# Investigation of the Trapping Mechanism for Transient Current-Voltage Behavior In CIGSS-Based Solar Cells

Pamela K. Johnson[1], James R. Sites[1]and Dale E. Tarrant[2]
[1]Colorado State University, Fort Collins, CO 80523, U.S.A.
[2]Siemens Solar Industries, Camarillo, CA 93012, U.S.A.

## ABSTRACT

Some thin-film CIS photovoltaic devices exhibit reversible transient behavior in their electrical properties induced by modestly elevated (70 - 100 $^{o}$C) temperatures. This paper evaluates changes due to light exposure and applied bias in cells fabricated by Siemens Solar Industries (SSI). When a constant bias was maintained across cells subjected to elevated temperatures in the dark, and subsequent moderate-temperature light exposure, reversible transient behavior was small. When the bias was cycled between zero and open-circuit voltage ($V_{OC}$), independent of illumination, the fill factor (FF) decreased for zero bias and increased at $V_{OC}$. Hence it is the bias rather than photon absorption that drives the transient current-voltage behavior in these cells. Investigations of the relationship between trapping mechanisms and transient behavior using the frequency and temperature dependence of capacitance showed clear cyclic behavior in the trap-response frequency. Trap density profiles were found to be relatively independent of measurement temperature, and the total trap density varied only slightly with the bias cycle.

## INTRODUCTION

As with many thin-film CIS photovoltaic devices, CIGSS absorbers made at Siemens Solar Industries (SSI) exhibit transient changes in electrical properties. The transient behavior exhibited generally improves performance for normal operating conditions [1]. This transient behavior is not an instability, since it is not encountered for normal operating conditions. Nonetheless, the changes are a complicating factor when trying to measure the photovoltaic parameters of devices or modules and for interpretation of accelerated environmental tests that include exposures to temperatures above normal operating conditions [2]. The U.S. National CIS R&D Team [3] is studying these effects with the goal of eliminating or minimizing them and improving overall device performance based on improved knowledge regarding the details of junction formation. While transient behavior has been observed for some time, the mechanism has not been understood. Hence, in this paper we attempt to identify what drives the transient current-voltage behavior in these cells and investigate potential correlations between the trap density profiles and the observed device properties during elevated-temperature cycles.

## EXPERIMENTAL

The details of transient behavior are dependent on the temperature-illumination-bias history of the cell. Conditions studied include thermal exposure in the dark (dark heat soaking) and exposure to light at moderate temperatures (light soaking.) All results reported in this paper are for 20-hour soaking cycles in an air atmosphere, though longer times are sometimes needed for complete reversibility. During dark heat soaking for the standard cycle, the cells were held at 85 °C and zero bias, $V_{OC}$, or maximum-power voltage ($V_{MP}$). During light soaking, the cells were near 50 °C at $V_{OC}$ or $V_{MP}$, and under approximately 0.7 suns illumination. For the all-dark cycle, the same temperatures and biases were used, but the illumination was eliminated. The data presented for the standard cycle is from three cells on the same substrate, as is the data presented for the all-dark cycle. The ability to simultaneously contact three cells on one 1" x 2" substrate minimized the likelihood of compositional gradients from one device to the next, thereby increasing experimental controls.

To examine trapping effects, capacitance vs. frequency measurements were taken at zero bias in a temperature range of 220 - 295 K. All capacitance-frequency-temperature data are for a cell taken through an all-dark cycle, with the bias cycled between zero and $V_{OC}$.

## RESULTS

### Current-voltage transient behavior

Experiments in which the light-soak part of the standard cycle was replaced by dark soaking showed similar transient behavior to the standard cycle. The results of the standard cycles and the all-dark soaking cycles are shown in figure 1. None of the

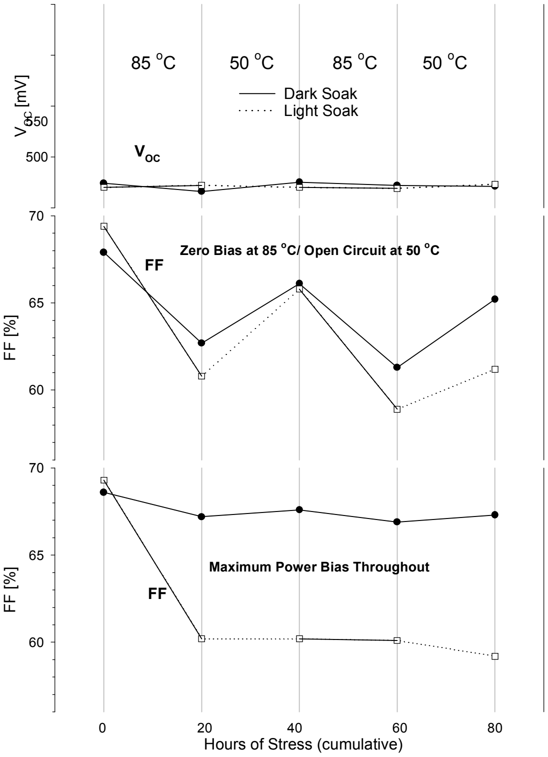

**Figure 1**. $V_{OC}$ and FF comparing alternating light/dark soaks to all-dark cycles. Top shows alternating bias, bottom fixed bias.

cells showed transients in open-circuit voltage, as illustrated for two cells in the top graph of figure 1. The fill factor versus cycle stage is shown immediately below the open-circuit voltage plots for when the bias was cycled between zero and $V_{OC}$. Independent of illumination, the fill factor decreased with zero bias and increased with bias near $V_{OC}$. The bottom graph shows the fill factor versus cycle stage for cells held at constant bias throughout the cycle. As is common regardless of bias during the first heat soak, the fill factor dropped irreversibly for one of the cells shown at this stage. A comparison of the current-voltage curves for the two cells held at $V_{MP}$ reveals that the main difference between the 20-hour measurement for each cell is in the "rollover" seen at voltages above $V_{OC}$. The cell which had the much more significant drop in fill factor exhibited much more rollover in the first quadrant, and somewhat more noticeable light-induced collection effects than the cell with little change in fill factor. Both of these phenomena contributed to the magnitude of the FF decrease. For the constant bias of $V_{MP}$, the fill factor did not show reversible transient behavior after the initial drop. Two other cells (not shown) were held at $V_{OC}$ throughout the cycle. These cells did not show reversible transient behavior, not did they show any other consistent behavior pattern. It is fortuitous that the most stable behavior is while the bias is $V_{MP}$, as this is the desired operating regime. Based on these observations we conclude it is the bias, not the photon absorption, which drives the transient current-voltage behavior in these cells.

## Capacitance-frequency-temperature transient behavior

To extract the trap density profiles using capacitance-frequency-temperature (C-F-T) data, one begins by identifying an average trap response frequency ($f_t$), where the magnitude of the slope of dC/d(lnf) is a maximum, for a range of measurement temperatures [4,5]. Figure 2 shows capacitance versus frequency at several temperatures following a zero-bias soak and following a $V_{OC}$ soak. In addition to extracting $f_t$ from

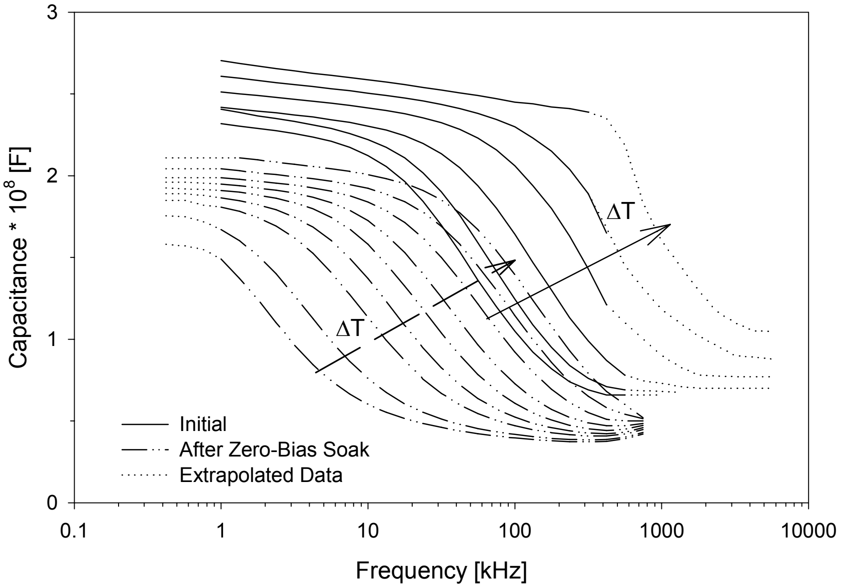

**Figure 2**. Capacitance versus frequency for two stages of the all-dark transient cycle. Temperature range is 220 - 295 K.

such a graph, we deduced the low frequency and high-frequency capacitance for different temperatures. In some cases, this required extrapolations to higher or lower frequencies preserving the functional form of the curves. The high-frequency capacitance should be inversely proportional to the depletion width, while the difference between the high- and low-frequency capacitance should be proportional to the integrated trap density.

The high and low frequency capacitance values for each measurement temperature and each leg of the 0/$V_{OC}$ cycle are shown in figure 3. The plots have relatively small slopes, indicating minimal change in the capacitance with measurement temperature. The five plots from each cycle stage are also clustered fairly closely together, indicating little change in the capacitance with cycle stage.

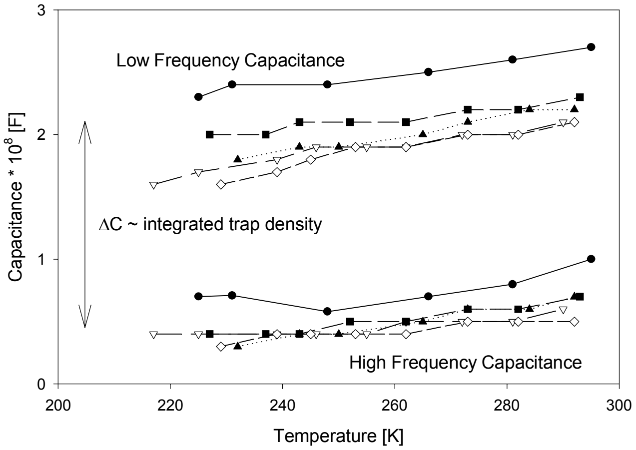

**Figure 3**. Zero-bias capacitance versus temperature. Low and high frequency capacitance is shown for each stage of the all-dark cycle.

Figure 4 shows a plot of trap-response frequency, $f_t$, versus cycle stage for the cell cycled between zero bias and $V_{OC}$, without illumination. It is clear that a cyclical behavior in $f_t$ exists.

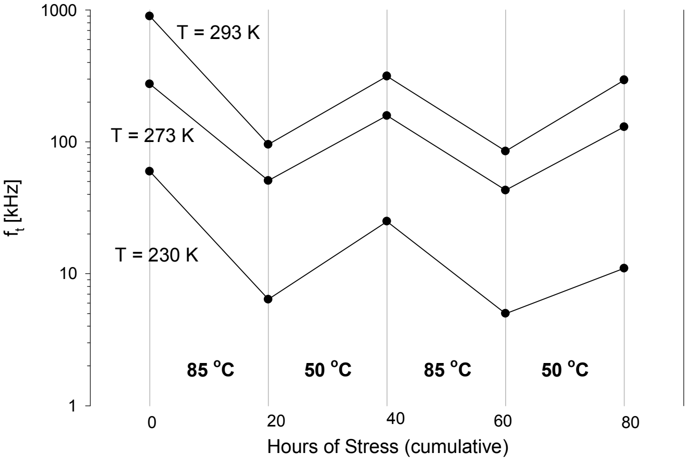

**Figure 4**. Trap-response frequency versus cycle stage for various temperatures for a cell taken through an all-dark cycle with varying bias.

A plot of $f_t$ versus inverse temperature can be extrapolated to zero inverse temperature to deduce an attempt-to-escape frequency ($f_o$) as discussed in [4,5]. Using $f_o$, the depletion width, the built-in voltage, which can be extracted from capacitance-voltage measurements, the energy position of the Fermi level in the n-type semiconductor, and dC/d(lnf), the trap density profile can be determined for each temperature at which C-F was taken. A typical result is shown in figure 5.

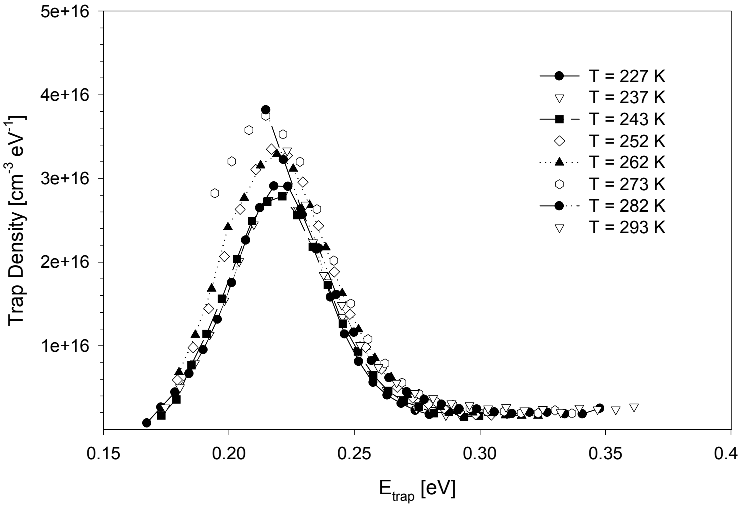

**Figure 5**. Estimated trap density as a function of trap energy (above the valence band) after the second dark soak (50 °C and $V_{OC}$).

The temperature spread of ~75 K is not sufficient for accurate determination of $f_o$. Hence an average value was taken to construct the graph in figure 6, which shows the trap density profile at each point in the cycle stage, assuming the same value of $f_o$ for each set of measurements. Note there is a general pattern of higher $E_{trap}$ values following the zero-bias soaks.

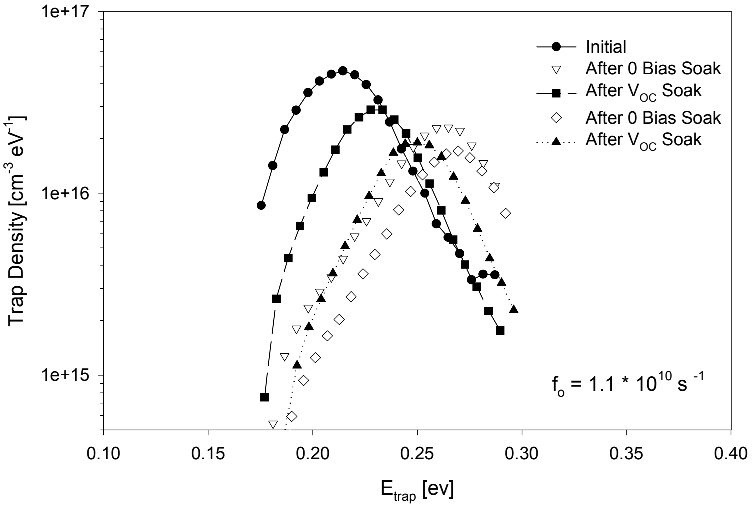

**Figure 6**. Estimated trap density as a function of trap energy for each cycle stage. Data taken near 230 K.

## DISCUSSION

We have found that a change in applied bias during soaking produces a transient current-voltage behavior and room-temperature depletion width, regardless of illumination. We have also found that a change in applied bias during soaking produces a transient trap-response frequency and may cause changes in the value of trap energy distribution. We anticipate that this knowledge, coupled with a broader temperature range of C-F measurements, will allow us to deduce more precisely whether trap density profiles change in a reversible manner during soaking cycles and the relationship the trap energies have to the Fermi level. Such information should provide the next step in elucidating the mechanism causing the transient current-voltage behavior.

## ACKNOWLEDGEMENTS

The authors are grateful to the National Renewable Energy Laboratory (NREL) for financial support of this work and for applying contact grids to the cells. We especially thank Kannan Ramanathan at NREL for J-V screening of the cells used. The authors also wish to thank SSI for providing devices. We also thank Jay Jablonski, David Warner and Bob Adame of Colorado State for design and fabrication of probes to multiple cells on the same substrate.

## REFERENCES

1. R. A. Sasala and J. R. Sites, "Time Dependent Voltage in $CuInSe_2$ and CdTe Solar Cells," *Proceedings 23rd IEEE Photovoltaics Specialists Conference*, 1993, p 543.
2. D. Willett and S. Kuriyagawa, "The Effects of Sweep Rate, Voltage Bias and Light Soaking on the Measurement of CIS-Based Solar Cell Characteristics," *Proceedings 23rd IEEE Photovoltaics Specialists Conference*, 1993, p 495.
3. The U.S. National CIS R&D team is a National Renewable Energy Laboratory sponsored activity under the Thin-film Photovoltaic Partnership Program.
4. T. Walter, et. al., "Defect Distribution and Metastability in Chalcopyrite Semiconductors," Mat. Res. Soc. Symp. Proc. **426**, 279, (1996).
5. T. Walter, et. al., "Determination of Defect Distributions from Admittance Measurements and Application to $Cu(In,Ga)Se_2$ Based Heterojunctions," J. Appl. Phys., **80**, 4411 (1996).