

Crystalline Silicon Short-Circuit Current Degradation Study: Initial Results

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CRYSTALLINE SILICON SHORT-CIRCUIT CURRENT DEGRADATION STUDY: INITIAL RESULTS

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ABSTRACT

Following our observation of slow degradation of short-circuit current (I_{sc}) in crystalline silicon (x-Si) modules that was correlated with ultraviolet (UV) exposure dose, we initiated a new study of individual x-Si cells designed to determine the degradation cause. In this paper, we report the initial results of this study, which has accumulated 1056 MJ/m^2 of UV dose from 1-sun metal-halide irradiance, equivalent to 3.8 years at our test site. At this time, the control samples are unchanged, the unencapsulated samples have lost about 2% of I_{sc} , and the samples encapsulated in module-style packages have declined from 1% to 3%, depending on the cell technology.

INTRODUCTION

Previously, we reported slow (0.25% to 0.60% per year) degradation of I_{sc} in x-Si modules that were stressed with real-time outdoor, accelerated outdoor, and accelerated indoor exposure techniques [1-3]. The degradation rates were linear with the total UV radiation exposure doses (our outdoor test site averages 274 MJ/m^2 of total UV per year). Several possible causes of the slow degradation were identified: 1) obscuration or absorption in the glass superstrate, 2) obscuration or absorption in the ethylene vinyl acetate (EVA) encapsulant, 3) degradation of the antireflection (AR) coatings, or 4) degradation of the p-n junctions. Isolating these possible causes in modules is not an easy task. Because modules contain a large number of cells connected in series, nondestructive current-voltage (I-V) and quantum efficiency (QE) measurements on individual cells are quite difficult or impossible. Nondestructive measurements of the superstrate glass and encapsulate materials are also impossible. Consideration of all the available evidence seemed to rule out obscuration or absorption (the first two causes), but we were unable to determine if the losses were caused by changes to the AR coatings or to the p-n junctions. The QE data from these modules showed that about 75% of the I_{sc} losses occurred at wavelengths longer than 800 nm, which was inconsistent with browning of EVA [4].

Because of the correlation with the total UV dose for all exposure methods, and because one indoor method used only UVA-340 fluorescent radiation, we hypothesized that UV radiation was responsible for the observed slow

degradation. Although we suspected that a simple thermal process was not responsible, we were not able to conclusively eliminate this cause. Therefore, in 2003, we initiated a new experiment using a sample set consisting of individual x-Si cells instead of modules, that was designed to isolate the exact cause of the observed I_{sc} degradation, if possible. If a thermal process is responsible for the degradation, cells stressed at elevated temperatures in the dark should degrade. On the other hand, if UV damage is responsible, unencapsulated samples should degrade faster than conventional module packaged samples, and cells that have UV blocking should show no degradation. The experiment will be run until at least ten years of equivalent outdoor exposure is accumulated.

Three different types of x-Si cells were obtained from the same two manufacturers that produced the modules used in the previous study. These are: 1) cast poly-Si with TiO_2 antireflection coating, 2) single-crystal Czochralski (Cz) Si with TiO_2 AR coating, and 3) single-crystal Cz-Si with textured front surface and no AR coating. All cells have factory-soldered ribbons for contacts, and the cells were assembled into three different package types: 1) unencapsulated (bonded to glass substrates with silicone rubber), 2) AFG Solatex/EVA encapsulation, and 3) Schott GG 495/EVA (UV-blocking colored glass) encapsulation. The encapsulated samples all have conventional Tedlar-polyester-Tedlar (TPT) backsheets. There is a total of eight cells of each type. Six of each type are currently being exposed to metal-halide 1-sun illumination inside an environmental chamber with the ambient temperature controlled to 18°C , which results in cell temperatures in the range 53°C - 63°C . No humidity is introduced into the chamber. UV irradiance is measured with an Eppley Total UV Radiometer (TUVR) calibrated by the NREL Solar Radiation Research Laboratory. One unencapsulated sample of each type is held in an oven at 55°C - 60°C without light, and three unencapsulated samples are retained as controls and are not stressed. The test protocol called for careful light I-V, dark I-V, and QE measurements of all cells initially and at each intermediate step when the exposure is interrupted. Light I-V measurements are made in accordance with ASTM E 948 [5].

RESULTS TO DATE

At the time of this writing, the samples have accumulated a total UV dose of 1056 MJ/m^2 . There have been no measurable changes to the open-circuit voltages ($\pm 2 \text{ mV}$

out of 600 mV), and one unencapsulated cell has a 10% loss of fill factor due to an increased series resistance. We note that none of the cells showed the rapid initial light-induced degradation of I_{sc} due to the boron-oxygen metastability in p-type Si solar cells [6]. It is not known if the cells were light soaked by the manufacturers prior to delivery.

Control and oven samples

Figures 1 and 2 show the measured I_{sc} values of the control and oven samples as a function of the total UV exposure dose, normalized to the initial baseline measurements. Although these samples were not exposed in the environmental chamber, they were retested at the same times with the exposed samples. These two plots demonstrate the excellent repeatability of the NREL standard cell measurement facility for I_{sc} . Comparison of the oven-exposed samples with the controls indicates there are no detectable changes.

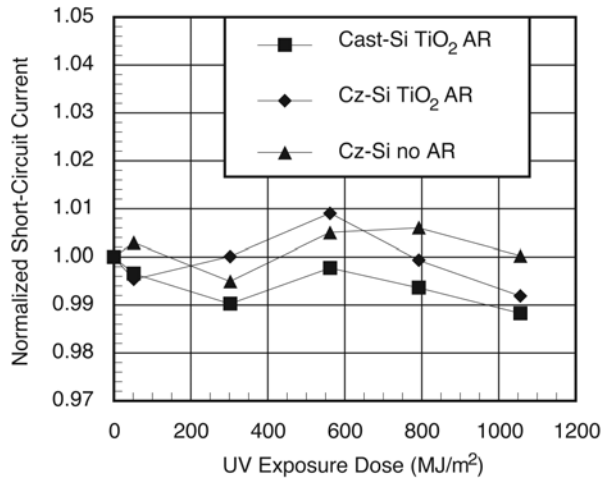


Fig. 1. Normalized I_{sc} versus total UV exposure dose for the unexposed control samples.

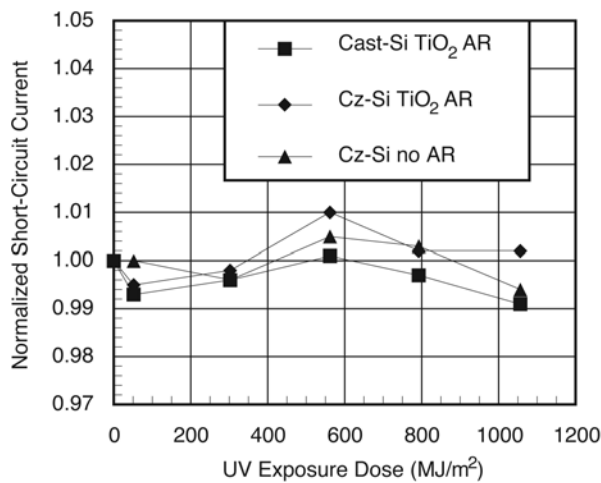


Fig. 2. Normalized I_{sc} versus total UV exposure dose for the samples held at 53°-63°C in the dark.

Solatex/EVA-encapsulated samples

The EVA-encapsulated samples are beginning to show losses of I_{sc} , which are listed in Table 1. With correlation coefficients near zero, it cannot be concluded that the cast-Si TiO₂ samples have changed. The Cz-Si TiO₂ samples, on the other hand, have linear correlation coefficients higher than 0.9; these trends are plotted in Fig. 3. Figure 4 shows the changes in the absolute QE for one of these samples (#2); note that all losses have occurred at wavelengths shorter than 700 nm.

Table 1. I_{sc} degradation rates and linear-fit correlation coefficients for the samples encapsulated with EVA in module-style packages under Solatex superstrates.

Sample	Rate (%/GJ/m ²)	r ²
Cast-Si TiO ₂ AR #1	+0.15	0.024
Cast-Si TiO ₂ AR #2	-0.51	0.173
Cz-Si TiO ₂ AR #1	-2.41	0.908
Cz-Si TiO ₂ AR #2	-2.70	0.906
Cz-Si no AR #1	-0.98	0.532
Cz-Si no AR #2	-1.38	0.605

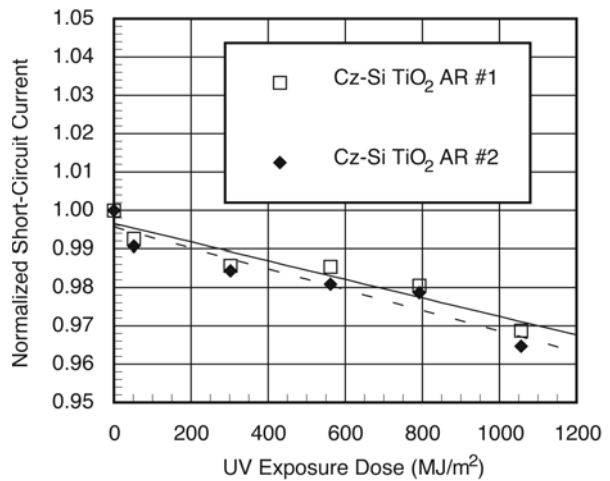


Fig. 3. Normalized I_{sc} versus total UV exposure dose for the Cz-Si samples with TiO₂ AR coating and encapsulated with EVA in module-style packages under Solatex superstrates.

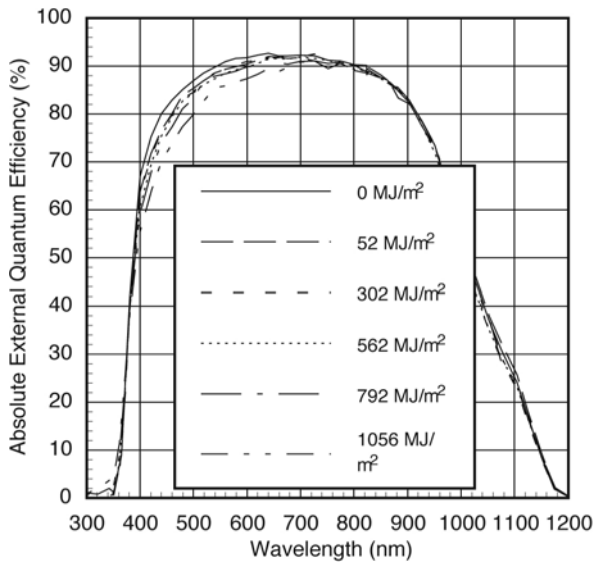


Fig. 4. Absolute external QE versus wavelength and total UV exposure dose for Cz-Si sample #2 with TiO₂ AR coating and encapsulated with EVA under Solatex superstrates.

Unencapsulated samples

Table 2 lists the I_{sc} linear degradation rates with corresponding correlation coefficients for the unencapsulated samples. The linear fits are illustrated in Fig. 5 for the cast-Si TiO₂ samples. Although the degradation in Fig. 5 is not large, it appears to be greater than the $\pm 1\%$ I_{sc} measurement repeatability, as seen in Figs. 1 and 2. The medium values of the correlation coefficients could indicate that UV dose is not the only cause of the degradation. It is interesting to note that there does not appear to be any differentiation between the cell types, unlike the EVA-encapsulated samples. There are no clear trends in the QE data that might indicate specific wavelength regions in which the losses are occurring.

Sample	Rate (%/GJ/m ²)	r ²
Cast-Si TiO ₂ AR #1	-1.16	0.428
Cast-Si TiO ₂ AR #2	-1.39	0.558
Cz-Si TiO ₂ AR #1	-1.11	0.672
Cz-Si TiO ₂ AR #2	-1.36	0.505
Cz-Si no AR #1	-1.93	0.849
Cz-Si no AR #2	-0.72	0.276

Table 2. I_{sc} degradation rates and linear-fit correlation coefficients for the unencapsulated samples.

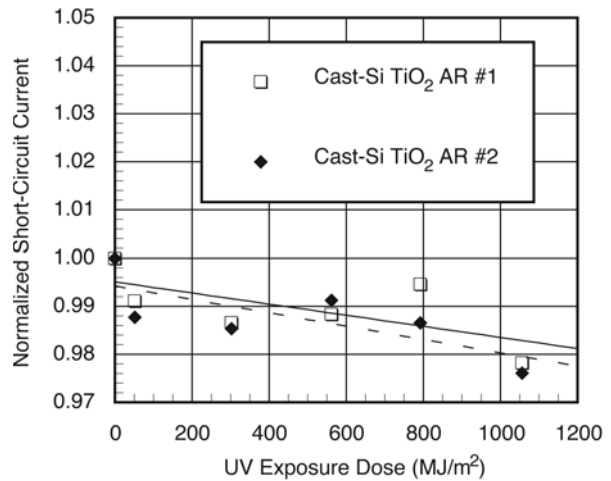


Fig. 5. Normalized I_{sc} versus total UV exposure dose for the unencapsulated cast-Si samples.

UV-blocking superstrate samples

At this point in the test program, it is apparent that the Schott GG495 UV-blocking superstrates are not stable enough for studying I_{sc} degradation. The instability is evident in the large swings in Fig. 6, which plots the normalized I_{sc} results for the cast-Si with TiO₂ AR coating samples. Including the results for the Cz-Si samples (Fig. 7), the plate-to-plate instabilities differ and are large enough to mask any changes in cell performance. It would be informative to study transmittance changes on a sample of GG495 glass as a function of UV exposure.

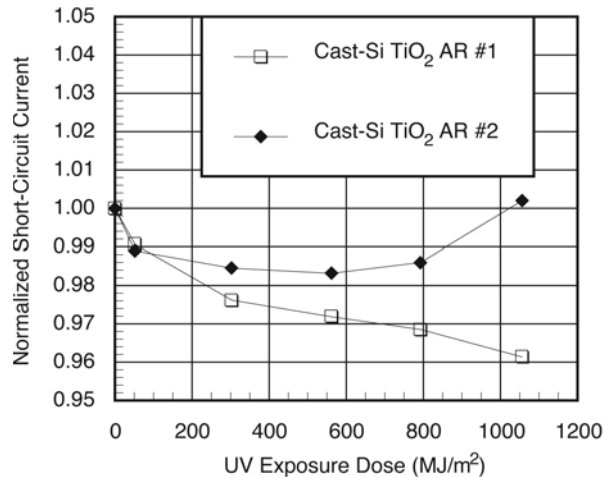


Fig. 6. Normalized I_{sc} versus total UV exposure dose for the cast-Si samples encapsulated under UV-blocking GG495 superstrates with EVA.

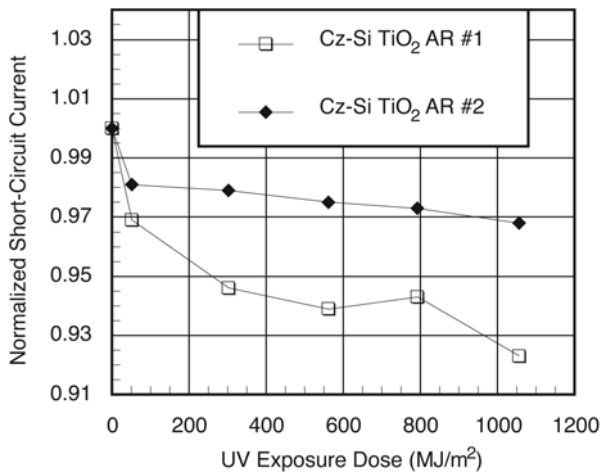


Fig. 7. Normalized I_{sc} versus total UV exposure dose for the Cz-Si samples encapsulated under UV-blocking GG495 superstrates with EVA.

DISCUSSION AND CONCLUSIONS

Undoubtedly the most disappointing results have to be with the UV-blocking superstrates. A way was needed to expose cells to light and at the same time prevent any UV radiation; colored-glass filters seemed to be the only solution. In hindsight, however, the transmittance instabilities of colored-glass filters are well known. It was hoped that the filters would stabilize after an initial exposure period of some length, but this has not yet occurred. Even if they do eventually stabilize, it would likely be impossible to draw any conclusions about changes in the cells.

The results from the unencapsulated and the Solatex/EVA encapsulated samples, on the other hand, are interesting and trends are becoming evident. First, the unencapsulated samples exposed only in the oven are unchanged, which would indicate that a solely thermal process is not responsible for losses of I_{sc} . This result is contrasted with the cells encapsulated under Solatex/EVA, which seem to be degrading linearly with respect to total UV dose in at least one case (Table 1 and Fig. 3). These I_{sc} losses are occurring at wavelengths shorter than 700 nm (Fig. 4), which is consistent with EVA browning [4]. The interesting point so far is that the degradation rates vary with the cell type (Table 1), which is consistent with the previous results on modules [1]. If EVA browning is the only process occurring, one would expect the rates to be independent of cell type.

Lastly, I_{sc} losses are beginning to be detectable in the unencapsulated cells (Table 2). These losses differ from those of the Solatex/EVA samples because so far they are all of similar magnitude, plus they do not appear to be wavelength-dependent. Soiling could explain these losses, but the appearance of these samples is still similar to those of the control and oven samples. Also, a simple cleaning step at the end of the long-term testing should indicate if soiling is responsible.

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