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*Presented at the 25th European Photovoltaic Solar Energy
Conference and Exhibition
Valencia, Spain
September 6 – 10, 2010*

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5200-49344
July 2011

Contract No. DE-AC36-08GO28308

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Characterization of Multicrystalline Silicon Modules with System Bias Voltage Applied in Damp Heat

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ABSTRACT: Because it is considered economically favorable to build arrays with high system voltage by serially connecting photovoltaic (PV) modules, it is necessary to explore the potential long-term degradation mechanisms that the modules may incur under such electrical potential. We performed accelerated lifetime testing of multicrystalline silicon PV modules in 85°C/85% relative humidity (RH) and 45°C/30% RH while placing the active layer in either positive or negative 600 V bias with respect to the grounded module frame. A negative bias applied to the active layer leads to more rapid and catastrophic module power degradation compared to a positive bias. This negative bias degradation is associated with significant shunting of individual cells as indicated by electroluminescence, thermal imaging, and I-V curves. Mass spectroscopy results support ion migration as one of the causes. Electrolytic corrosion is seen occurring with the silicon nitride antireflective coating and silver gridlines, and there is ionic transport of metallization at the encapsulant interface observed with damp heat and applied bias. Leakage current and module degradation are found to be highly dependent on the module construction, with factors such as encapsulant and front glass resistivity affecting performance. Measured leakage currents range from about the same as those seen in published reports of modules deployed in Florida (USA) to about 100 times higher when undergoing environmental chamber testing.

Keywords: Multicrystalline Silicon, Module, Reliability

1 INTRODUCTION

Serially connecting photovoltaic (PV) modules to build arrays with high system voltage is considered to be economically favorable based on reduced wiring and inverter costs [1]. However, this requires exploration of potential long-term degradation mechanisms that the modules may incur under such electrical potential. The Jet Propulsion Laboratory (JPL) investigated PV module leakage current under system bias in the 1980s [2]. They studied the electrolytic corrosion mechanisms associated with the current that flows from the active layer of the module through the encapsulant to ground via the module frame and the acceleration of the degradation that occurs as a function of temperature and humidity of the module environment.

The National Renewable Energy Laboratory (NREL) later performed indoor and outdoor testing to characterize the long-term effects of system voltage applied to active layers of solar cells. It was found that current flows on the surface of the glass and through its bulk in humid conditions, but at lower humidity, current flows through the encapsulant/glass interface between the module frame and the active layer. Activation energies were also extrapolated for each process [3]. Indoor studies reviewed by Osterwald [4] indicated how corrosion occurs in the SnO₂:F transparent conductor layers in a-Si and CdTe modules when the active layer is biased negative with respect to the grounded module frame. Such damage is reduced by lowering humidity, reducing voltage potential between the frame and the active layer, changing from soda-lime glass to borosilicate glass, and moving the module mount from the glass edge to adhesive bonding on the module rear.

Subsequent outdoor tests by BP Solar [5], the Florida Solar Energy Center (FSEC) [6,7], and others documented how system bias affects leakage current in an actual hot and humid environment. Thin-film modules displayed leakage current outdoors often in the range of 0.1 to 8 mA in wet conditions. FSEC has also published how ions may migrate in fielded modules [8].

In high-efficiency, back-contact crystalline-silicon cells, a significant but readily reversible polarization affect was seen when a negative charge that developed over the cell surface because of leakage current (ion migration) through the glass face in positively biased strings led to annihilation of minority carriers in the n-type base. Specifying the positive terminal of the string as the grounded conductor has since mitigated this problem [9].

SOLON [10] and NREL [11] recently published studies detailing how system bias may also lead to shunting of multicrystalline solar cells. It is understood that negative-bias degradation involves the cells' junction properties because SOLON's work showed that widening of the depletion width through appropriate doping in the cell improved resistance to shunting. The NREL study indicates that dark I-V measurements show degradation or improvement in the diode-junction recombination parameters when negative or positive bias, respectively, are applied to the active layer. Ionic transport to the junction region was proposed as one of the possible mechanisms. A number of methods to mitigate degradation caused by high voltage potential were proposed, ranging from variations in the cell's silicon nitride antireflective coating to increasing the resistance to leakage current in the package design.

In this work, we further explore the degradation mechanisms such as the corrosion and the ionic motion that the stress of system bias exerts on PV modules. The leakage current and the path of that current—and how the module packaging contributes to them and the resulting degradation—are examined.

2 EXPERIMENT

Six commercially available Si module models in the 160–230 W_p range were subjected to 85°C/85% relative humidity (RH) in positive or negative 600 V bias, DH(+) or DH(-), respectively. The voltage bias was applied to the shorted module leads and the frame was grounded. The rated system voltage of these modules ranged from

600 to 1000 V. The current that flowed through each module under bias was monitored continuously over the course of the damp heat test. Modules were characterized by light and dark I-V measurements, imaged thermally, optically, and by electroluminescence. Two replicas of one of these module designs were stepped through a series of temperatures and RH stresses to determine the activation energy of current flow.

A designed experiment was carried out to test the effect of module packaging. The designs shown in Table 1 were constructed using 156-cm² multicrystalline cells encapsulated in single-cell mini module configurations. Additionally, the cells in the mini module group were divided into high lifetime (ingot center), low lifetime (ingot top or bottom), and mixed areas that include regions of low lifetime associated with the ingot edge that could be seen in electroluminescence. These frameless mini modules were placed in 45°C/30% RH with -1000 V applied to the shorted module leads with respect to the front glass surface, on which an anti-static carbon paste was applied to maintain the surface at ground potential. The samples were characterized for performance by Suns-Voc [12], thermal imaging, and electroluminescence.

Table 1. Constructions of one-cell mini modules. Six replicas per design were made.

Design	Glass	Encapsulant
1	Quartz	EVA
2	Soda-lime with sodium barrier	EVA
3	Soda-lime	EVA
4	Soda-lime	EVA with sodium acetate
5	Soda-lime	Ionomer-thermoplastic
6-control	Soda-lime	EVA

3 RESULTS AND DISCUSSION

3.1 85°C/85% RH with positive bias—commercial modules

In modules with the cells in the DH(+) configuration, corrosion of the silver grid fingers was apparent (Fig. 2). In aqueous solutions with bias applied to the cell, the reaction $Ag \rightarrow Ag^+ + e^-$ exists, whereby the Ag dissolution is proportional to the voltage applied [13]. The oxidation of the silver is a factor leading to increased series resistance of the module [11]. Leakage current has been reported to be greater with positive bias applied to the cell because of the comparative ease of ionization of the Ag anode, which provides the source of ionic migration leading to a leakage current through the wet encapsulant medium [2]. We however observed higher current flow with positive bias to the active layer in model 1 only (Fig. 1). In most cases, the ionic motion was apparently limited in a place weakly influenced by the direction of the bias.

The silicon nitride antireflective (AR) coating of the cells was observed to thin relatively uniformly—more rapidly in the case when there was greater moisture ingress, such as with delamination. Silicon nitride degradation was significantly more severe in model 1 compared to others tested. Not only was silicon nitride thinning observed in model 1 with bias applied, but also to a small extent in those tested in 1000 h at 85°C/85%

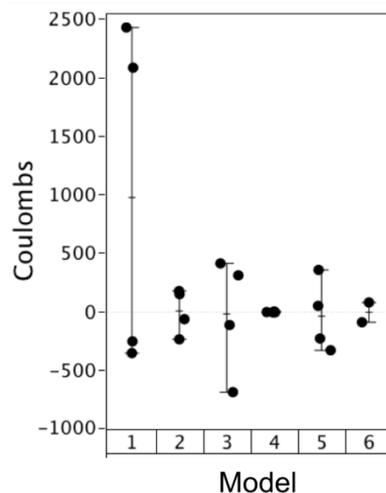


Fig. 1. Coulombs transferred for six module models after 1000 h of 85°C/85% relative humidity testing. Negative coulombs are indicated when negative bias is applied to the active layer. The models, excepting model 1, exhibit a similar rate of charge flow for either polarity.

RH without bias. Silicon nitride films are found to react with water at high temperature and pressure to form hydrous silica [14].

Because the silicon nitride degradation occurred much faster with bias applied, the reaction appears to be accelerated electrolytically. It has been reported that the AR coating on a cell comes under attack in a 0.1 molar HCl solution when a bias of 9 V is applied; however, the nature of the AR coating was not specified in that work [13].

Ionic transport from the bus ribbons to module edge was the principal phenomenon that was studied by JPL with the XTEST mini module sample geometry, whereby an electrode representing the grounded frame is positioned in the encapsulant at a set distance from a single cell [2]. Ion migration between the cell and electrode is precipitated with bias, temperature, and humidity. More recently, NREL has shown that when conduction occurs along the front surface of glass, such as in high relative humidity, conduction through the glass dominates with activation energy around 0.9 eV for crystalline-silicon modules, whereas the glass/encapsulant interface conduction is more prevalent at lower relative humidity with activation energies of 0.4—



Fig. 2. Region of a module (model 1) after 2000 h in damp heat with + 600 V applied to the active layer with respect to the grounded module frame. There is evidence of grid-finger corrosion and metal-ion transport from the bussing, especially in regions of de-adhesion in the model package seen on the bottom right of the image.

0.6 eV [3]. In these outdoor tests, the humidity inside the encapsulant is likely to become equilibrated, so the measured humidity in this case is that of the package exterior. The humidity increases the conduction of the face of the glass and bleeds current to ground.

Two replicas of module model 1 were subjected to various temperatures (Fig. 3) and relative humidities (Fig. 4) in the positive bias configuration. At a constant RH of 30%, the activation energy of these modules for current flow was 0.86 eV, which corresponds closely to the activation energy of current flow through glass (0.9 eV) [3]. This suggests current flow through the module face as the rate-limiting path for leakage, even at modest RH. Resistivity of the polymeric materials used in PV modules is orders of magnitude higher than soda-lime glass [15]. If the interfaces were to degrade in humidity or because of ultraviolet light, the current flow can revert through the interfaces. This was observed in model 1 placed at 85°C/85% RH with +600 V applied to the active layer with respect to the grounded module frame for 2000 h (Fig. 2). Current flow in this model was significantly elevated, as can be seen in Fig. 1.

This module design was also placed at 85°C with humidity stepped up to 85%. In the 65% to 70% range, there appears to be additional current flow mechanisms leading to a much higher current leakage. This is in contrast to the work of JPL, which found that leakage

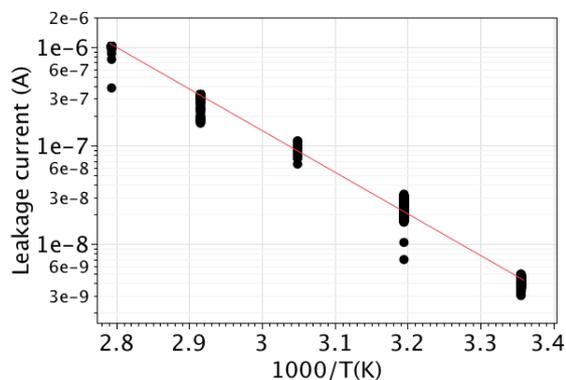


Fig. 3. Plot of leakage current of a module (model 1) at five temperatures (25°, 40°, 55°, 70°, and 85°C) and 30% RH. The activation energy for the current flow was 0.86 eV, which is similar to that reported for soda-lime glass. The voltage applied to the active layer was +600 V.

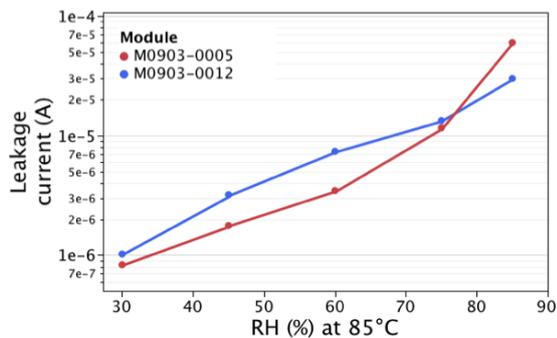


Fig. 4. Median leakage current as a function of RH at 85°C for two replicas of model 1. In the range of 60%–85% relative humidity, leakage current increases significantly. The voltage applied to the active layer was +600 V.

current saturates at higher humidity levels, but in parallel to the work of BP Solar, which found that the interfacial adhesion rate drops precipitously at 85% RH compared to 60% RH [5]. Considering that we observe interfacial ion migration in this model design in 85°C/85% RH (Fig. 2), there is remarkable consistency between the high leakage current, reduced interface strength, and visible ionic motion in model 1. In the framework of the results of del Cueto [3], we may consider that with weakened interfaces for reasons such as higher humidities than seen in outdoor tests, the leakage current can revert from through-glass to the encapsulant/glass interface.

3.2 85°C/85% RH with negative bias—commercial modules

Commercial modules were tested in 85°C/85% RH with –600 V applied to the active layer. Fill factor was the major source of power loss, and the root cause was cell shunting, which has been demonstrated previously for modules stressed in such conditions [10,11]. Significant differences in the performance of the modules can be seen after 1000 h, at which time some modules retained all their power, and some modules lost all their power (Fig. 6). Also of note was that the cells used in the construction of the modules that exhibited some of these extremes were reported to be from the same cell maker, pointing to the packaging as being an important modulator of this shunt degradation.

As with the positive bias case discussed above, silicon-nitride thinning occurred with increased moisture ingress, but much more drastically. Negative potential on the active layer can pull Na from the soda-lime glass toward the cell surface [16]. Studies of decomposition of silicon nitride have shown that sodium assists in the oxidation of silicon nitride at high temperature to form sodium silicate [17]. Although the chemistry of this system requires further study, the application of negative bias to the active layer in the sodium and-water-saturated

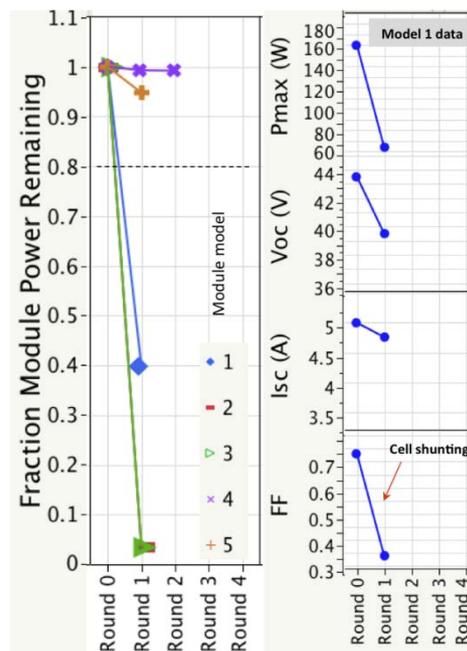


Fig. 6. Performance of five commercial modules in 85°C/85% RH, –600 V applied to the active layer for 1000 h rounds (left), and the detailed module test results for model 1 (right).

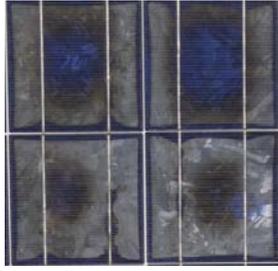


Fig. 7. Complete removal of the silicon nitride cell coating seen after 1000 h in 85°C/ 85% RH with -600 V applied to the active layer. Silicon nitride remains, however, in the center of the cell where water concentration is expected to be lower.

environment results in electrolytically assisted stripping of silicon nitride from the cell in a faster, more localized way than in the DH (+) configuration (Fig. 7).

Although migration of Na ions under bias has been studied in thin-film modules, the effects have not been well established in c-Si modules. SIMS analysis was carried out, comparing the silicon surface of a module exposed for 1000 h in 85°C/85% RH to a control that had never been encapsulated. The stressed sample was removed from an area of a module that exhibited delamination for ease of removal from the encapsulant. Although sample preparation was enabled because of the delamination, shunting in these regions tended to be lower according to thermal imaging; therefore, concentration of species causing shunting may be higher elsewhere. Also, one should note that the textured multicrystalline surface leads to inaccuracies in the depth resolution. With these provisos, it can be seen that a very high Na concentration exists in the vicinity of the surface of the stressed sample (Fig. 8). Cu, a species known to shunt junctions very effectively [18], can be seen in concentrations that are as much as one order of magnitude higher in the stressed sample compared to the control. The concentration of Fe was not found to be elevated in the stressed sample compared to the control, evidence that elevated Fe concentration is not a cause of the observed shunting degradation in the DH (-) configuration.

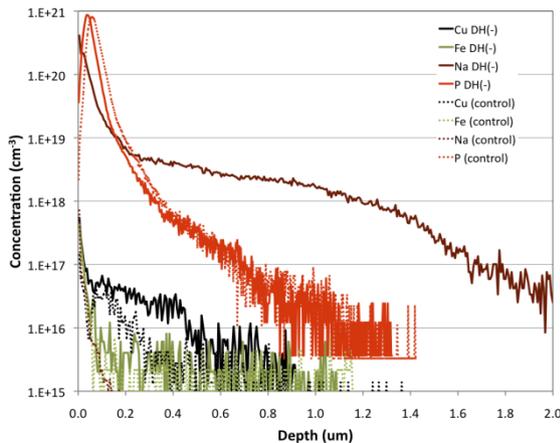


Fig. 8. SIMS analysis of a cell in a module that has undergone 1000 h of 85°C/85% RH with -600 V applied to the active layer. Significant Na accumulation and up to an order of magnitude higher Cu concentration is seen near the surface. Fe concentration was not significantly changed.

JPL attempted to make correlations between coulombs leaked per unit length of edge of the module frame (ground electrode) and the power degradation [19]. They suggested that precipitous (>50%) degradation occurred between 1 and 10 coulombs per centimeter (C/cm) of charge transfer. These results were obtained for stress conditions in the range of 70°–80°C, RH between 0% and 100%, and voltage bias between 30 and 500 V; however, the polarity of the bias was not specified. We examined this relationship for the six commercial module designs. The results shown in Fig. 9 (top) for +600 V bias applied to the active layer trend consistently with JPL results. Further, there is a noticeable and reasonably reproducible degradation of about 5% with charge transfer in the 0.1–1.0 C/cm range for the various models tested. After examining the degradation with negative bias to the active layer in Fig. 9 (bottom), one can see that the power is significantly degraded with less than 1.0 C/cm charge transfer—always more than 20% and usually more than 70% degraded. These results, however, offer little resolution in the 0.01 to 0.1 C/cm range. Bracketing the degradation over a decade, the failure occurs somewhere in the range of 0.02 to 0.2 C/cm.

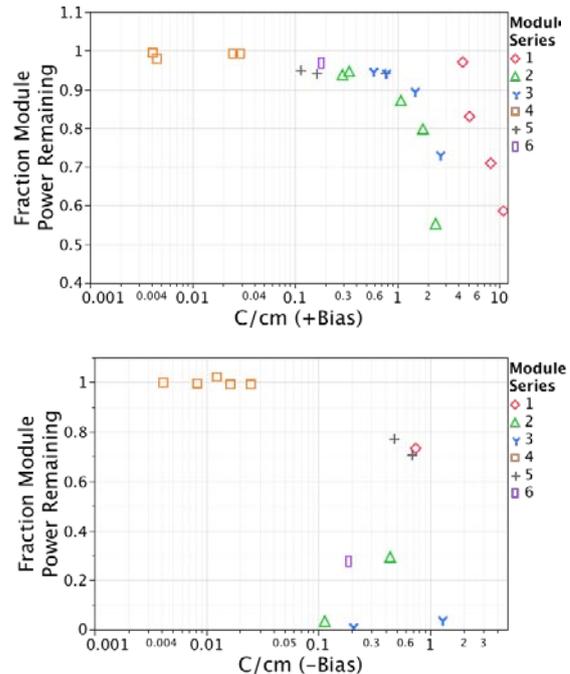


Fig. 9. Fraction of module power remaining vs. accumulated charge transfer for commercially available crystalline-Si modules with +600 V bias to active layer (top) and -600 V bias to active layer (bottom).

3.3 45°C/30% RH with negative bias—one-cell mini modules

One-cell mini modules with various constructions were exposed to -1000 V bias applied to shorted leads of the module in a 45°C/30% RH chamber. These chamber conditions were chosen to achieve an average activity for water that a module encapsulant may see in Florida (USA). An anti-static carbon-containing film was applied to the module faces over the cells with the goal of keeping the front surface at ground potential, as rain, mist, or condensation on the module face would provide, but in a constant and uniform manner.

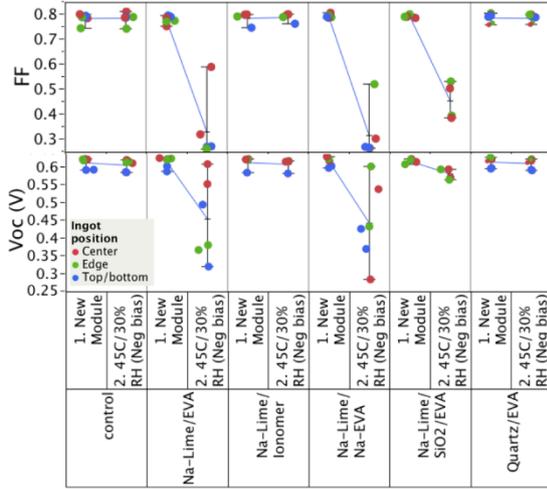


Fig. 10. Loss of pseudo fill factor (FF) and open-circuit voltage (Voc) after 140 h at 45°C/30% RH with -1000 V bias applied to the active layer for five mini module constructions (plus controls). Cells were made with wafers from various positions in the ingot. Control modules were not stressed.

The effect of this stress on mini module performance is shown in Fig. 10. The performance can be divided into three categories. (1) Samples with a quartz face or soda-lime glass in combination with an ionomer encapsulant did not degrade. (2) Soda-lime glass with an added SiO₂ barrier, as is used by the thin-film PV industry to mitigate Na migration, performed in an intermediate manner, but still showed significant degradation. (3) Conventional ethylene vinyl acetate (EVA) or EVA with added sodium acetate using soda-lime glass performed the least favorably. Based on these tests, there is no relationship between the degradation and the various impurities such as Fe and O that exist in higher concentrations in the silicon wafer at the ingot edges. Ingot edge regions that appeared dark due to lower lifetime in electroluminescence had no correlation with shunted regions after bias according to thermal imaging.

We have previously speculated that glass AR coatings may improve the performance of modules undergoing system voltage stress [11]. The present results further support this hypothesis because the soda-lime glass with an added SiO₂ barrier yields an improvement over the samples without the barrier (Fig. 10). Manufacturers such as SunPower have indicated that such films used as AR coatings are of higher purity than the glass itself and thus resist ion leaching [20].

The mini module data are applied in Fig. 11 to further understand the relationship between power degradation and coulombs per centimeter of module edge when there is a negative bias on the active layer. It is confirmed that less than 1x10⁻⁵ C/cm has no measurable effect on performance. Marked degradation occurs in the 0.001–0.01 C/cm range. We could not, however, resolve the effect of the SiO₂ film on glass with regard to reducing current flow, despite its ability to slow the voltage-bias degradation.

Whether it is because of the mini module design or the anti-static C paste that is used to transfer charge to

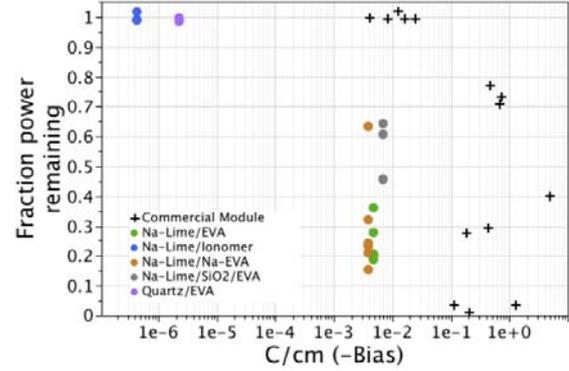


Fig. 11. Loss in power (as estimated by Suns-Voc technique) for five mini module constructions, superimposed over those results of commercial modules.

the cell more efficiently, the mini module degradation rate is much faster than that found in the damp-heat chamber-loaded commercial modules on a C/cm basis (Fig. 11). We therefore chose to exclude the mini module data in our estimate of 0.02–0.2 C/cm as the threshold for degradation of real modules in the DH(-) configuration that we extracted from the commercial full-size module data in Fig. 9 (bottom). It must, however, be considered that some differences in this threshold may be expected depending on current paths and nature of the materials used.

To put the lower limit of this range, 0.02 C/cm, in perspective, model 1 is analyzed further. Considering a leakage current through the glass at the IEC 61215 ed. 2 section 10.15 wet-leakage current limit, the area is 1.2 m², the resistance limit 33.2 MΩ, and the current 3 x 10⁻⁵ A at 1000 V. With a perimeter of 475 cm, 9.5 C would flow to reach this 0.02 C/cm threshold, and it would reach this threshold in 88 h. This is on the same order of the results previously reported for a module to degrade under system bias [10]. Instantaneously measured leakage currents of model 1 and the calculated time to reach 0.02 C/cm are given in Table 2 for other environmental conditions. The simplifying assumption that current is stable over time is made, which increases the uncertainty. Examples of mini module leakage

Table 2. Estimated time to failure for a 165 W mc-Si module in -1000 V bias (0.02 C per cm module frame threshold). Except for the current defined by the IEC 61215 ed. 2 limit, the leakage current was measured under the conditions indicated.

Conditions	Leakage current (A)	Time to 0.02 C/cm (h)
IEC 61215 ed. 2 wet-leakage current limit	3 x 10 ⁻⁵	88
85°C/30% RH (chamber)	9 x 10 ⁻⁶	293
55°C/30% RH (chamber)	1 x 10 ⁻⁷	26,400
55°C/~30% RH anti-static glass surface (outdoors)	2.2 x 10 ⁻⁴	12
33°C/~30% RH wet glass surface (outdoors)	4 x 10 ⁻⁸	66,000

current vs. time relationships have been previously published [2]. The time to reach the 0.02 C/cm threshold is seen to strongly depend on the environmental and surface condition. The leakage current was measured to be linear with applied voltage up to -1000 V.

Under hot conditions such as 85°C, which is shown to occur on roof-mounted modules with marginal air gap, and with moderate humidity, the degradation is predicted to be quite rapid. The wet-module condition at 33°C led to relatively slow predicted degradation; however, it would be expected that with higher temperature and increased conductivity in the water film (such as with salt mist or ion-containing pollution), the degradation would move toward the more rapid anti-static film-on-glass condition.

The current flowing from the active layer to ground has been also measured at NREL (Golden, Colorado, USA) [3], and the Florida Solar Energy Center (FSEC) [7]. At these locations, maximum leakage current of 2×10^{-6} A and 8×10^{-6} A, respectively, are reported under high humidity conditions. Outdoor-mounted mc-Si modules at NREL have recently been reported not to degrade under system voltage bias [21]; however, such modules at the more hot and humid FSEC location have degraded 4%–10% in power over several years [22]. Both studies, however, apply bias day and night, which accelerates the degradation through the humid (but cooler) night conditions. More work is therefore necessary to understand the degradation rate associated with high system voltage bias in fielded modules.

4.0 SUMMARY AND CONCLUSION

Differing degradation mechanisms are observed under positive and negative system bias voltage in damp heat and the rate of degradation is strongly differentiated by the polarity of the bias. A negative system bias applied to the active layer leads to more rapid and catastrophic module power degradation within 1000 h. This is associated with significant shunting of individual cells. A positive system bias is associated with Ag grid-finger corrosion and ion migration from the cell or interconnect metallization to the grounded module frame, especially in areas of high moisture ingress and weakened encapsulant. Based on the measured activation energy for module leakage current of 0.86 eV, ion transport through glass is the dominant mechanism at 30% RH (25°–85°C), and the magnitude of the leakage current is generally independent of bias direction except in a module design with high moisture ingress and weakened encapsulant adhesion. The threshold for severe degradation of 1–10 C/cm is still applicable per the work of the Jet Propulsion Laboratory (1985) for (+) bias to active layer, but we additionally find that 0.1–1.0 C/cm leads to ~5% degradation. A 0.02–0.2 C/cm threshold is proposed for (-) bias to active layer based on measurements of six commercial crystalline-silicon modules. Some types of degradation observed, such as electrolytic corrosion, will happen after many years in hot/humid environments, but others, such as ion migration, happen more quickly and are of pressing concern. Higher electrical resistance packaging will help reduce electrolytic and ion migration-related degradation, which can be controlled by choices including the glass and its coatings, the encapsulant, and the frame.

ACKNOWLEDGEMENTS

We thank David Trudell and Ed Gelak for help with the accelerated lifetime testing; Steve Rummel, Allan Anderberg, and Keith Emery for module measurements; Yu Wang, Kaitlyn VanSant, Ron Sinton, Michael Quintana, and Prof. Govindasamy Tamizhmani for helpful discussions. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory.

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