# Micron-Resolution Photocurrent of CdTe Solar Cells Using Multiple Wavelengths

**Jason F. Hiltner**[1] **and James R. Sites**
Department of Physics, Colorado State University
Fort Collins, CO 80523-1875
[1]current address: Corning Inc., Sullivan Park Research Center, Corning, NY 14831

## ABSTRACT

An apparatus developed recently at Colorado State University utilizes a diffraction-limited optics system and a high-resolution translation system to measure the laser-induced photocurrent at resolutions of 1 μm and equivalent incident laser intensities of 1 sun (100 mW/cm$^2$). Multiple lasers in the 635-830 nm range can be easily selected by changing the fiber-optic connectors. The spot profile and location are unchanged when different lasers are selected. In addition, a laser temperature tuned through the 825-857 nm range allows measurement of local variations in the quantum efficiency near the CdTe band gap, which track intermixing of CdS/CdTe. This capability extends the previous analysis, which includes the separation of series resistance and shunting effects. The effect of post-deposition processing and elevated temperature stress on local variations in electrical and optical parameters, especially using the near-bandgap wavelengths, are examined using a series of samples fabricated at NREL.

## INTRODUCTION

Polycrystalline thin-film solar cells are poised to provide power to terrestrial markets in the near future. The use of these materials necessitates uniformity considerations not generally employed in single-crystalline material. Investigation of the spatial uniformity of photocurrent collection has recently been aided by the development of an apparatus which features micron spatial resolution with near-solar incident intensities. The details of this technique are available elsewhere [1,2,3]. Observations provided by the instrument include the overall uniformity of collection, as well as more detailed characterization of the cause of local reductions in response. A recent addition to the system allows multiple wavelengths with energies near and slightly below the CdTe band gap (1.5 eV) to be used. Temperature tuning of a solid state laser allows smooth adjustment of photon wavelengths through the 825-857 nm range, corresponding to photon energies of 1.50-1.45 eV. This addition was stimulated by photoluminescence observations of bandgap lowering in this material system, which has been attributed to diffusion of sulfur from the CdS window layer into the CdTe absorber [4,5,6]. The $CdTe_{1-x}S_x$ system exhibits band-bowing; small amounts of sulfur in CdTe will reduce the bandgap approximately 10 meV/at.%. [7].

## EXPERIMENTAL

The system used in this study (see figure 1) utilizes a laser beam focused by a microscope objective onto the sample, with the light incident perpendicular to the junction. The laser power density used is controlled to be very near solar densities, so that generation of electron-hole pairs takes place under conditions similar to standard operation of the solar cell. The collected

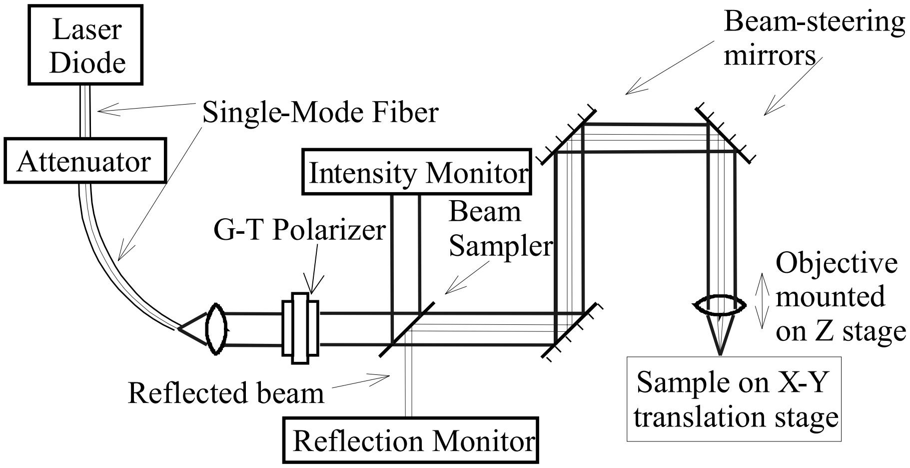

**Figure 1.** Schematic of experiment.

photocurrent scaled to the incident power at each position of laser-beam incidence on the device then represents the local apparent quantum efficiency (AQE) of the region. By translating the device under the laser beam, a map of the local AQE can be generated. Typically, 100, 10, and 1 µm laser spot sizes are used to map areas of 5×5 mm, 500×500 µm, and 50×50 µm, respectively.

Since data over the same region on the cell will be presented at various wavelengths, it should be noted that the position and shape of the focused beam does not vary significantly with wavelength. This is illustrated in figure 2, which shows the power through a 5 micron pinhole for two lasers. That the size and inferred position of the center of the pinhole do not change indicates

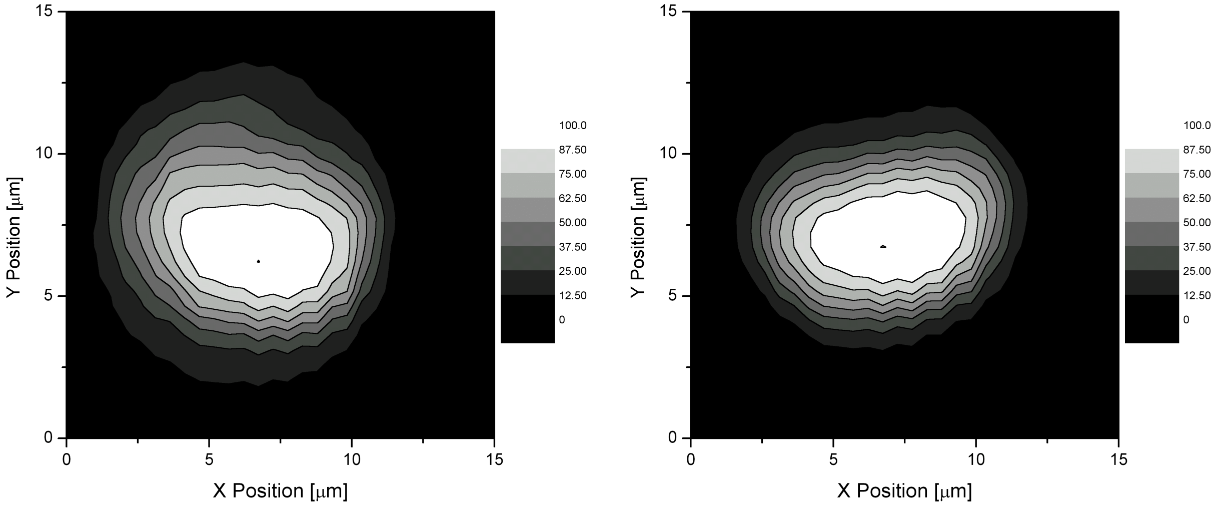

**Figure 2.** Normalized laser power through a 5 micron pinhole for two lasers, illustrating the independence of the spot size and position on wavelength.

that the shape and size of the focused beam does not depend strongly on wavelength. Other lasers show similar behavior.

The solar cells included in this work are standard polycrystalline thin-film CdS/CdTe structures fabricated at the National Renewable Energy Laboratory (NREL). In one case, the post-CdTe-deposition $CdCl_2$ treatment typically used to improve performance was omitted. In addition, the device treated with $CdCl_2$ was subjected to elevated-temperature stress for 10 days. The stress conditions were 100 °C, under illumination, with the cell at open circuit. The effect of this type of stress on CdTe solar cells has been documented in some detail [8,9]. Comparison of the same areas on the cell before and after stress (to within ±1 μm) then shows local effects of stress on the device response. Data at multiple resolutions and with multiple wavelengths was taken on the devices with and without $CdCl_2$, while comparison of the local response of identical areas on the $CdCl_2$-treated cell was also performed before and after stress.

## RESULTS

The spatially-dependent response to above-bandgap photon energies for a GaAs cell and NREL CdTe cells with and without the $CdCl_2$ treatment is shown in figure 3. The plots show the AQE over a 50×10 μm area, and are color-coded in a consistent format with respect to variations from the mean value. The figure shows that the $CdCl_2$ treatment dramatically improves the uniformity of response for photon energies above the CdTe bandgap.

Another way to present the variation in response is to calculate the maximal variation over the entire area shown. Scaled to the mean response and repeated at multiple wavelengths, one obtains the wavelength dependence of variation in response. Figure 4 again shows that

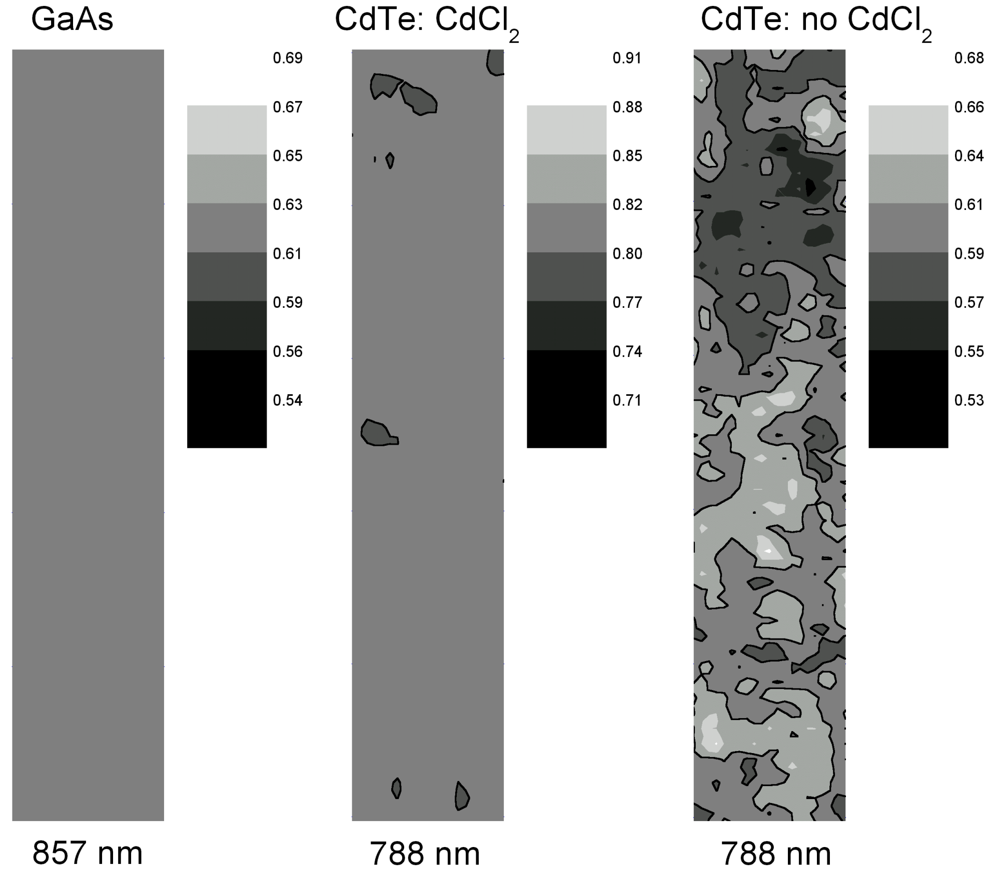

**Figure 3.** Response to above-bandgap photon energies for three cells, illustrating the relative uniformity of response over a 50×10 μm area.

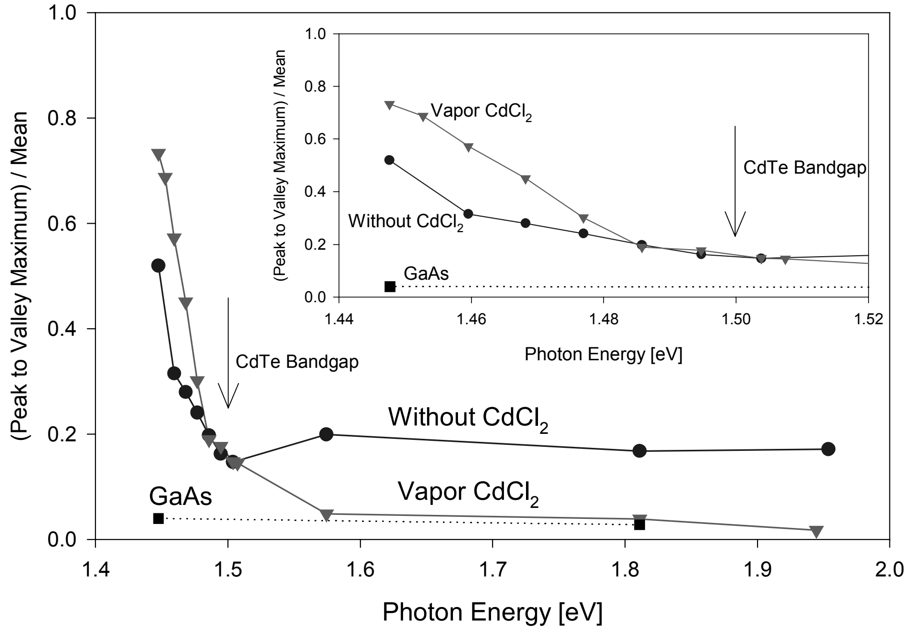

**Figure 4.** Variation in collected current over a 50×10 μm area for various photon energies.

the GaAs cell exhibits very little variation in response (as expected for a single-crystal material), and that the CdTe cell not treated with $CdCl_2$ shows the largest variation for above-bandgap photon energies. However, when photon energies slightly below the CdTe band gap are used, variations in response are largest for the $CdCl_2$-treated cell.

The wavelength dependence of response for photon energies near and below the CdTe band gap is shown explicitly in figure 5, which shows islands of enhanced response developing

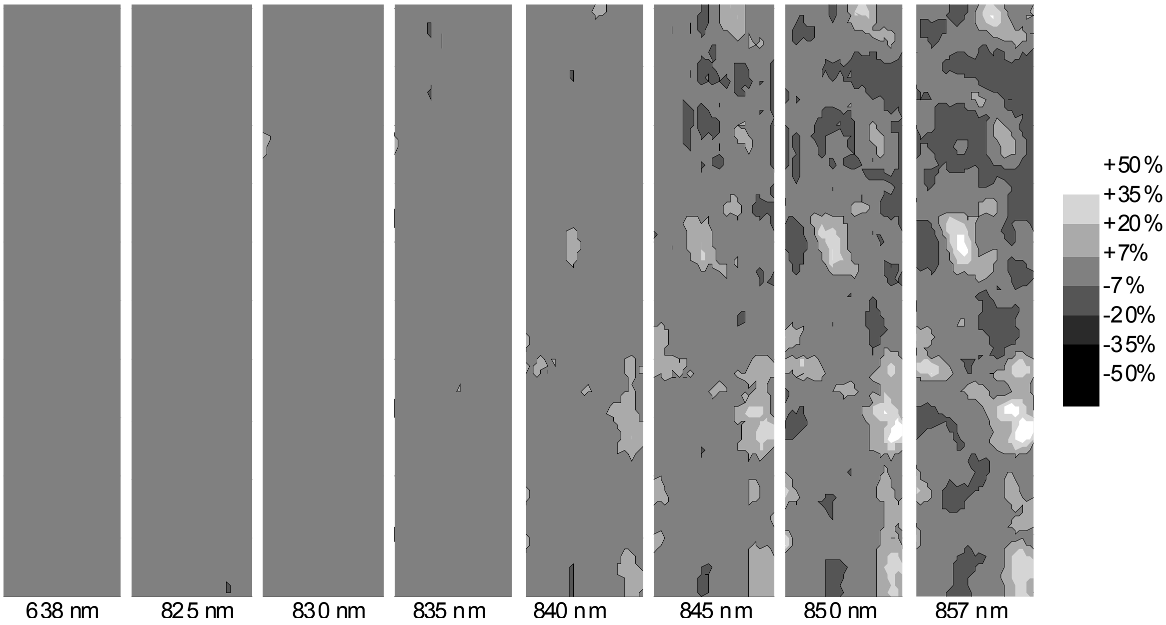

**Figure 5.** Response over a 50 × 10 μm area on the $CdCl_2$ treated cell with multiple wavelengths as labeled. The contrast in each case is consistent with the variation from the mean value. Identical conditions were used for each set of data: 1 micron spot, 1 sun.

as the photon energy is decreased below the pure-CdTe band gap near 835 nm. The larger AQE is almost certainly due to the presence of the lower-bandgap alloy $CdTe_{1-x}S_x$, as mentioned above. A small local increase in sulfur content results in higher local absorption of photons with energy below the pure-CdTe bandgap. The cell which was not treated with $CdCl_2$ does not show this behavior, strongly suggesting that variations in bandgap are due to the treatment. It follows therefore that $CdCl_2$ penetrates non-uniformly to the CdS/CdTe surface, where it enhances the intermixing of CdS and CdTe. It is also possible that $CdCl_2$ simply aids the penetration of sulfur which is present non-uniformly, due to variations in diffusivity or the presence of high defect density regions.

The response of identical areas on the NREL $CdCl_2$-treated cell device was also mapped before and after 10 days of elevated-temperature stress. The cell exhibited losses in open circuit voltage, fill-factor, and short circuit current as a result of the stress [3]. Figure 6 shows 500 × 100

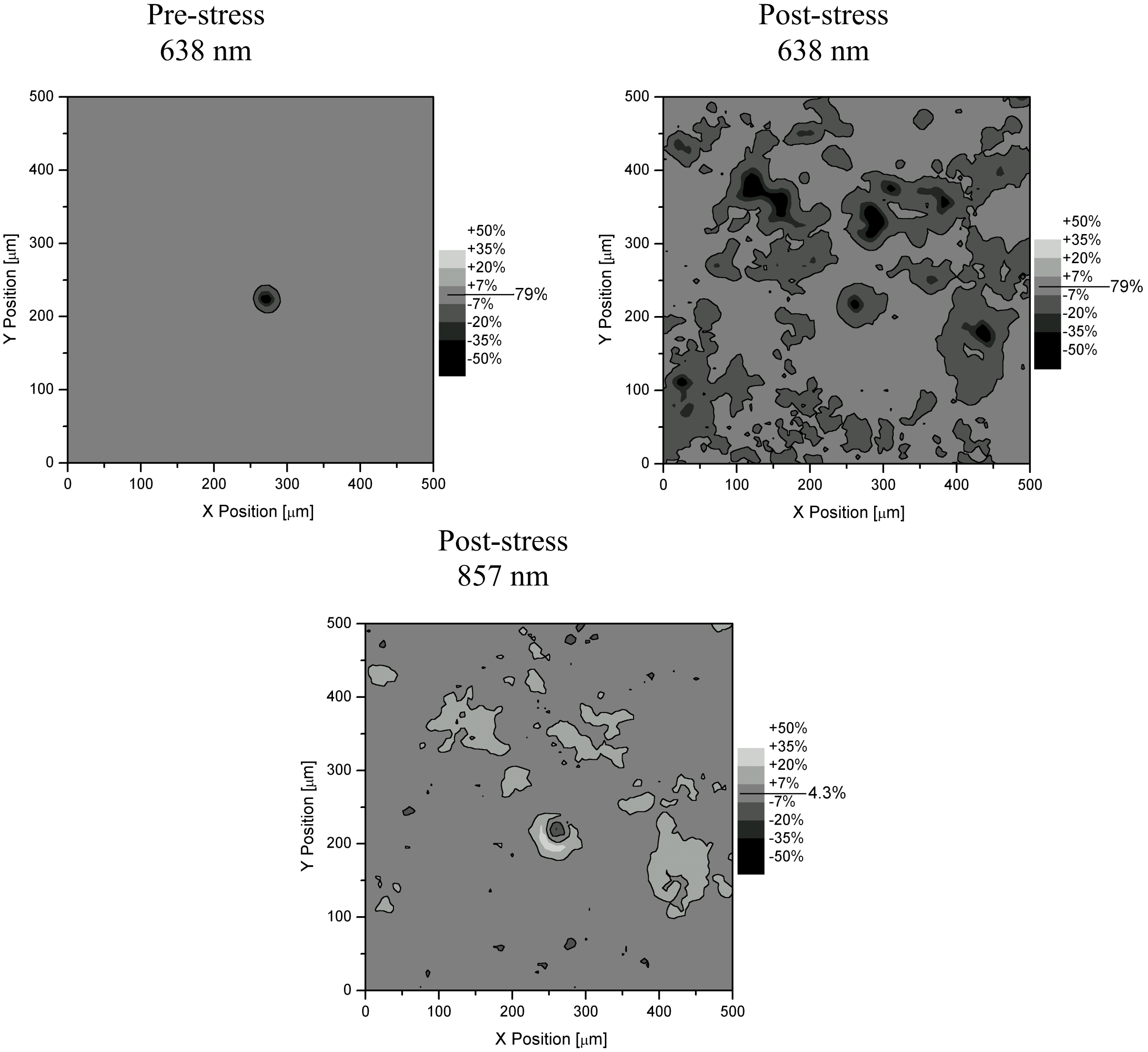

**Figure 6.** Response over a 500 × 500 μm area on the $CdCl_2$ treated cell before and after stress with two wavelengths as labeled. Data was taken in each case with a 10 μm spot at 1 sun illumination.

μm data taken with a 10 μm spot size. Before stress, a single feature is apparent with the 638 nm laser. After stress (top-right graph), the feature is still identifiable, but several additional regions of reduced collection have appeared, indicating that the stress degraded the cell non-uniformly. The response to the 857 nm laser (bottom graph) reveals that regions that degraded after stress also exhibit higher response to sub-CdTe-bandgap photon energy, which again is almost certainly due to the presence of lower-bandgap $CdTe_{1-x}S_x$. These features were not affected by stress. Note also that there is a fairly large area that was unchanged by stress.

## CONCLUSIONS

The effects of the commonly used $CdCl_2$ post-deposition treatment on the spatial uniformity of response has been investigated. The process improves the overall uniformity of response for photon energies above the absorber band gap. The treatment also, however, results in increased spatial variation in the band gap, resulting from formation of the lower band gap $CdTe_{1-x}S_x$ (where $0<x<0.2$). This effect is presumed due either to non-uniform penetration of $CdCl_2$ to the interface, which results in variations in the amount of intermixing at the CdS/CdTe interface, or the possibility that $CdCl_2$ simply acts as a fluxing agent, aiding diffusion of sulfur already present non-uniformly.

In addition, subjecting the $CdCl_2$-treated cell to elevated temperature stress produced local reductions in response preferentially in regions where the decreased band gap, i.e. increased sulfur alloying, was observed. The correlation between variations in band gap and the reductions in collection is likely due to confluence of sulfur and other impurities through fast diffusing regions.

This study represents, to the author's knowledge, the first evidence of spatially non-uniform degradation of CdTe solar cells due to elevated-temperature stress. The results also indicate for the first time that regions which contain the lower bandgap $CdTe_{1-x}S_x$ alloy are preferentially degraded.

## ACKNOWLEDGMENTS

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