NREL/CP-520-22921 • UC Category: 1250

Effect of Light Intensity on Current Collection in Thin-Film Solar Cells

T.J. McMahon and B. von Roedern

Presented at the 26th IEEE Photovoltaic Specialists Conference, September 29–October 3, 1997, Anaheim, California

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under contract No. DE-AC36-83CH10093

Prepared under Task No. PV704401

September 1997

EFFECT OF LIGHT INTENSITY ON CURRENT COLLECTION IN THIN-FILM SOLAR CELLS

T.J. McMahon and B. von Roedern
National Renewable Energy Laboratory, Golden, CO 80401-3393

ABSTRACT

We have measured the current-voltage curves of thin-film solar cells using focused laser spots (30 - 500 μm) using DC and modulated (AC) photocurrent techniques. The AC short-circuit current response (I_{SC}) and the AC fill factors (FF) decrease for small spot sizes corresponding to several 100 sun light intensities. Laser line scans across the devices produced significant but reproducible spatial fluctuations in AC I_{SC}. These spatial variations depend on spot size and are reduced by scanning with lower light intensity. The reduction of AC FF and AC I_{SC} was largest in a-Si:H, intermediate in CdTe and $CuInSe_2$ (CIS), barely noticeable in some $Cu(Ga,In)Se_2$ (CIGS) cells and absent in a silicon cells. The observations on CIGS and some CIS cells can be explained by internal series resistance, but field dependent collection and recombination effects must be invoked to explain results on most thin-film solar cell materials. Such field modification is not accounted for in standard exponential diode equation models.

BACKGROUND

The effect of sheet resistance (RA) on thin-film cell and module performance can be calculated and is well understood. However, series resistance internal to the cell structure is not easily quantified, and a lumped series resistance (R_{ser}) deduced from cell measurements cannot differentiate between internal, sheet resistance, or grid contributions. To enhance our failure-analysis activity at NREL, we have employed a new method to determine the internal series resistance (vertical rather than lateral components) of thin-film solar cells [1]. The method involves illumination of a small area of the cell with light sufficiently intense to make the internal resistance easily observable. It works particularly well on some CIS and CIGS cells with small internal series resistance values with RA products between 10^{-2} and 10^{-4} ohm cm^2. These values would be difficult to measure with standard techniques, and involves small spot intensities of several hundred suns. Even so, this technique is especially valuable for spotting small changes in back-contact resistance during accelerated stress testing and in identifying the source of any increased series resistance.

Delahoy, et al., attempted to explain AC photocurrents with applied bias using only a series resistor and, in some cases, found discrepancies between the modeled fit and the experimental data [1]. They found that an R_{ser}-only model cannot account for a large enough reduction of the photocurrent under reverse bias conditions of at least one of the CIGS cells measured. We find this discrepancy is modest in the case of CIS devices, but was much larger in the case of the CdTe and a-Si:H cells reported in this paper.

Crandall, et al. [2], developed a model for voltage-dependent collection in a-Si:H solar cells resulting from a collapse of the space-charge region with increasing carrier generation (up to 2 suns) and enhanced with lower operating temperatures. The model appears to fit the deterioration of the AC FF adequately when intensities are on the order of 1 sun, but the applicability of the model begins to fail in cases when I-V is diminished with small spot sizes (high intensities), even under reverse bias conditions. In this paper, we report on the measurement of a-Si and CdTe cells, which are somewhat more problematic because the RA products are larger and the AC photocurrent does not saturate even at reverse bias.

EXPERIMENT

With our equipment, a small region of the cell is illuminated by a chopped and focused HeNe laser beam, and the AC current in the external circuit is recorded as a function of cell bias for both forward and reverse polarities as in Ref. 2. A single-element lens focuses a 1-mW HeNe laser beam to spot sizes between 30 and 500 μm. The lens is mounted on a micrometer-driven translation stage that allows the diameter of the laser spot falling on the cell to be varied, while maintaining constant total optical flux. The cell is mounted on an x-y stage that can be translated by stepper motors. The modulated AC photocurrent is measured with an operational amplifier and a lock-in amplifier synchronized to the chopper.

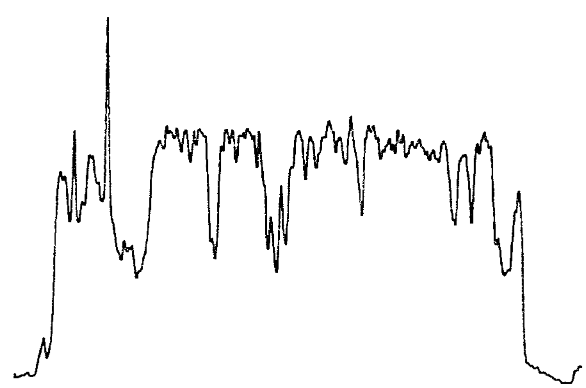

Fig. 1a. HeNe laser spot scan using a 30-μm diameter spot at full tensity on a CdTe cell (1400 suns).

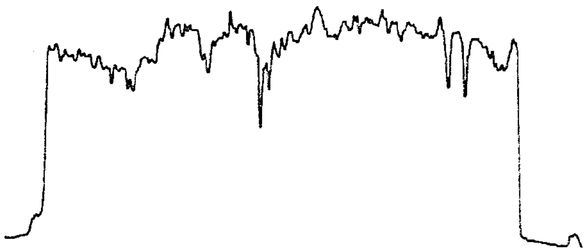

Fig. 1b. HeNe laser spot scan using a 30-μm diameter spot at 0.01 full intensity on a CdTe cell. (14 suns).

With this system we can measure high- and low-intensity spot scans as shown in Fig. 1a and 1b, without or with using a ND 2.0 neutral-density filter (1% transmission) to characterize the spatial uniformity of a cell. Scans a and b are across the same line on a CdTe cell and each is entirely reproducible; i.e., these fluctuations are not due to noise. The high peak in 1a is due to scattering off a flaw (e.g., dust or particle in film) and usually appear as a dip in response at lower intensity, as seen in Fig. 1b. This is because the somewhat smaller number of carriers generated by the scattered light are more efficiently collected than for the unscattered, focused beam that would have generated a much higher density of carriers. Reducing the intensity for 14 suns on down to 1 sun elliminates many of these fluctuations leaving only those due to artefacts. We believe that the poorly responding locations on these CdTe cells, especially when measured with high intensities, are due to additional recombination in regions where the internal R_{ser} is high. In contrast to the conclusions on spot-scan results for CdTe cells by Galloway, et.al. [3], we believe the variation in local values of R_{ser} is the cause of band flattening, and hence greater recombination and not variation in recombination properties.

Spot-scan profiles of a-Si and crystalline Si cells are smooth and profiles on CIS solar cells show much finer detail than CdTe cells. The spatial nonuniformity and its intensity dependence is an interesting phenomenon by itself. However, we limit the following discussion in this paper on the intensity dependence of the I-V response as the light intensity increases with increased focussing of the laser beam.

RESULTS AND MODELING

We first apply the technique to CIGS and Si cells as shown in Fig. 2. For large beam diameters the photocurrent generated by the cell is fully collected for all values of reverse bias applied to the cell, thereby accounting for the saturated signal. As the cell moves into forward bias, some of the photocurrent recombines or flows back through the dark portion of the diode, and the AC photocurrent is diminished. A PSpice circuit simulator can be used to model curves such as seen in Fig. 2. (see Ref. 1) The equivalent circuit that corresponds to the illuminated portion of the cell is a resistor, R_{ser}, in series with the diode and an AC current source, I_{AC}, that produces the current from the chopped laser light as shown in Fig. 3. The family of curves measured on a

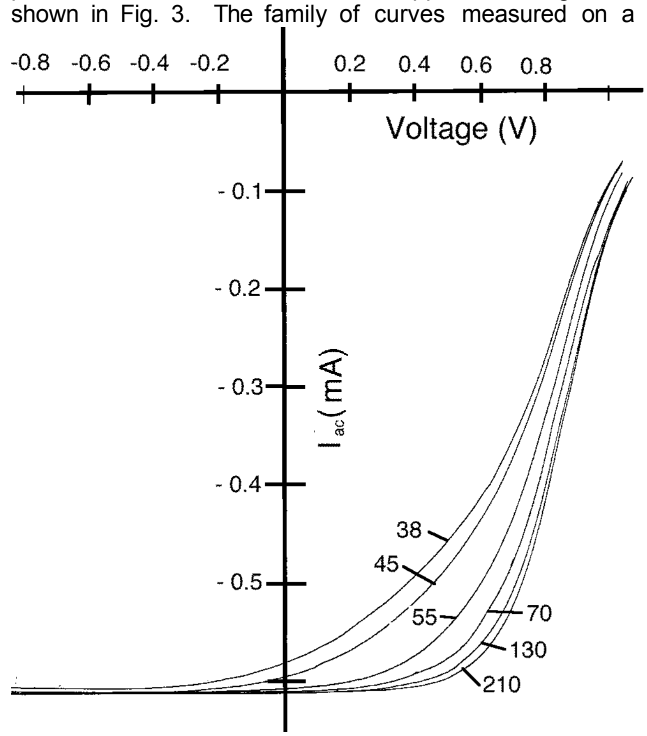

Fig. 2. AC photocurrent I-V's on a CIGS cell. Spot size diameters (μm) increase to the right as noted.

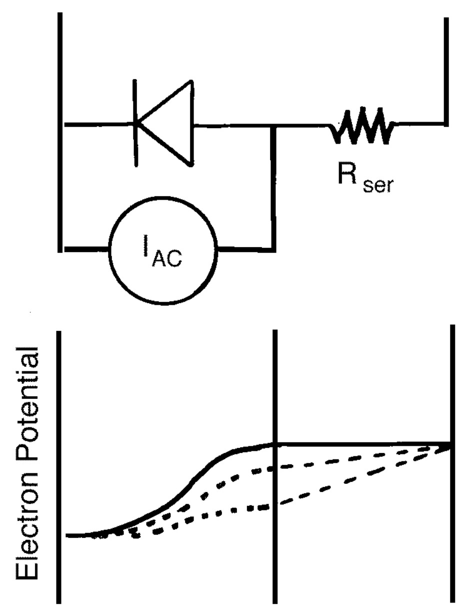

Fig. 3. (Above) Equivalent circuit of illuminated portion of cell. (Below) Electron band equivalent.

crystalline Si cell, using the same spot sizes and voltages as for curves in Fig. 2, show no internal series resistance effects whatsoever, i.e., the curves overlay each other.

The same data-collection methods were applied to a-Si:H, CdTe, and some poorer CIS cells. We see a large drop in photogenerated current with decreasing spot diameters (Figs. 4 and 5) that is not seen in good CIS, CIGS, and Si cells as were shown in Fig. 2. Figs. 4 and 5 show that these AC photocurrents vs bias voltage with varying spot size are not constant. Higher current densities and flatter bands, as depicted in the lower portion of Fig. 3 by the dashed lines, result in more recombination and less current to the external circuit. Modeling requires a voltage-dependent AC photocurrent in addition to the internal series resistor to account for this recombination. However, for these non-ideal cases in which the current out of the cell is dependent on cell bias and photon density, the curve fitting becomes ambiguous. An internal resistance can still be salvaged from these curves by measuring the voltage offsets along a constant current line of 0.1 mA, for example, in Fig. 4, and dividing these voltages by 0.1 mA. The resulting RA product for this a-Si cell is 0.14 ohmcm^2, as calculated from all but the smallest spot size data. The measured size of the smallest spot is more difficult to determine and may be somewhat larger than 30 µm. When applying the internal series resistance method of Ref. 1 to thin-film a-Si cells, voltage-dependent carrier collection must be used in addition to the internal series resistor to explain AC photocurrent data on the thin-film cells examined in this study.

Similarly, the RA product for the CdTe cell in Fig. 5 is 0.024 ohmcm^2. There is a more severe problem with RA values derived from the two smaller spot sizes. When applying this technique to CdTe cells, care must be taken

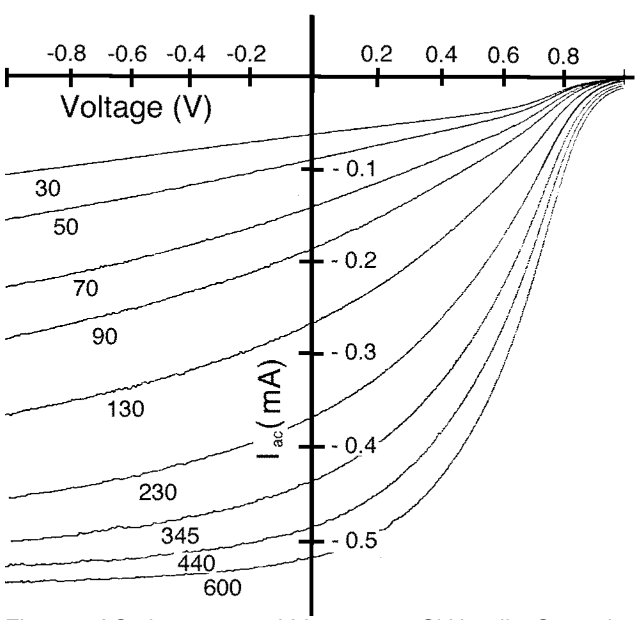

Fig. 4. AC photocurrent I-Vs on an a-Si:H cell. Spot size diameters (µm) increase to right as noted.

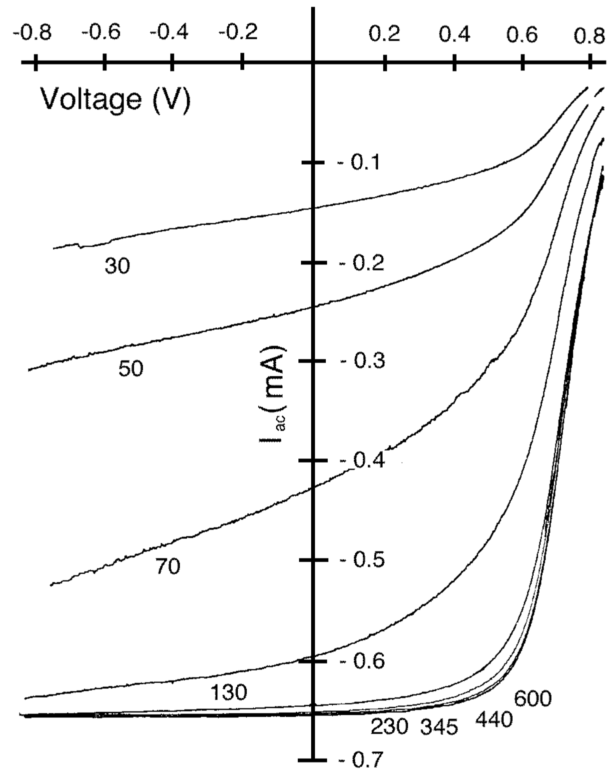

Fig. 5. AC photocurrent I-V's on a CdTe cell. Spot size diameters (µm) increase to right as noted.

that the smaller spot sizes are not located on a small scattering defect or a photocurrent-deficient location, as seen in Fig. 1a. The simple expectation for a constant RA product may not hold. Such analysis is helpful for interpreting spot-scan measurements as carried out in Ref. 3. Even though there are these additional difficulties, it is still possible to separate internal resistance from sheet-resistance effects.

DISCUSSION

Voltage-dependent current collection has been invoked by other groups to explain the diode behavior in CIS and CdTe-based cells(e.g., see Ref. 4). In making the current source shown in Fig 3 voltage dependent, we can obtain good fits for the AC photocurrent I-V curves even in those instances when the I-V curves change dramatically with decreasing spot size, as seen in Figs. 4 and 5. The curves measured with the smallest spot sizes (intensities equivalent to several hundred suns) can no longer be reconciled with the exponential diode equation with any combination of diode quality factor, saturation current, and R_{ser}. The failure of normal excess diode-current models to fit these AC photocurrents, and the need to resort to a voltage dependent photocurrent, is likely due to a collapse ot the electric field within the cell due to the high carrier densities. Such field modification is not accounted for in standard exponential diode-equation models.

Crandall, et al. [2], modeled the performance of a-Si:H cells operating near 1-sun intensity in terms of voltage-dependent collection caused by field collapse due to higher carrier densities or lower operating temperatures. The model predicts a softening of the I-V curve as he observed, but applying it to our observations of reduced AC photocurrents at small spot size (high intensities) remains a problem. Crandall's model predicts an $I \alpha G^{3/4}$ increase in I-V with generation rate due to field collapse which explains what we observe exactly at the largest spot sizes in the a-Si:H. However, in both CdTe and a-Si:H cells the response rolls over to less than an $I \alpha G^{1/2}$ at higher intensities, presumably due to R_{ser} effects.

Sometimes less than expected short-circuit current densities (which cannot be increased when a reverse bias is applied) is observed in nonoptimized cells even under 1-sun intensity illumination. Such losses have been labelled "deep penetration" and "unknown" losses in the analyses by Sasala, et al. [5]. Thus, while we agree with the concept of voltage-dependent carrier collection, we cannot be certain that the voltage dependence caused by field collapse is modeling the observed data correctly when the intensities are varied by orders of magnitude. Increasing recombination (decrease in collection and I-V which we observe in all a-Si:H and CdTe cells) measured with the highly focussed beams is an important factor and could play a role in other, less optimized devices even at 1-sun intensities. Sometimes, even in the case of high-efficiency crystalline Si solar cells, it has been found necessary to invoke nonconstant (current dependent) values for R_{ser} [6].

CONCLUSION

We have shown that photo carrier collection is diminished in thin-film cells measured under high intensity, small-area illumination. In a-Si:H, CdTe, and some CIGS cells the ability to function well at high intensities is limited by R_{ser} and increased recombination due to voltage-dependent-carrier collection losses. In spite of this nonlinear collection at high intensity, the small-spot AC photocurrent technique can still be used to determine internal RA products in a number of different absorber materials. Response variation on spot scan maps on CdTe are due to local variations in internal R_{ser} and are enhanced by voltage-dependent carrier collection losses. Finally, an additional voltage-dependent collection loss due to field collapse, not accounted for in standard diode models, may be required to explain the response of many, less than optimal, solar cells even at 1-sun intensity.

ACKNOWLEDGEMENTS

We thank Murray Bennett, Chris Ferekides, and Rommel Noufi for the cells used in this study and Dick Crandall for most valuable discussions. This work was supported under the U.S. Department of Energy contract number DE-AC36-83CH10093.

REFERENCES

[1] A. E. Delahoy and Adam M. Payne, "Determination of the Internal Series Resistance of CIS and CIGS Photovolaic Cell Structures", 25th IEEE PV Spec. Conf., Washington, DC, May 1996, p. 841.

[2] R. S. Crandall, J. Kalina, and A. Delahoy, Mat. Res. Soc. Symp. Proc. Vol. **118** (1988), p. 593.

[3] S. A. Galloway, A. W. Brinkman, K. Durose, P. R. Wilshaw, and A. J.Holland, Appl. Phys. Lett 68, 1996, p.3725.

[4] W. N. Shafarman, R. Klenk, and B. E. McCandless, Proc. 25th IEEE PV Specialists Conf., May 1996, p.763.

[5] R. A. Sasala, X. X. Liu, and J. R. Sites, Int. J. Solar Energy, **12**, (1992) 17.

[6] P. P. Altermatt, G. Heiser, J. Zhao, A. Wang, S. R. Wenhem, and M. A. Green, Proc. 13th European Photovoltaic Solar Energy Conf. (Nice, France Oct 1995), p. 382.