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Stabilization of High Efficiency CdTe Photovoltaic Modules in Controlled Indoor Light Soaking

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Stabilization of High-Efficiency CdTe Photovoltaic Modules in Controlled Indoor Light Soaking

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ABSTRACT

The performance and stabilization of large-area, high-efficiency 9%, CdTe photovoltaic (PV) modules maintained under controlled light-soaking nominally at 800 Watts/m^2 irradiance and 65°C module temperature are investigated. Degradation of module performance occurs predominantly in the first few hundred hours of exposure under these conditions; these symptoms included losses in fill factor (FF), open-circuit voltage (V_{oc}), and short-circuit current (I_{sc}), which amount to between 7% and 15% total loss in performance. Higher stabilized performance was achieved with lower copper content in the back contact. Transient effects in module V_{oc} and I_{sc} were observed, suggesting partial annealing thereof when stored under low-light levels. Performance changes are analyzed, aided by monitoring the current-voltage characteristics in situ during exposure.

1. Introduction

Recently, research on CdS/CdTe cells [1–4] has emerged that identifies cell bias and elevated operating temperatures as stress conditions capable of driving and accelerating performance changes and degradation. The bias can come from fixed electrical bias in the dark or can develop from loading under illumination. The degradation appears to stem from copper (Cu) migration from the back contact—originally put there to improve device quality—into the device and through to the CdS-CdTe junction. This mechanism was shown [1] to induce formation of a blocking contact, likely at the back of the device, which appears capable of explaining both losses in V_{oc} and FF, plus changes observed in forward bias of the current-voltage (I-V) characteristics. Moreover, it seems that some of the diffused Cu and correlated changes in performance are partly reversible [1, 5]. Still, it is difficult to find references that report or explain losses in I_{sc} upon stress testing of CdTe. This paper features an analysis of the performance and I-V characteristics of CdTe PV modules subjected to elevated module temperatures and continuous illumination.

2. Experiment

Four CdTe PV modules manufactured in glass superstrate configuration—SnO_2:F/CdS/CdTe/back-contact—with full EVA-glass laminate encapsulation were investigated. They were exposed in groups of two at a time in a controlled climate chamber: group 1 and 2 serial nos. are, respectively, 405, 703 and 206, 401. Their aperture areas are about 1 m^2. The back contact is a proprietary Cu-containing electrical contact whose concentration was reduced by 40% for the second group of modules. The modules were exposed to simulated solar intensity using metal halide lamps operated at 820 ± 20 W/m^2 irradiance, exhibiting typically ±15% spatial uniformity over the test plane. The spectral content of the lamps was measured and found to integrate to within +5% to –12% of the AM1.5 global spectrum irradiance for all wavelength intervals evaluated between 400 and 900 nm. A calibrated crystalline silicon sensor (±1.5% accuracy) was mounted inside the chamber within the ±2% spatial-uniformity band of the test plane for continuous monitoring of light intensity. Module temperatures were controlled via circulating air inside the chamber within a span of 65° ± 7°C. Lower temperatures and intensities were set for limited time occasionally to measure performance at alternate conditions in situ, using a data acquisition system (DAS). Thin-film thermocouples were bonded to the backsides of each module, for continuous temperature monitoring. Total exposure times were 1130–1240 hours per module.

Prior to any exposure, the modules' I-V characteristics were baseline tested at standard reporting conditions (SRC) and in the dark using the Spire pulsed simulator, the large-area continuous solar simulator (LACSS), and SOMS outdoor test beds. Generally, all LACSS data reflect dual sets of measurements taken: 1) in the 'storage state' traced after the module had lain under low-light level conditions for 1–7 days; and 2) in 'light-stabilized state' traced just after a 10-minute soak at 1-sun on the LACSS, after allowing it to cool back down to 25°C. This procedure was performed to ascertain possible transient effects. The modules were taken out of light-soaking periodically for testing their performance at SRC.

Three of the modules were electrically connected to a PC-based DAS that afforded active power tracking and I-V curve tracing during exposure. This was implemented using commercially available, programmable, electronic loads (not power supplies) whose control modes include loading set to constant voltage, current, or resistance. This hardware, interfaced to a Windows NT-based PC via RS-232, came under control of code that performed I-V traces on user-select schedule, and loaded the modules at all other times. Electrical connections to the modules employed a traditional four-wire measurement scheme. The irradiance at the test plane and module temperatures were continuously monitored using an analog input board mounted inside the PC-DAS. For these three modules, in-situ I-V traces were routinely taken every 30 minutes, while power tracking data were sampled every few seconds and averaged in standard intervals of 5 or 10 minutes. The I-V curves taken during exposure were traced sweeping both directions: down from V_{oc} to I_{sc} and back up from I_{sc} each time. Each trace was taken in about 40 seconds total. The fourth module was kept under fixed resistive load near its optimum power point, and its voltage was monitored and recorded manually.

3. Exposure Effects: Measurements at SRC

Figure 1 is a composite graph of the I-V parameter data taken on the LACSS, showing efficiency and FF data in the upper portion, plus V_{oc} and I_{sc} data in the lower portion, plotted against exposure time at nominally 820 W/m^2 irradiance for the first group of CdTe modules. In upper and lower portions, respectively, efficiency and V_{oc} data are read along the left-hand abscissa, whereas FF and I_{sc} data are read from the right. Also portrayed in Fig. 1 are dual sets of data reflecting storage and light-stabilized measurements that appear vertically offset from each other at coincident exposure times along the ordinate. For example, for module 405 after ~200 hours exposure, the storage-state efficiency and FF are, respectively, ~8% and 61.8%, while light-stabilized values are, respectively, ~7.6% and 61%. In all cases, light-stabilized values are lower than those measured when the modules are first tested after storage. From the upper part of Fig. 1, note that the efficiency drops from about 8.8% at baseline down to ~8% for 'storage' values, 7.4%–7.6% for light-stabilized data, after 1200 hours of exposure. All of the I-V parameters (FF, V_{oc}, and I_{sc}) exhibit the same trend vis-à-vis the two states after exposure—degradation from baseline values that become worse for data taken after 10-min. light-stabilization than for data taken first following storage under low-light levels at room temperature. After enough exposure, differences of ~0.4%–0.5% in absolute efficiency values are discovered between the two states, whereas at baseline, there are no significant differences between them.

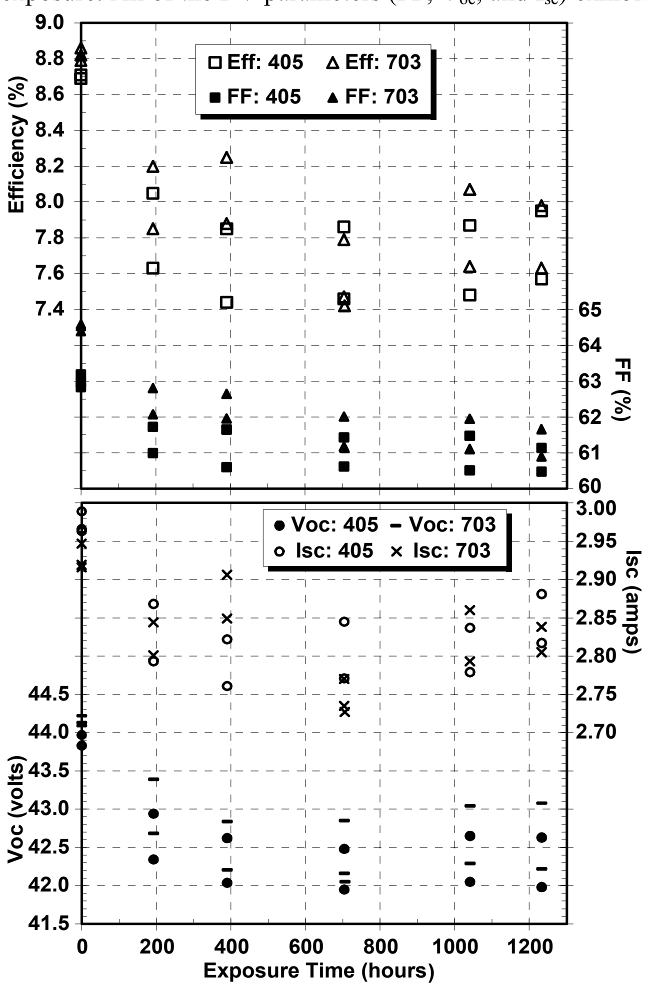

Figure 1. IV Parameters of modules 703 and 405 measured on the LACSS at SRC, plotted against exposure time at 820 ± 20 W/m^2 irradiance, 65°C temperature, showing FF and efficiency data in the top portion, V_{oc} and I_{sc} data in bottom portion of the graph.

Figure 1 shows that most of the degradation occurs during the first 400–600 hours of exposure under the conditions chosen. This observation is consistent with that reported [2] in the literature obtained under slightly higher stress temperatures. For both modules in the first group, the total efficiency losses after ~1240 hours of exposure amounted to 14%–16% relative to baseline values, by way of light-stabilized measurements—but only 10% going by storage-state values. The declines in total performance occur via aggregate losses sustained in all of the I-V parameters, comprising a 4% loss in V_{oc} for both modules; 4% and 7% losses in I_{sc}, respectively for module 703 and 405; and 6% and 4% losses in FF, respectively for 703 and 405. Conversely, judging by Spire data (not portrayed in Fig. 1), performance changes obtained after 1240 hours of exposure accrued to 9% losses relative to baseline for both modules, comprising nearly equally partitioned relative-percent losses of ~3% for each of the I-V parameters (V_{oc}, I_{sc}, and FF). However, it is noted that Spire data primarily reflect upon storage-state values.

For the second group of modules exposed (nos. 401 and 206), the I-V characteristics at SRC were tested less frequently because data for the first group indicated stabilization occurred largely after ~600 hours of exposure. Instead, both modules in this group were connected to electronic loads during exposure so as to monitor their I-V characteristics in situ. The stability achieved for this group, ~8% efficiency, was better than that of the first group. Module performance (using LACSS light-stabilized data as benchmark) degraded substantially less overall after ~1130 hours of exposure: 7%–11% relative to baseline, comprising primarily 5%–7% losses in V_{oc}; and insignificant changes in FF and I_{sc} in one module, and 4% I_{sc} loss for the second. This stands in contrast to the first group in which similarly partitioned losses were obtained in each of V_{oc}, I_{sc}, and FF; albeit similar transient behavior are discovered between storage-state and light-stabilized I-V data revealing slightly worse performance just after the 10-min. soak, that is noticeable only after hundreds of hours exposure.

4. Exposure Effects: Dark-IV Data

Figure 2 depicts the dark I-V data taken for module 405, at various times during its exposure history, on the LACSS at 25°C. A very similar set of dark I-V data is obtained for the other module in the first group. The effects of exposure appear significant after the first few hundred hours and saturate after that. Accounting for module unit cell area, the extrapolated values of reverse saturation current density (J_0) increase by factors of 20–43 overall after 1034 hours exposure: from ~0.9–1.0*10^{-7}A/cm^2 at baseline for both modules and up to ~2*10^{-6} and 4*10^{-6} A/cm^2, respectively, for 405 and 703. The shunt conductance values increase by about a factor of 2, going from $6.4*10^{-5}$ to $1.4*10^{-4}$ S/cm^2 for no. 405 and from $1.4*10^{-4}$ to $3.7*10^{-4}$ S/cm^2 for no. 703. The diode quality factors derived from dark I-V data range from 2.3–2.5 at baseline to 3.4–3.5 after exposure for both modules. These apparent diode factors may be somewhat artificially high due to shunting or other module effects.

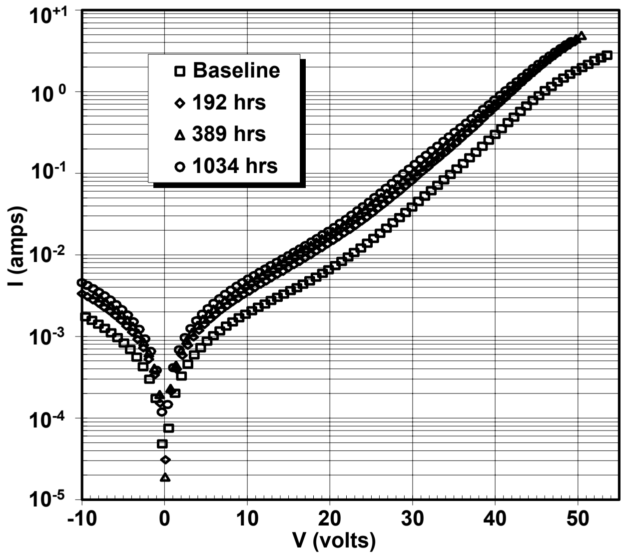

Figure 2. Semilog plot of module 405 dark I-V data at 25°C, taken at four times during its exposure.

5. Exposure Effects: In-situ I-V Measurements

Early on, it became clear that module I-V characteristics exhibited transient behavior after having undergone sufficient light exposure at 65°C. This is illustrated by data taken using the PC-DAS. Figure 3 shows a sequence of four I-V curves traced for module 703 (first group) over a 3-hour period taken immediately after the modules were put back into light-soaking after having lain under low-light level conditions for several days. All the curves are traced starting from V_{oc} to I_{sc} first, and then biasing back up to V_{oc}, at 535 W/m^2 irradiance and various temperatures. The I-V curves are numbered chronologically beginning with #1 measured at 18°C temperature, then #2 at 40°C, #3 at 62°C, and #4 at 19°C. For the first three traces, the V_{oc} data drop with increasing temperature as expected, but note that there appears to be little effect on I_{sc}. Then, after cooling and equilibrating the module back down to 19°C for trace #4, the measured V_{oc} and I_{sc} data are displaced significantly to lesser values with respect to earlier data: V_{oc} matches that previously taken at 40°C and I_{sc} is 10% lower than any of the previous values. Also, for the third curve measured at 62°C, there is substantial hysteresis between data taken biasing down from V_{oc} and that going back up to V_{oc}; this hysteresis disappeared when the module was cooled back down for the fourth curve. This or similar transient behavior in I-V characteristics were observed between storage and light-exposed states every time the modules were put back into light-soaking after having been removed for testing on the solar simulators or having lain under low-light levels.

Figure 4 portrays FF, V_{oc}, and I_{sc} data, respectively, in bottom, mid, and top portions of the graph, plotted against exposure time for I-V data traced for module 401 (group 2). These data are not corrected to one common temperature, but about 99% of these occur within the range of 67° ± 3°C.

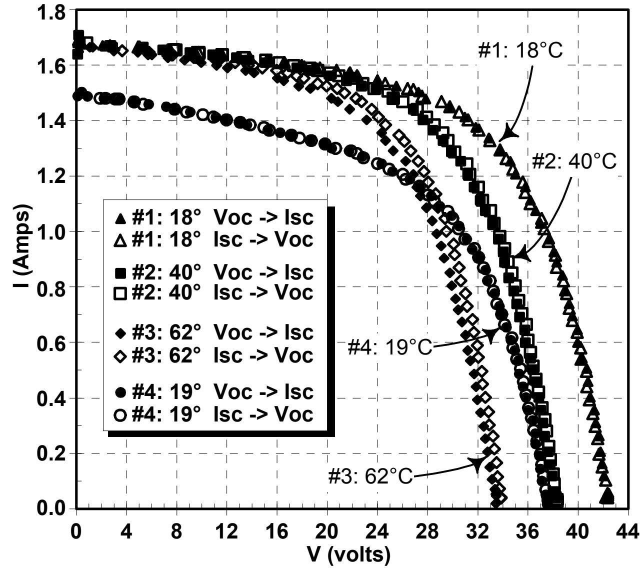

Figure 3. Sequence of four I-V curves taken in situ for module 703 after 390 hours of prior exposure, starting the fourth period of exposure, at low irradiance (535 W/m^2) and four temperatures, showing data traced in both directions.

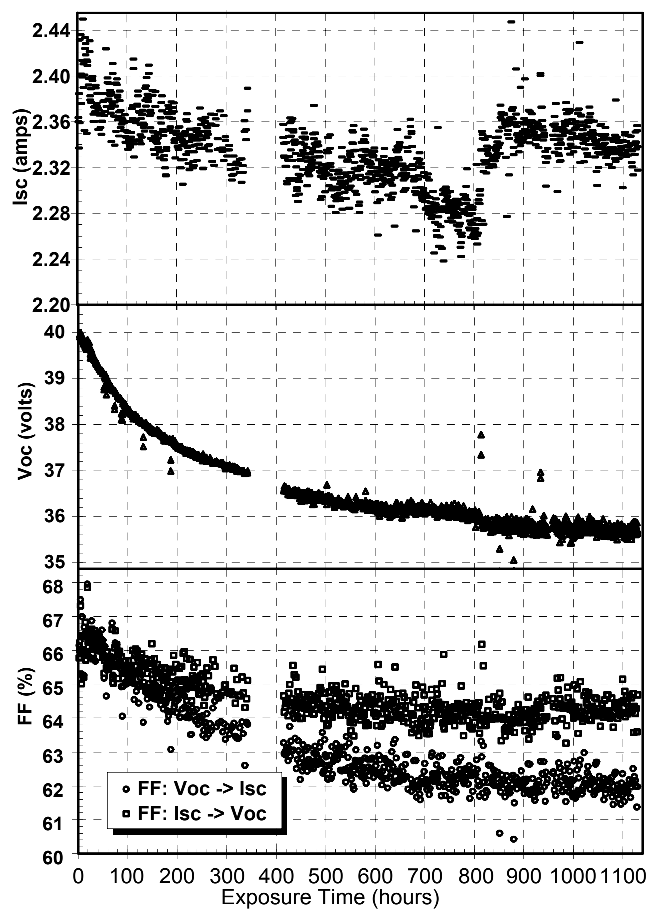

Figure 4. I_{sc} (top), V_{oc} (mid), and FF (bottom) data taken in situ during exposure at nominally 810 ± 20 W/m^2 and 65°C temperature for module 401 plotted vs. exposure time.

The data in Fig. 4 show the differences between FF values measured while tracing in opposite bias directions —down from V_{oc} to I_{sc} first and then back up to V_{oc}—that become evident after several hundred hours of exposure. In actual field operation, such transient effects may not be too important due to tracking around the optimum power point. Note the leading source of degradation for this module occurs due to losses in V_{oc}, dropping about four volts. The I_{sc} data show some changes with exposure that may not be very significant; the discontinuity observed in I_{sc} occurring after ~800 hours is due to a lamp change that resulted in slightly higher intensity thereafter. A similar set of in-situ data measured for module 703 (first group) shows similar loss in V_{oc}, similar degradation of the FF, and somewhat higher loss in I_{sc}. Both modules 703 and 401 were loaded at about their optimum power point throughout their exposure.

Figure 5 portrays the temperature dependence of V_{oc} and I_{sc} (module 703), measured in situ at various times during exposure, specifically at the beginning or end of the third and fourth periods. The legend above the graph itemizes the symbols corresponding to each period: roman numerals refer to the period (III or IV); the B or E suffixes refer to the designated period's beginning or end, respectively. Figure 5 shows that toward the end of periods III and IV, the values for V_{oc} at 28°C temperature are about 38.5 volts, and its rate of change with temperature is between –0.13 V/°C and –0.14 V/°C. In contrast, at the beginning of the fourth period, V_{oc} is 41 V at 28°C, and its temperature derivative is about –0.19 V/°C. For normalized I_{sc} (referenced to 822 W/m^2), the slopes with temperature appear equal, but its absolute values are offset considerably from each other. In effect, this exercise has measured transient phenomena that were observed to persist over 20 hours, and which appeared to equilibrate more readily with increasing temperature.

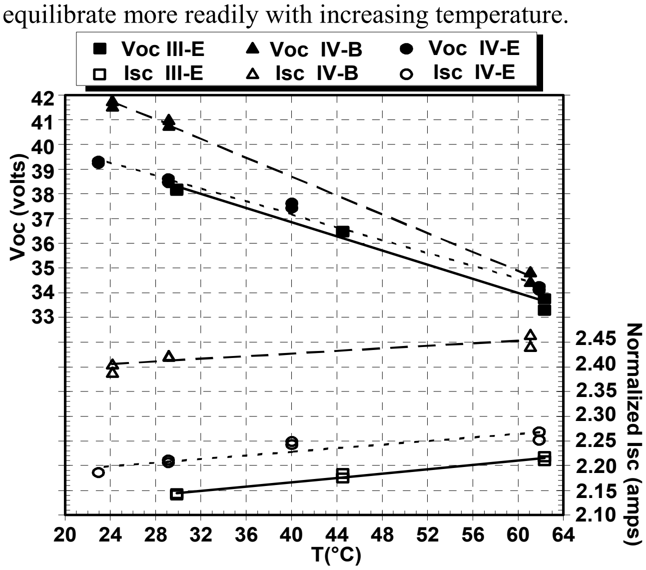

Figure 5. Dependence of Voc and Isc (normalized) data with temperature at 822 W/m^2 irradiance, for module 703, at the end of the third semester (III-E) plus beginning (IV-B) and end (IV-E) of the fourth semesters of exposure.

6. Discussion and Conclusions

The data indicate that CdTe modules can degrade with light exposure at elevated temperature (65°±7°C), suffering 7% to 15% overall performance losses that accrue mostly in the first 400–600 hours exposure. However, losses sustained by the second group of modules amounted to about half the losses incurred by the first, stabilizing around 7.9% to 8.5% efficiency gauging by stabilized LACSS data, and corrected Spire and SOMS data—indicating that lower Cu content in the back contact is beneficial for stabilized performance. We observed that degradation could emerge from either a combination of declines in all, or mostly just one, of I_{sc}, V_{oc}, and FF. Transient effects were observed in both data sets, taken in situ and at SRC, becoming prominent only after sufficient exposure. The FF values obtained from I-V curves measured tracing down from V_{oc} were consistently worse than those found by tracing up from I_{sc}, obvious only after 400 hours exposure had elapsed. This hysteresis is similar to that reported previously [6], and may be due to trap defects in the CdTe that partly anneal during dark storage, and are reactivated readily after more exposure. Unless mitigating steps are taken, transient behavior observed in V_{oc} and I_{sc} data is expected to complicate accurate determination of temperature coefficients for these modules.

7. Acknowledgements

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