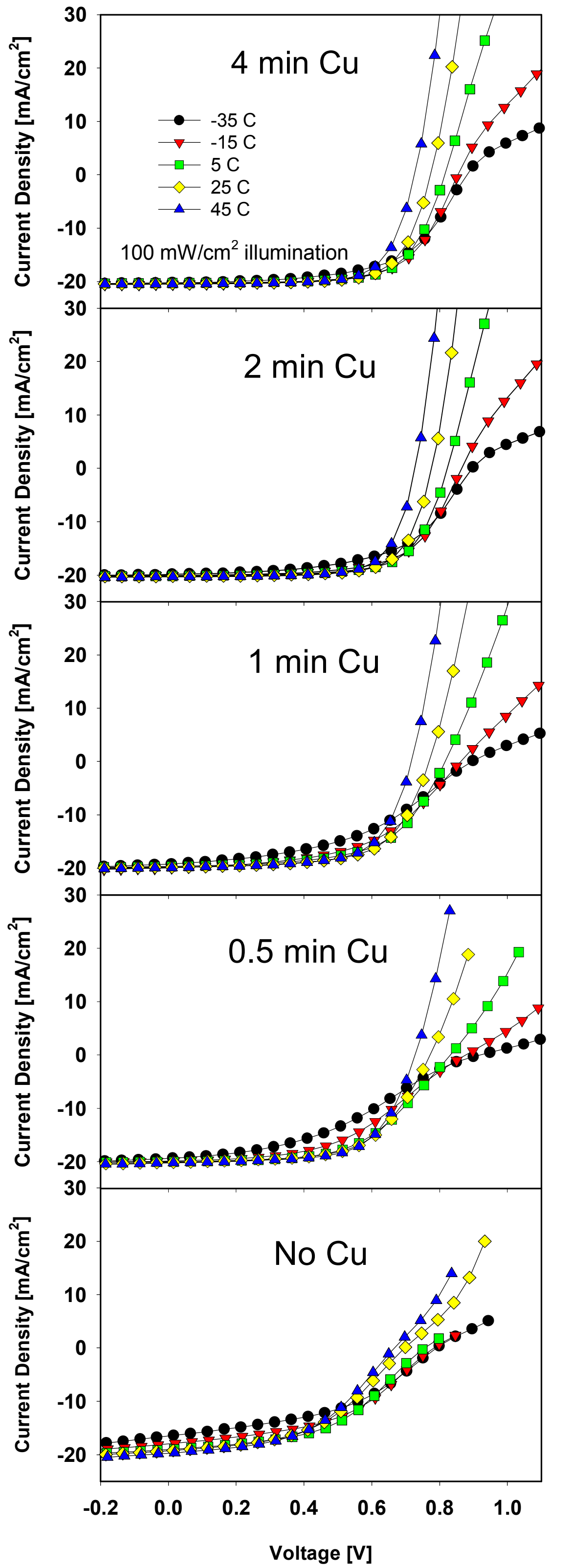

Fig. 2. Temperature dependence (-35 to +25°C) of J-V curves for different copper concentrations.

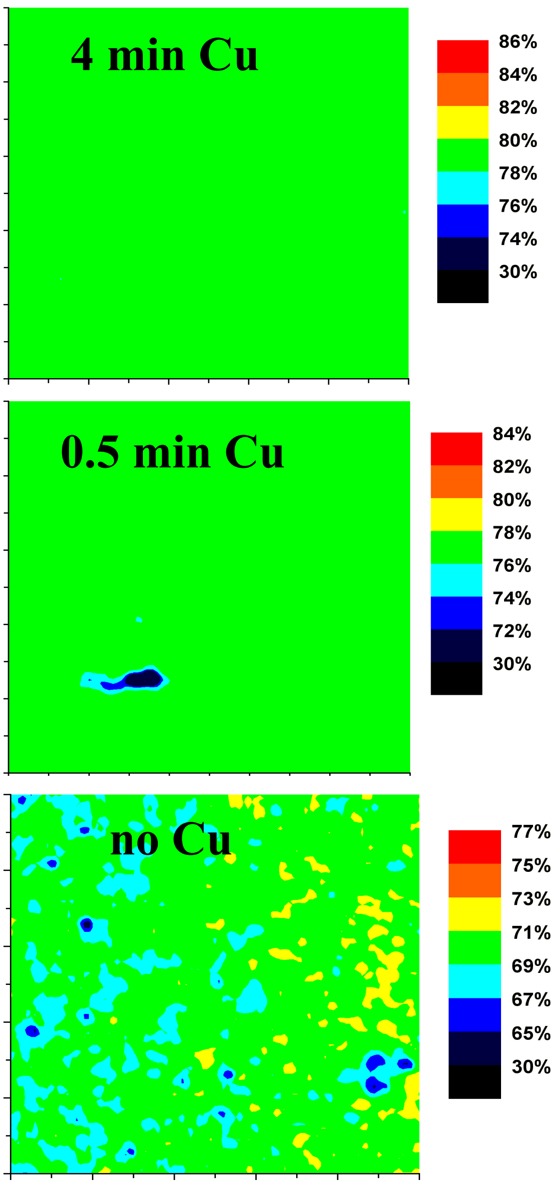

Fig. 3. Initial QE photomaps for three Cu-concentrations. Areas shown are 500x500 μm. Wavelength was 637 nm and local intensity approximately one sun.

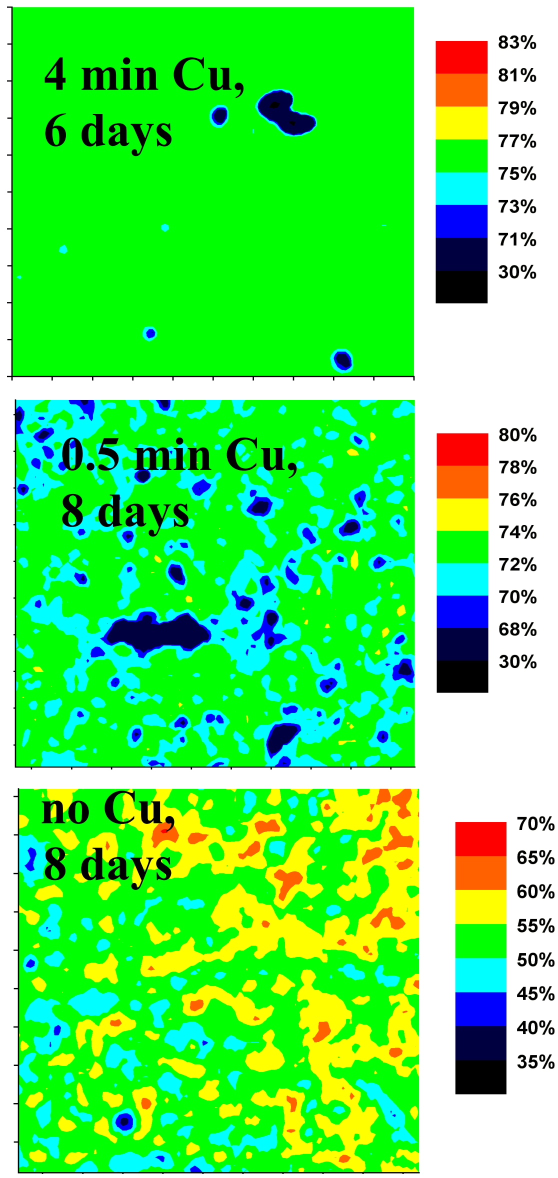

Fig. 4. Photomaps of same areas shown in Fig. 3. after approximately one-week stress at 100ºC in the light at short-circuit. Scale gradations for no Cu increased to 5%.

Fig. 4 shows the same cell areas as Fig. 3 after approximately one-week elevated-temperature stress at short circuit. This stress is equivalent to several years at a typical range of operating temperatures [6]. The high-Cu cell has developed a few local areas of reduced QE, possible related to repeated contacting, but the cell is generally unaffected. The low-Cu cell has become less uniform, and in particular, the initially low-photocurrent feature has become significantly larger. The zero-Cu cell has become much less uniform (note that the scale gradations have changed from 2% to 5%), and the average QE is reduced to about 50%. Thus, the use of copper in a CdTe cell's back contact leads to (1) a superior fill-factor, (2) more uniform photovoltaic response, and (3) much less change in uniformity of response when the cell is subjected to elevated-temperature stress.

The changes in J-V curves with stress time are shown in Fig. 5. The initial curves correspond to the photomaps from Fig. 3. The high-Cu cell showed almost no change in J-V after 50 days of elevated-temperature stress, corresponding to 50-100 yrs in the field. The low-Cu one, however, showed significant changes after a few days, and the zero-Cu one after a few hours. The primary change in the J-V curves is seen in fill-factor, which is consistent with an increase in the diode barrier at the back contact. The voltage changes relatively little, and the current decrease occurs in a major way only when the distortion of the curves becomes extreme. Other cells, which were stressed at open-circuit, changed in a similar fashion to those shown, but the time scale was accelerated by a factor of 3 to 10. This voltage effect, which has been generally observed, can likely be attributed to the lower internal field at higher voltage [6].

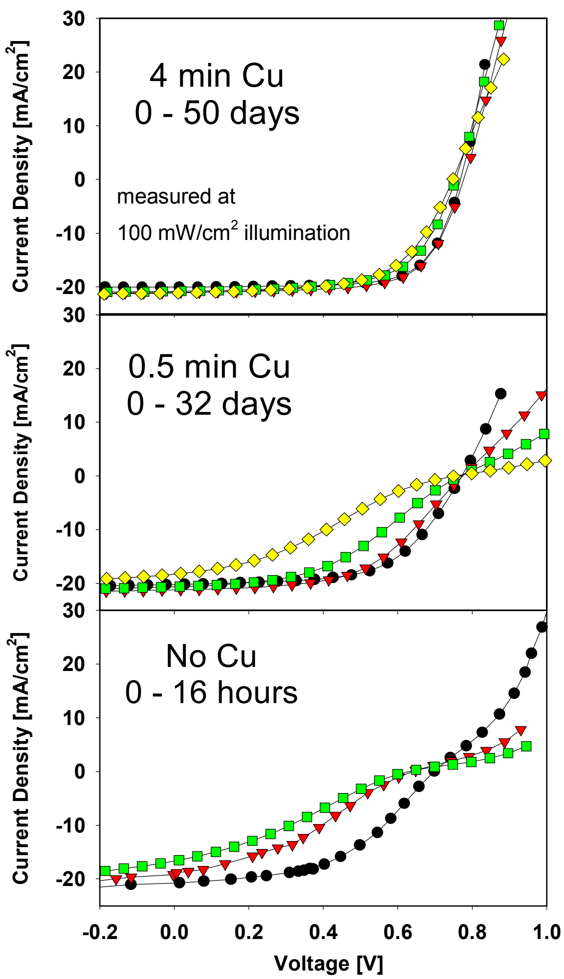

Fig. 5. Changes in J-V curves towards lower fill-factors with illuminated elevated-temperature stress (100°C, short-circuit).

DISCUSSION

The amount of copper used in the formation of back contacts to CdTe cells clearly has a large impact on cell performance and stability. Similar results have now been obtained using three different techniques to introduce the copper, so they should be taken as reasonably general. The primary effect on the J-V curve is a much lower fill-factor when the copper level is low or zero.

Physically, copper in the back-contact region produces a lower-barrier contact junction, though there is continuing discussion whether it does so by heavily doping the CdTe or by forming a physically distinct layer. In practice, there may be a continuum between these possibilities that lead to near-identical cell operation. In any case, the current capacitance results imply that the addition of copper leads to a transition region a few tenths of a micron thick with much larger hole density than the bulk of the CdTe.

The J-V curves change in the direction of the low-Cu curves when the cells are subjected to elevated-temperature stress. Hence, there is a reasonable argument that the primary stress effect is to move copper away from the contact area and reduce its beneficial role in the contact. The performance of both Cu-free as-deposited cells and those subjected to stress varies considerably over the cell area on a distance scale of a few tens of microns. With sufficient copper, however, the time scale before Cu-movement affects performance is long compared to generally accepted product lifetimes.

ACKNOWLEDGEMENTS

The authors are grateful for many constructive discussions within the U.S National CdTe R&D Team. Financial support was provided by the U.S. National Renewable Energy Laboratory under Subcontract ADJ-1-30630-06.

REFERENCES

[1] S.E. Asher et al, "Determination of Cu in CdTe/CdS Devices Before and After Accelerated Stress Testing," *Twenty-eighth IEEE PVSC*, 2000, pp. 479-482.

[2] T.A. Gessert, private communication.

[3] K.L. Barth, R.A. Enzenroth, and W.S. Sampath, "Advances in Continuous, In-Line Processing of Stable CdS/CdTe Devices", this conference.

[4] G. Stollwerck and J.R. Sites, "Analysis of CdTe Back-Contact barriers," *Thirteenth European PVSEC*, 1995, pp. 2020-2023.

[5] J.F. Hiltner and J.R. Sites, "High-Resolution Laser-Stepping Measurements on Polycrystalline Solar Cells," *Sixteenth European PVSEC*, 2000, pp. 630-632.

[6] J.F. Hiltner and J.R. Sites, "Stability of CdTe Solar Cells at Elevated Temperatures: Voltage, Temperature, and Cu Dependence," *AIP Conf. Series* 462 (1998) pp.170-175.