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Degradation Analysis of Weathered Crystalline-Silicon PV Modules

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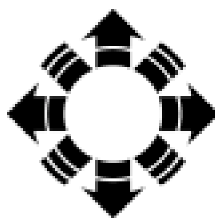

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DEGRADATION ANALYSIS OF WEATHERED CRYSTALLINE-SILICON PV MODULES

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ABSTRACT

We present an analysis of the results of a solar weathering program that found a linear relationship between maximum power degradation and the total UV exposure dose for four different types of commercial crystalline Si modules. The average degradation rate for the four modules types was 0.71% per year. The analysis showed that losses of short-circuit current were responsible for the maximum power degradation. Judging by the appearance of the undegraded control modules, it is very doubtful that the short-circuit current losses were caused by encapsulation browning or obscuration. When we compared the quantum efficiency of a single cell in a degraded module to one from an unexposed control module, it appears that most of the degradation has occurred in the 800 – 1100 nm wavelength region, and not the short wavelength region.

INTRODUCTION

Recently we reported the results of a solar weathering program that subjected six different types of commercial PV modules to a number of real-time and accelerated exposures [1]. The weathering methods used were real-time outdoors at fixed tilt, accelerated outdoors at global normal irradiance and with 3× mirror enhancement (Outdoor Accelerated-weathering Test System, OATS), indoors under fluorescent light in the "A" range (UVA-340), and indoors under xenon arc (Atlas XR-260 Weatherometer).

Following well-established ASTM weathering standards developed by the materials industry [2], the exposure totals were quantified by the time integral of the UV irradiances. Standardized weathering test methods use UV doses rather than total irradiance doses because outdoor aging of materials such as paints and plastics can only be correlated with accelerated tests through UV exposures. For the four crystalline-Si module types in this study (both single and polycrystalline), a linear correlation between the normalized module maximum output power (P_{max}) and the total UV dose was found. Using the average annual UV dose for our outdoor site, 274 MJ/m^2, these rates translate to an average absolute maximum power point degradation rate of 0.71% per year. There was no correlation between the time-integrated total irradiances and the P_{max} losses.

ANALYSIS

For this work, we analyzed the degradation of these modules and determined that the losses in maximum power are almost entirely caused by losses in short-circuit current (I_{sc}). Table 1 summarizes these results and indicates that the open-circuit voltages (V_{oc}) and fill factors (FF) have changed only slightly. Note that the I_{sc} loss rates for the two single crystalline types and for the two polycrystalline types are nearly identical. Single #1 and Single #2 were produced by the same manufacturer, as were Poly #1 and Poly #2. This suggests these that rates may be intrinsic to the particular wafer processes used.

Fig. 1 shows the I-V curve parameters as a function of the total UV exposure dose for module type Single #2 in Table 1 (five different modules, one for each of the exposure methods). These figures, which are representative of the results from all four module types, show little or no

Table 1. A summary of the degradation rates observed in four types of crystalline Si modules subjected to the real-time and accelerated solar weathering program reported in Ref. [1]. Two different manufacturers are represented here; all four types have a nominal V_{oc} of 21 V. Also listed are the magnitudes of the initial rapid light-induced degradation caused by oxygen contamination.

Module Type	Power	P_{max} Rate	I_{sc} Rate	V_{oc} Rate	FF Rate	P_{max} Init. Loss	I_{sc} Init. Loss
	(W)	(% / year)	(% / year)	(% / year)	(% / year)	(%)	(%)
Single #1	11	-0.88	-0.59	-0.12	-0.14	-2.75	-2.26
Single #2	16	-0.76	-0.60	-0.14	-0.02	-3.87	-3.34
Poly #1	9	-0.70	-0.25	-0.14	-0.24	-2.34	-2.25
Poly #2	18	-0.53	-0.24	-0.08	-0.08	-2.56	-2.34

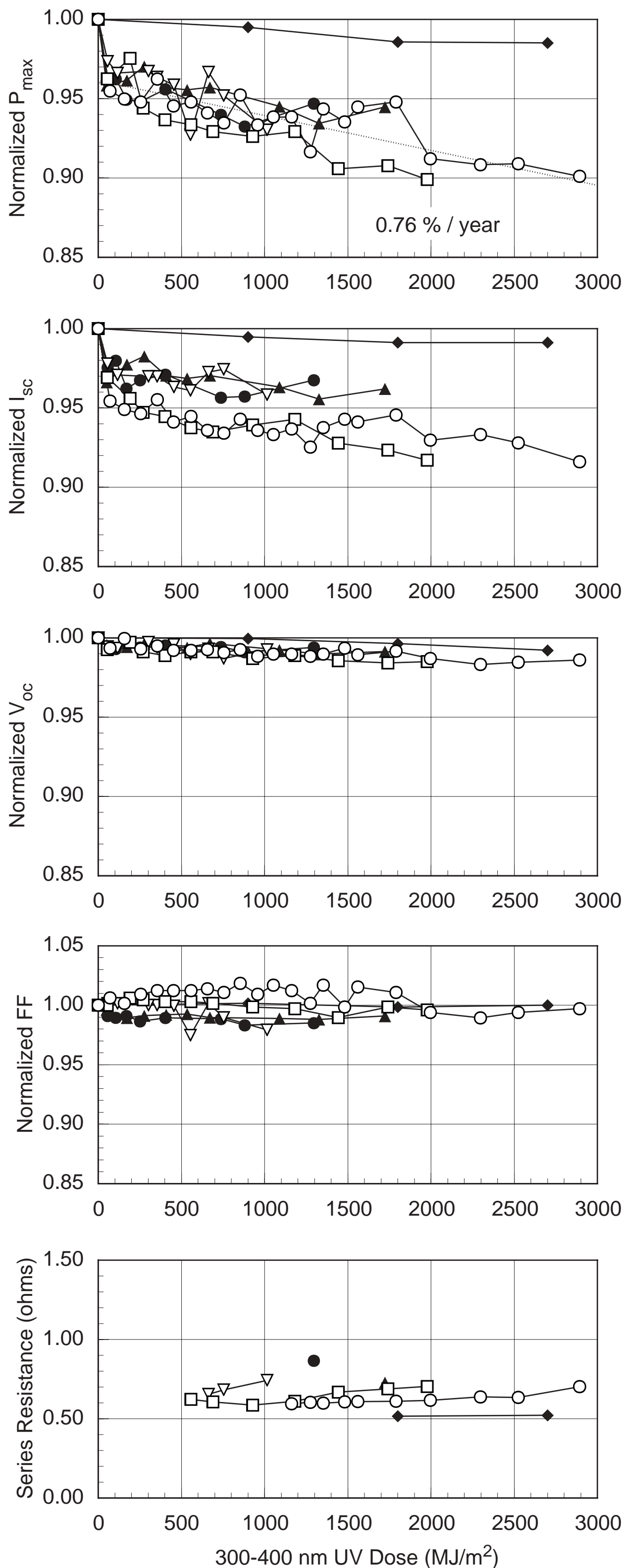

Fig. 1 (a-e). Normalized P_{max}, I_{sc}, V_{oc}, and FF, plus series resistance, for module type Single #2. Exposure methods are: control (◆), OATS 1× (●), OATS 3× (▲), real-time (▽), UVA (□), and XR-260 (○) (see Ref. [1]).

changes in FF and only slight drops in V_{oc}. Fig. 1e indicates slight increases in series resistance have occurred, but these are not yet large enough to cause any changes in FF.

Also visible in Figs. 1a and 1b is the rapid light-induced I_{sc} degradation of about -2% to -3%. This well-known phenomenon occurs immediately on initial illumination in boron-doped P-type crystalline Si solar cells with oxygen contamination and saturates within 50 h [3]. The slow I_{sc} degradation is evident after this initial drop, resulting in the two-line segment graph.

PREVIOUS RESULTS

Module outdoor weathering tests that show degradation of only I_{sc} and with roughly comparable rates have been published in the literature. Ref. [4] reported degradation rates of -0.53% to -0.76% per year in three modules measured monthly for 3.5 years. Similar measurements on three other modules at the same location with mirror enhancement (and therefore much like the OATS 3× experiment) had rates of -1.30% to -2.10% per year).

In Ref. [5], a shorter 1.5-year experiment was reported that showed rates of -3.7% to -5.0% per year in six identical modules, again with negligible changes to FF and V_{oc}. Assuming initial rapid I_{sc} drops of -2.5%, these rates correspond to about -0.8% to -1.7% per year of slow degradation. Note that these modules were exposed with varying voltage biases (0 V to 1.8 kV) between the frame and module leads, but there was no correlation between the degradation and the voltage bias.

POSSIBLE CAUSES

At this point, the analysis becomes a search for possible causes of the slow degradation. Only four causes appear to be worth investigating: 1) obscuration or absorption in the glass superstrate, 2) obscuration or absorption in the ethylene vinyl acetate (EVA) encapsulant, 3) degradation of the p-n junctions, or 4) thermal degradation.

We attempted to determine if obscuration or absorption could have caused the reductions in I_{sc} by careful side-by-side visual comparison of the degraded modules against the unexposed control modules. For all modules except those designated type Single #1 in Table 1, there were no visible differences between the exposed modules and the controls. In the case of the Single #1 UVA-340 and XR-260 modules, browned areas were visible. These areas were first noticed at the corners of the modules and then progressed along the edges. Lastly, brown areas became visible over the cells, similarly to previously reported EVA browning cases [6]. The UVA-340 module was darker than the XR-260; this module was exposed at a temperature about 10°C hotter [1]. Because of these results, it is possible that type Single #1 lacked UV-absorbing Ce glass, which has been found to minimize EVA browning.

In the past, degradation of P_{max} and I_{sc} in modules that show browning has been assumed to be caused by EVA degradation [4,6], but without conclusive evidence to support this assumption. Because browning is such a striking change in module appearance, the assumption is perhaps a natural one. In fact, a study of EVA discoloration as a function of accelerated exposure [7] concluded that: "solar cell performance degradation cannot be fully attributed to the extent of encapsulant discoloration." It is important to note that this study did not use unencapsulated samples to compare with the encapsulated ones. An analysis of losses in one module from the infamous Carrisa Plains system of the 1980s showed that only a 3% loss of I_{sc} could be attributed to EVA discoloration, and this module had severely brown areas directly over the solar cells [8]. In fact, this analysis concluded that most of the degradation in the Carrisa Plains system was caused by hot spots resulting from inadequate module bypass and blocking protection, and not browning.

On the other hand, we have measured I_{sc} losses up to 8% in modules without any visible yellowing, even though of the four Si module types in our program, only one type showed any evidence of EVA discoloration. We are therefore led to believe that the gradual loss of I_{sc} is not caused by obscuration or absorption, and instead must be a process operating on the semiconductor p-n junction.

An important clue about the effect is that it appears to depend solely on UV light. In Fig. 1, the Xe exposure (labeled XR-260) had a total irradiance of about 2000 W/m^2, whereas in the UVA-340 fluorescent experiment the total irradiance is only about 40 W/m^2, as it contains very few photons with wavelengths longer than 385 nm [1]. Even with this large irradiance difference, the degradation rates for both tests are nearly identical. Note that the XR-260 UV irradiance was about 50 W/m^2, which is just 20% higher than the UVA-340 irradiance.

In an effort to understand the nature of these current losses, we obtained quantum efficiency (QE) measurements of individual cells in two of the single-crystal Si modules characterized in Fig. 1 (type Single #2). Because unexposed QE data were not available, a cell from the control module was substituted. This QE curve was then scaled so that when integrated with the global reference spectrum, the resulting current density was equal to the I_{sc} of the XR-260 module before exposure. A similar procedure was used for an QE curve obtained from the XR-260 module, except that this curve was scaled to the I_{sc} after exposure. These are plotted in Fig. 2, which indicates that losses of both short and long wavelength response have occurred.

The magnitudes of these two losses were quantified by subtracting the exposed curve of Fig. 2 from the unexposed, and then performing a trapezoidal integration with the standard global reference spectrum [9]. Fig. 3 shows this integration as a function of wavelength, and indicates that the long wavelength loss is 2.5 times larger than the short wavelength one (although keep in mind that this analysis could not separate the rapid and slow degradation modes). Ref. [6] indicates that EVA yellowing does not occur in the near infrared region, which is further evidence against obscuration as the cause. EVA degradation cannot be ruled out as cause of the slight short wavelength loss in the 450 nm region, however.

If it is assumed that the slow degradation is caused by changes in the p-n junction, and considering that identical degradation rates are obtained with sunlight, Xe, and UVA-340 illumination, the very high absorption coefficient of UV

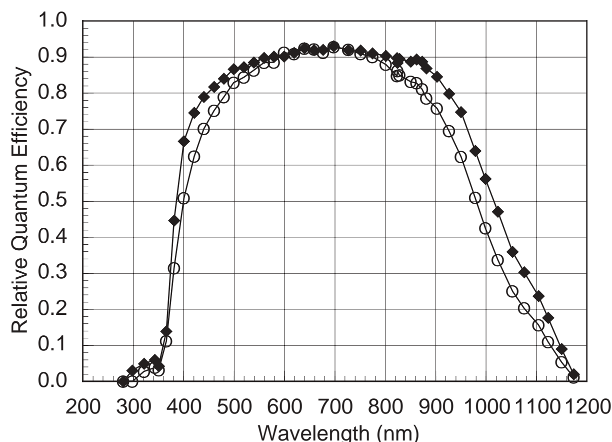

Fig. 2. Relative quantum efficiency for two individual cells from the Single #2 control and XR-260 modules, normalized to the unexposed (◆) and exposed (○) I_{sc} values of the XR-260 module (see text).

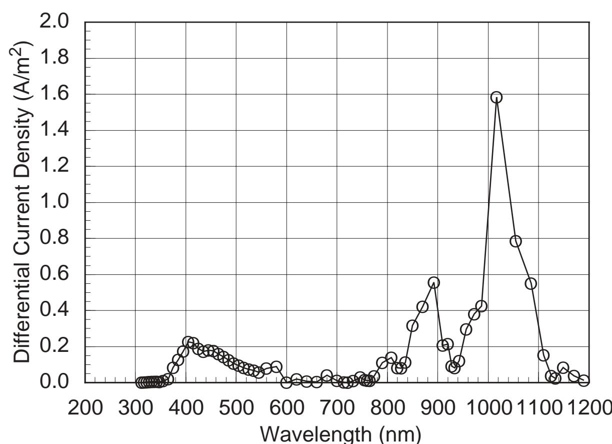

Fig. 3. The difference between the two QE curves in Fig. 2, weighted by the standard global reference spectrum, as a function of wavelength. The total I_{sc} loss in the exposed cell was -6.7%; the short wavelength loss was -1.8% and the long wavelength loss was -4.9%. Note that the total loss amount includes the rapid initial light-induced degradation of -3.8%.

irradiation would seem to indicate such changes are occurring at or near the Si surface. For wavelengths shorter than 400 nm, penetration depths into Si are less than 0.3 µm [10].

Finally, if the slow degradation we observed was due to a thermal process, it would be expected that the modules would degrade at different rates because the module temperatures were different [1]. Instead, they all degrade at similar rates, which seems to imply a cause that is not thermally activated.

FUTURE WORK

Diagnosing the slow I_{sc} degradation is problematic because a module is not a single device, but is actually composed of more than 30 devices electrically connected in series. The module I_{sc} is limited by the cell with the lowest I_{sc}, which can be affected by not only degradation but also measurement artifacts such as spatial nonuniformity of illumination. For the same reasons, reliable module quantum efficiency measurements are difficult to perform. Therefore, a new long-term Si degradation study is currently planned that will use individual cells rather than modules. The sample set will have large-area cells encapsulated in module-like packages and also bare unencapsulated cells.

CONCLUSIONS

Analysis of data from a long-term solar weathering study of commercial crystalline Si modules has revealed a slow I_{sc} degradation, which began after the rapid initial light-induced degradation caused by oxygen contamination in boron-doped Si solar cells. The rate of the slow degradation may be intrinsic to individual solar cell manufacturing processes. Because of a linear correlation between the slow degradation and the UV exposure dose, and because the same rates were observed under UVA-340 fluorescent illumination, the degradation is probably caused by UV absorption at or close to the top Si surface. Quantum efficiency measurements indicate that the bulk of the I_{sc} losses (both rapid and slow) occurred in the response region above 700 nm. Considering previous literature reports of I_{sc} losses with our results, it is very unlikely that the slow degradation was caused by encapsulation browning. The degradation also does not seem to be thermally activated.

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