

Development of New Techniques of CdS/CdTe Solar Cell Enhancement

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Recent progress included improvement of solar-cell efficiency, comparison of cells made with key fabrication variations, documentation of temperature dependence and carrier density, and construction of a functional minimodule of 24 connected solar cells. Much of the progress has been due to the close collaborative nature of the project, where the fabrication skills at Moldova State University (MSU) have been combined with the measurement and analysis expertise at Colorado State University (CSU). The picture below shows faculty members Sites and Potlog, along with PhD student Alex Pudov, making measurements in Colorado.



Jim Sites (CSU), Tamara Potlog (MSU), and Alex Pudov (CSU).

A total of 21 CdTe cells have been recently evaluated in detail. The current-voltage curve for the highest efficiency cell is shown below in Fig.1, along with the best cell made early in the project and a high-quality cell from First Solar, LLC, the leading manufacturer of CdTe solar cells in the U.S. The latter is target result for the work at MSU.

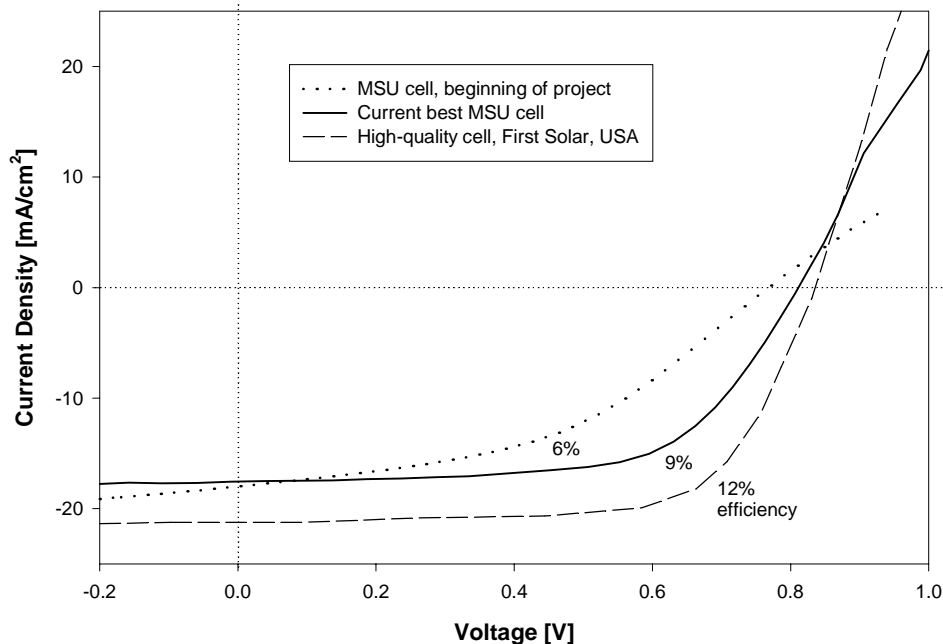


Figure 1. Comparison of highest-efficiency MSU cell with earlier cell and manufacturing target.

During the past year, the primary improvement has been in the fill-factor of the cells, which is due to a more ohmic back contact resulting from a pure tellurium layer at the back of the CdTe. There has also been a small increase in voltage. To equal the efficiency of the U.S. manufacturer's

cell, which is made by a similar deposition process, there needs to be further improvement in the back contact. More importantly, however, the current density needs to be increased. The loss that needs to be addressed occurs for short wavelengths, as can be seen in Fig. 2, which compares the quantum efficiencies of four Moldovan cells with a high-current U.S. cell.

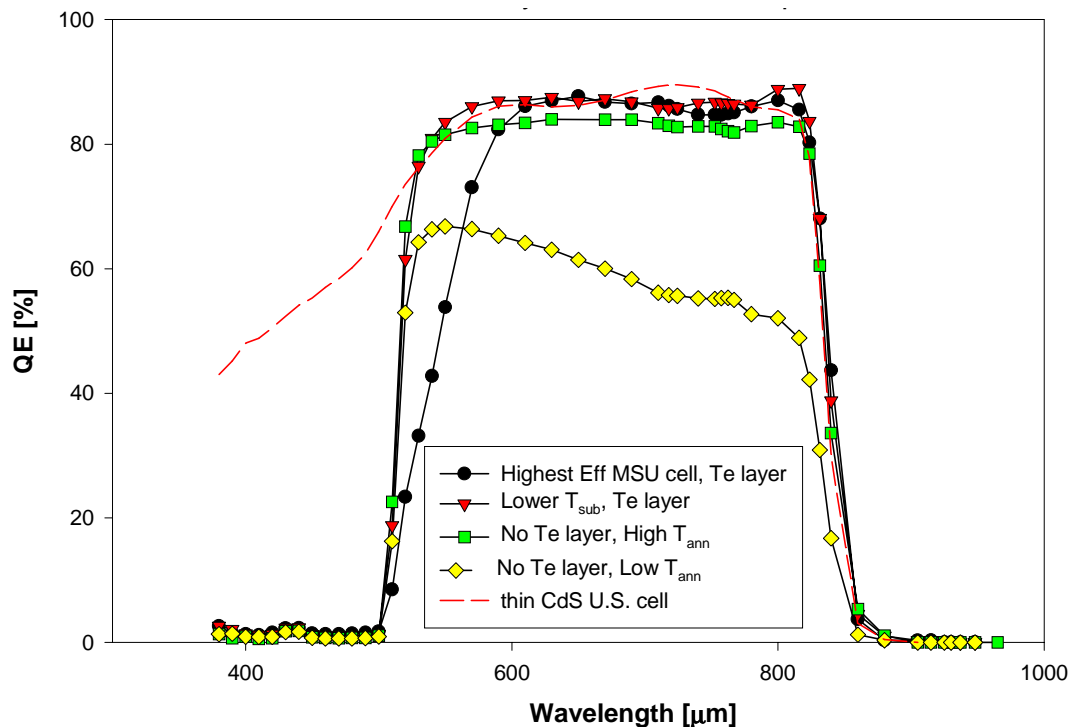


Figure 2. Quantum-efficiency comparison of four MSU-fabricated cells and one thin-CdS cell.

The quantum efficiency (QE) for three of the MSU cells is reasonably good for wavelengths between the band gap of the CdS window layer (510 nm) and that of the CdTe (845 nm). The primary loss over this range is the reflection of the cell. The highest-efficiency cell in this group has the most gradual transition between 500 and 600 nm, which is characteristic of intermixing between the CdTe and CdS layers. A second cell, deposited at a lower substrate temperature, has less intermixing. Two cells made without the Te layer are more sensitive to post-deposition annealing, and the one annealed at too low a temperature had a distinctly lower QE at all wavelengths. Below 510 nm the current generation of all the MSU cells is negligible. The U.S. cell shown for comparison has partially solved that problem by using a much thinner CdS layer. The result is that its current density is about 20% larger. Clearly a goal of the MSU/CSU collaboration needs to be good cells with thinner CdS.

The current-voltage (J-V) curves for the same four Moldovan cells from Fig. 2 are shown below in Fig. 3. The curve for the cell made without the Te layer and with insufficient air-anneal (diamonds) is quite washed out and has a reduced current corresponding to the low QE shown above. The other cell made without the Te layer (squares), but more successfully annealed, is clearly superior, but it also shows “rollover” at higher voltages, which is characteristic of a non-ohmic back contact. The use of the Te layer to improve the back contact (circles) was successful in this respect. However, when an otherwise identical cell was deposited at a lower substrate temperature (triangles), the voltage was reduced and the series resistance was increased.

Temperature dependent measurements often reveal additional information about solar cell operation. Fig. 4 shows the temperature dependence of J-V for two cells. The one on the left was fabricated with the additional Te layer before the metallic back contact, and the one on the right without the additional Te. In both cases, the cell’s open-circuit voltage increased at reduced

temperatures at the expected rate of approximately $-2 \text{ mV}/^\circ\text{C}$. In both cases also, current flow becomes more limited as temperature is reduced. The mechanism for current limitation in the two cases, however, is clearly different. With the Te layer, as noted above, the curves are quite linear, at higher voltages. Without the tellurium, they show the characteristic “rollover” behavior, which becomes more pronounced as temperature is reduced. The conclusion is that the Te is acting favorably to reduce the back-contact barrier. Again the highest-efficiency cell, the one highlighted in Figs. 1 and 3, was fabricated with that Te layer.

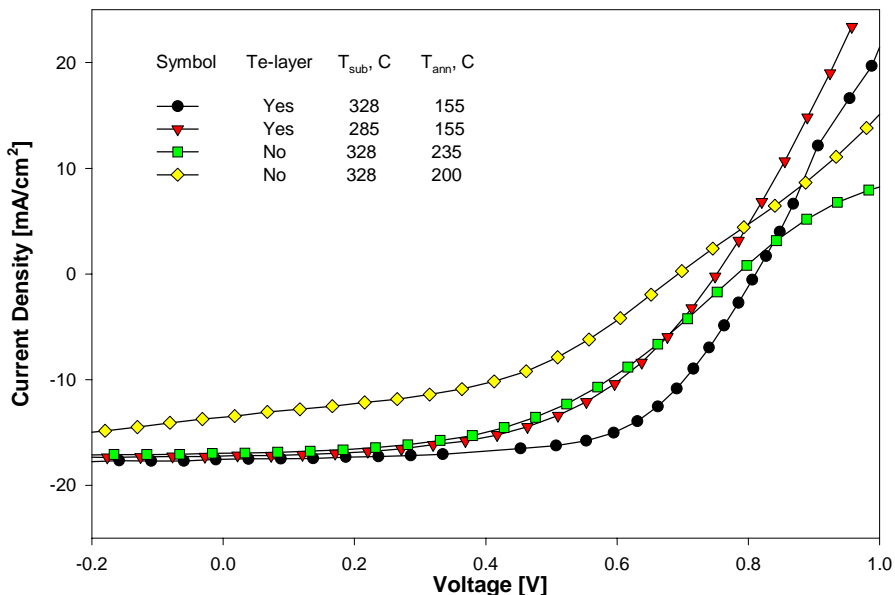


Figure 3. Current-voltage curves for same Moldovan cells as Fig. 2.

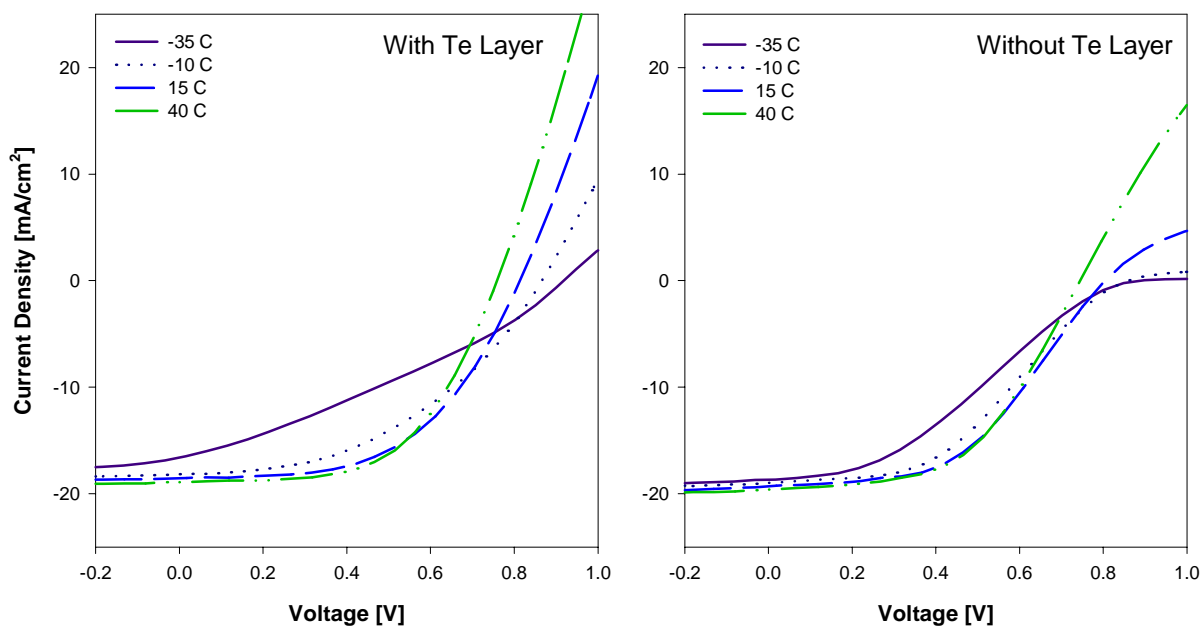


Figure 4. Temperature dependence of cells with and without Te prior to back-contact deposition.

Capacitance, as illustrated in Fig. 5 for one CdTe cell, has also been measured as a function of temperature. Analysis of the capacitance vs. voltage (C-V) can be used to determine the hole density of the CdTe absorber. All of the Moldovan cells showed a hole density in the low 10^{14} cm^{-3} range, which is consistent with CdTe cells made elsewhere. Fig. 5 shows that C^{-2} vs. V is larger at lower temperatures, which means that the capacitance and the hole density, also as expected, are smaller. The inset shows that temperature dependence.

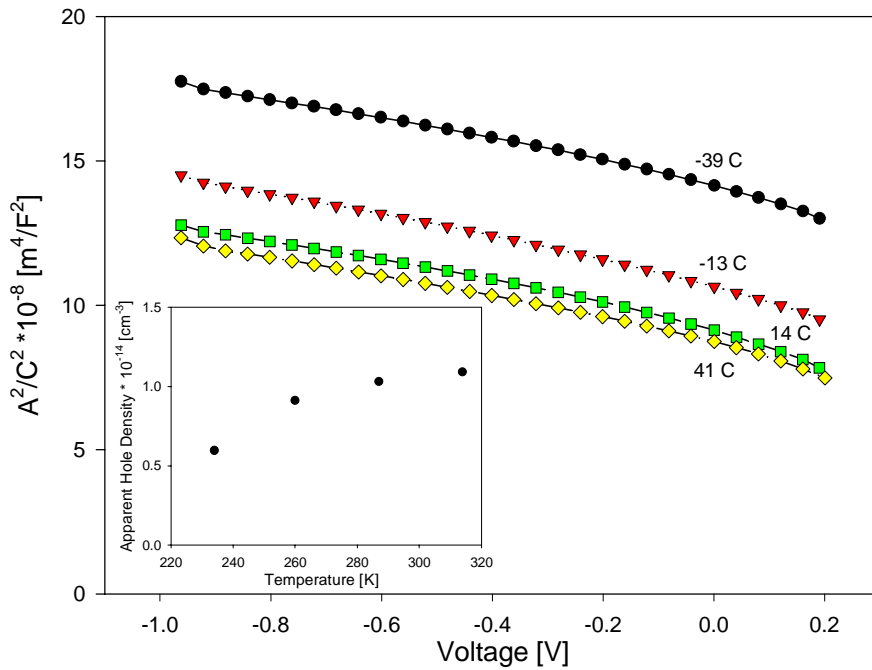
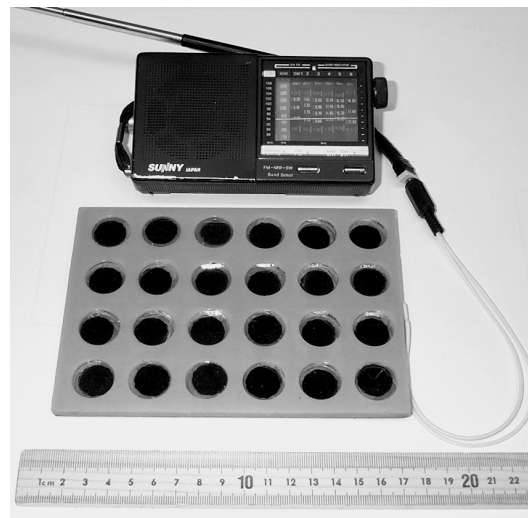


Figure 5. Capacitance as a function of temperature, and the resulting hole densities.

In addition to fabricating individual CdTe solar cells, the group at MSU has constructed an array of 24 connected cells, which we refer to as a minimodule. It produces about 0.3 watt of power, which is sufficient for the small radio shown.



Made-in-Moldova CdTe Minimodule

Publication and Presentation. In addition to the joint manuscript previously submitted to the journal *Solar Energy Materials and Solar Cells*, a MSU-CSU abstract entitled “Photovoltaic Properties of CdS/CdTe Solar Cells as a Function of Processing Parameters” has been submitted for presentation at the ISES Solar World Conference to be held in Sweden in June.

Next Steps. We plan to complete the measurements on the solar cells described above. One measurement such measurement that we have not yet made is to contrast the spatial response of the cells with and without the Te back-contact layer. The objective is to see whether the Te layer assists the solar cell uniformly, or whether its effect is to improve local area of weaker photovoltaic response. We also plan to deposit a proven U.S. back contact on the Moldovan deposited CdS/CdTe to see whether such a contact makes a significant difference in cell performance. More generally, we will be exploring ways to continue the collaborative effort, which has shown considerable success to date.