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SYSTEM VOLTAGE POTENTIAL-INDUCED DEGRADATION MECHANISMS IN PV MODULES AND METHODS FOR TEST

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ABSTRACT

Over the past decade, degradation and power loss have been observed in PV modules resulting from the stress exerted by system voltage bias. This is due in part to qualification tests and standards that do not adequately evaluate for the durability of modules to the long-term effects of high voltage bias experienced in fielded arrays. High voltage can lead to module degradation by multiple mechanisms. The extent of the voltage bias degradation is linked to the leakage current or coulombs passed from the silicon active layer through the encapsulant and glass to the grounded module frame, which can be experimentally determined; however, competing processes make the effect non-linear and history-dependent. Appropriate testing methods and stress levels are described that demonstrate module durability to system voltage potential-induced degradation (PID) mechanisms. This information, along with outdoor testing that is in progress, is used to estimate the acceleration factors needed to evaluate the durability of modules to system voltage stress. Na-rich precipitates are observed on the cell surface after stressing the module to induce PID in damp heat with negative bias applied to the active layer.

INTRODUCTION

Module qualification tests such as IEC 61215 and IEC 61646 for c-Si and thin-film modules, respectively, have shortcomings in their ability to evaluate some degradation mechanisms that modules experience. For example, voltage bias was identified as a stress factor in 1978 for inclusion into the qualification testing by the Jet Propulsion Laboratory (JPL) [1], and the need was called out again in 2005 by Swanson [2] for both high efficiency SunPower modules and conventional multicrystalline Si modules; however, a test to measure for durability to continuous system bias was not included in the present module qualification standards as it was deemed too stressful [3]. This unfortunate omission has cost the industry significant trouble and expense based on the numerous published and unpublished reports of degradation modes found under certain conditions in every common module technology related to the stress that the modules experience when mounted in arrays with increasingly high system voltage. Publications highlighting outdoor power degradation, mechanisms, or requirements for testing for high-voltage degradation include BP Solar [4] for amorphous-silicon (a-Si) modules, Florida Solar Energy Center (FSEC) [5] for a-Si and multicrystalline-silicon (mc-Si) modules, and SOLON [6] and NREL for mc-Si modules [7]. Sensitivities to elevated voltage for CdTe modules have also been indicated [8]. NREL [9] and FSEC [10] have reported activation energies for leakage paths through modules mounted outdoors, and information about the mitigation of system bias degradation on the module level has also been discussed in an NREL publication [11].

One mechanism of degradation associated with system bias is polarization, whereby current through the front glass leads to accumulation of trapped charge over the active layer. This charge can influence the surface field of the semiconductor active layer [2]. In severe cases, accumulation of mobile ions, such as Na, leads to delamination when the active layer is biased negatively [4,12]. In mc-Si modules, PID associated with a negatively biased active layer also leads to positive ions such as Na moving from the glass toward the active layer, but the observed cell shunting that results speculatively suggests incorporation of deleterious ions in the active layer [7]. Modules made of packaging materials that leak almost no current to ground, such as quartz front window layers and resistive thermoplastic encapsulants, do not degrade under system bias stress tests [13]. Material properties on the cell level that modulate the extent of PID have also been previously analyzed [6]. Usually in the presence of elevated humidity within the module, degradation by electrolytic corrosion occurs and macroscopic transport of ionized conductor metal may be observed [13-16]. In all these cases, current flow involving ionic motion in some part of the circuit between the high-voltage active layer of the module to ground is involved. There are publications showing how module leakage current to ground increases with environmental chamber temperature and relative humidity (RH) for samples designed to test for electrolytic corrosion [14-16] and with commercial modules [13]. Relationships between the accumulated leakage current and module power degradation were also shown.

We need to determine stress factors and levels for a test of modules' durability to system voltage that will serve the needs of materials and component makers, module makers, and PV customers. To do so, we must understand further the active degradation mechanisms and how they vary according to stress factors such as temperature, humidity, and bias. With this understanding, we can ensure that the stress levels for each factor are representative and reasonable to carry out in

consideration of cost, time, and effectiveness to evaluate modules' resistance to system voltage degradation.

In this paper, we evaluate the environmental conditions that factor into system voltage-induced degradation mechanisms. Considering these, we discuss the accelerated stress tests and suitable levels that reproduce the field-observed PID. We report on chamber step stress tests performed on mc-Si mini-modules to evaluate the relationship between level of stress and PID. This is followed by an analysis of acceleration factors as a function of temperature using leakage current measured in fielded modules as a basis and a discussion of the strategies and limitations for accelerated lifetime testing for PID. Finally, an evolving model for PID degradation is discussed.

RESULTS AND DISCUSSION

Accelerated stress factors and levels to test module durability to system voltage should be chosen in view of actual stresses incurred in the field, and the level of acceleration chosen such that the same mechanisms seen in the field are activated. With this, short-duration and cost-effective tests are sought. The stress factors examined here are system voltage, humidity, and temperature.

Outdoor Tests for Stress Factor Identification

JPL has shown how conductivity of encapsulant and leakage current increases with increased RH and temperature [14]; however, in fielded modules, humidity within the module packaging changes relatively slowly unless the packaging is compromised. In contrast, it changes rapidly over the module exterior surface according to the weather. Figure 1 shows leakage current of a module in Florida, USA, with –600 V applied to the active layer scaled logarithmically with the solar irradiance over the course of a day. It can be seen that the wet module associated with the morning dew or rains leads to an elevated leakage current as the system voltage rises with the sun. The leakage current decreases significantly when the module dries and the surface resistance increases (Figure 1, inset). Despite that conductivity of glass and encapsulant increases with temperature, the leakage current remains controlled by humidity, as can be seen by the correspondence between the calculated module surface RH and leakage-current curves when the irradiance and module temperature are higher in the middle of the day. It is therefore concluded that a wet environment will activate system voltage degradation mechanisms more than a hot, dry environment, based on the elevated leakage current.

Methods and Stress Levels for Accelerated Testing

The combination of voltage, humidity, and temperature must be applied at appropriate levels to test for system-voltage degradation mechanisms. Here, we examine

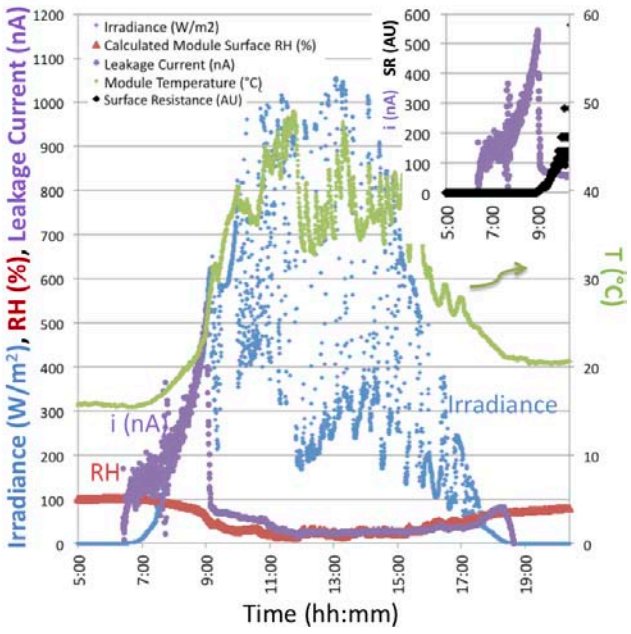

Figure 1. Leakage current to ground, irradiance, calculated module surface relative humidity (RH), and module temperature over a one-day period in Florida. The module is horizontally mounted, the active layer is biased to scale logarithmically with irradiance to a maximum voltage of –600 V with the module leads connected to a load resistor to maintain approximately P_{max}. The leakage current is highest when morning dew is on the module face and the surface resistance (SR) is low (inset). When the module is dry, the current most closely follows the calculated module surface RH.

levels based on the results in the literature, the outdoor test results (above), and further experimentation.

Voltage Bias

Application of nameplate system voltage has been shown to reveal sensitivity to polarization and PID mechanisms [6,13] within about 100 h. Increasing voltage beyond the module's nameplate rating may lead to alternate catastrophic breakdown mechanisms such as partial discharge, which is already evaluated in other tests such as IEC 61730-2.

In chamber stress testing, voltage to replicate system voltage bias may be applied to the shorted module leads (a Stanford PS 350 was used in our tests). The external module components are connected to ground through a resistor over which voltage is measured to determine leakage current. A voltage divider may be used to prevent a short circuit through the module packaging from applying a voltage that exceeds the specifications of the voltmeter (see Fig. 2). It must be ensured that the module mounting hardware is of sufficient resistance even in a humid test environment such that leakage current to ground flows through the measurement circuit. The module may be

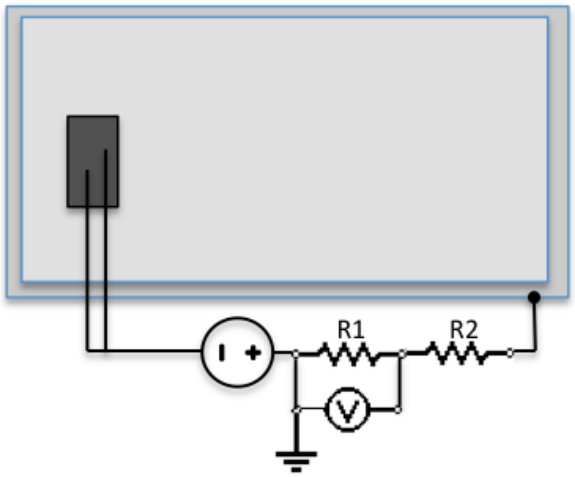

Figure 2. Application of voltage to the active layer of a PV module via the shorted leads. The leakage current is monitored by a voltmeter across a resistor R1 connected to ground. The voltmeter may be protected from overvoltage by a second resistor R2.

intermittently disconnected to evaluate its dark IV characteristics *in situ*. Common among the test methods used to evaluate the system-bias voltage degradation is the application of a medium on the module that creates an efficient path to ground. Testing has been carried out in an accelerated manner in environmental test chambers [7,14] and saline water baths [2]. Variants to achieve grounding to the module face include placing it on a wet towel and application of a conductive paste; however, leakage path may be unrepresentatively constrained with such methods and miss detection of degradation mechanisms associated with leakage current through the edges and rear should the conductive medium be applied only to the module face. A comparison of the favorable traits of three configurations to test modules for system voltage durability is shown in Table 1. In this work, testing was carried out in an environmental chamber, with either uniform humidity or conductive paste applied specifically to the glass to drive current through the glass.

	Environmental Chamber	Water tank	Conductive paste
Multiple modules	✔		✔
Temperature and humidity control	✔		
Tool people have	✔	✔	✔
Uniformity	✔		
Cost		✔	✔
Safety	✔		

✔ = favorable

Table 1. A comparison of the traits of three mediums to test modules for system voltage durability.

Humidity

Humidity is seen to be a key factor in the circuit that enables a leakage current (see Fig. 1). Conductivity of glass increases with RH up to 100% [17]. Because modules regularly see surfaces at 100% RH (dew, rain, wet snow), it is reasonable to test with 100% RH applied to the module. This is readily achievable by applying water, wet towels, or conductive paste to the module. In the case of an environmental chamber, approaching 100% RH leads to the concern that small temperature variations will cause uneven condensation and excess stress on the tool if specialized testing equipment is not used. We therefore select a conventional level of 85% RH for chamber tests.

Temperature

Although choices for test levels for humidity and voltage are relatively straightforward, there are several considerations for choosing temperature. A frequently heard criticism is that the 85°C/85% RH 1000 h damp heat test represents an unrealistically high activity of water for module materials, causing accelerated hydrolytic degradation of the polymeric materials [18] and extensive electrolytic corrosion that is not seen in fielded modules stressed by system voltage [7]. Raising the test temperature would lead to increased diffusion rate of water into the module, a higher saturation limit, and higher ultimate water content. The encapsulant of a mc-Si module that experiences heating in the sun is dried regularly such that the equilibrium humidity contained in the encapsulant is lowered. We see that leakage current is not increased over the course of a day as the temperature rises (Fig. 1), so excessively increasing the temperature to activate leakage current-related degradation mechanisms would not support what we observe in the field. On the other hand, some level of humidity is required to test for susceptibility to electrolytic corrosion over the lifetime of a module in an accelerated manner. Considering these factors, the optimum test temperature is not deduced *a priori*.

To test the effect of temperature under constant RH, two modules were placed in an environmental chamber and connected to a circuit as shown in Fig. 2 with –600 V bias applied to the active layer. The chamber was held at 85% RH, and the temperature was ramped in stages from 25° to 85°C with 4-h holds. The temperature ramps were done quickly to avoid saturating the module's interior with humidity over the course of the test. Figure 3 shows the Arrhenius behavior of the two modules, a new one and one that was pre-stressed and soiled. The fit of the data for the new module displays Arrhenius behavior over the temperature range tested with activation energy E_a=0.94 eV (90.7 kJ/mol). This suggests a range of temperatures that the module can be exposed to achieve a single, thermally activated current flow mechanism for the presumably constant humidity within the module. The data for the soiled and pre-stressed module indicate that an additional conduction mechanism is active at low temperature, which may be associated with the conductivity

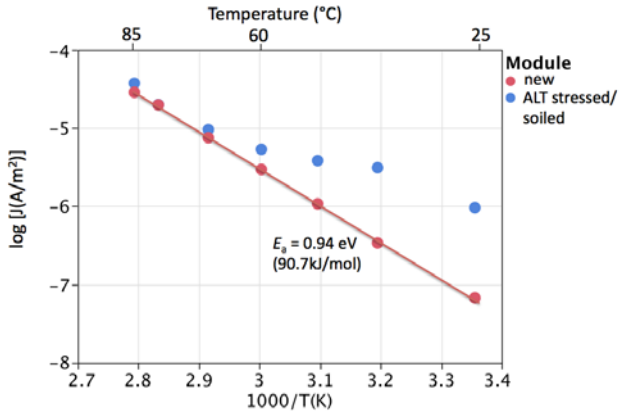

Figure 3. Arrhenius behavior of leakage current normalized to active area of modules in 85% RH as a function of temperature. A new module displays such behavior over the range 25° to 85°C, whereas a pre-accelerated lifetime test (ALT)-stressed and soiled module displays greater leakage current at lower temperature.

of the soil or the existence of alternate leakage paths, before the dominant damp heat-controlled current flows at higher temperature. In addition to water, materials such as clay soil, volcanic soil, and salt deposit would be expected to significantly reduce resistance across the glass face to the module frame.

The choice of testing time revolves around the question of how long it will take for modules in the field under system voltage stress to show signs of degradation. Field tests to determine this answer are being undertaken by a number of groups, but results are just beginning to be obtained. The precedent indicator of the extent of degradation is the coulombs leaked by the module at system voltage. Coulombs normalized to length (cm) of frame edge have been used as a metric. JPL [14] found that 1–10 C/cm was the onset for severe degradation, although some modules exhibited degradation greater that 20% when reaching the 10^{-4} C/cm range. Some of the samples were specifically designed to test electrolytic corrosion with mass transport of ions between the simulated frame edge and the cell. Using modern commercial silicon modules, we found in chamber tests that severe degradation could occur around 0.02 C/cm when the active layer was negatively biased at –600 V rated system voltage, but our findings generally agreed with the JPL results for positive bias. As pointed out by DelCueto and McMahon [9], in higher humidity environments, it is expected that the main transport path of ions will be normal to the active layer, encapsulant, and glass, and then lateral on the damp glass surface to the frame. When the wet glass surface is not the limiting resistance in the circuit, it makes more sense to normalize leakage current to module active area (i.e., current density).

Testing Mini-Modules for PID

A relationship between coulombs leaked by the module and degradation is useful, but this is expected to be an oversimplification. The path of current flow, through the glass versus through the packaging interfaces, will affect the mechanism; high humidity and mobile ion concentration in the encapsulant will promote ionic current through the encapsulant toward the frame and lead to electrolytic corrosion. For PID, it was shown that simple annealing of the module at 100°C leads to a partial reversal of the degradation [6]. This thermally activated process will most certainly be active in fielded modules on hot sunny days, so after a wet period characterized by high leakage current and PID, sufficient heating of the module is expected to lead to a degree of recovery of module power. Level of stress also matters with respect to the active degradation mechanism. Modules exposed to the NREL Test-to-Failure protocol (–600 V, 85°C/ 85% RH, 1000 h) recovered only marginally with application of reverse bias [13], whereas PID induced at lower temperature (48°C) recovered almost completely on reversal of the bias in about 100 h [6].

To explore further the effect of module packaging, level of stress, and reversibility, a group of one-cell mc-Si mini-modules was exposed to increasing levels of temperature and humidity. The sample construction was described previously [13]. Negative 1000 V bias was first applied to the active layer, followed by a recovery with positive 1000 V bias. This sequence was repeated incrementally at higher temperature and RH combinations. Carbon-containing paste was applied over the glass face to induce through-glass current flow and associated degradation mechanisms. The samples were given one week in the chamber at the step-level temperature and humidity before voltage was applied to the shorted module leads for 130-h periods. Changes in pseudo fill factor (pFF) determined by Suns-Voc after each segment of the test are shown in Fig. 4. The change in pFF represents losses associated with shunt resistance and carrier recombination, but is void of series resistance. Junction shunting is the main loss mechanism associated with PID [6,7].

The following observations are drawn based on this step stress test: pFF is not completely recovered after the first application of positive bias at 45°C, 30% RH. The pFF is further degraded after each subsequent +1000 V recovery cycle. On the other hand, there is significantly less change in the median pFF with subsequent –1000 V degradation cycles at higher temperature and humidity, although several samples degraded extensively at 60°C, 60% RH, and –1000 V. An increase in leakage current at higher temperature/voltage levels was confirmed (Fig. 4b). Modules encapsulated with high electrical resistance thermoplastic or using quartz did not exhibit any degradation.

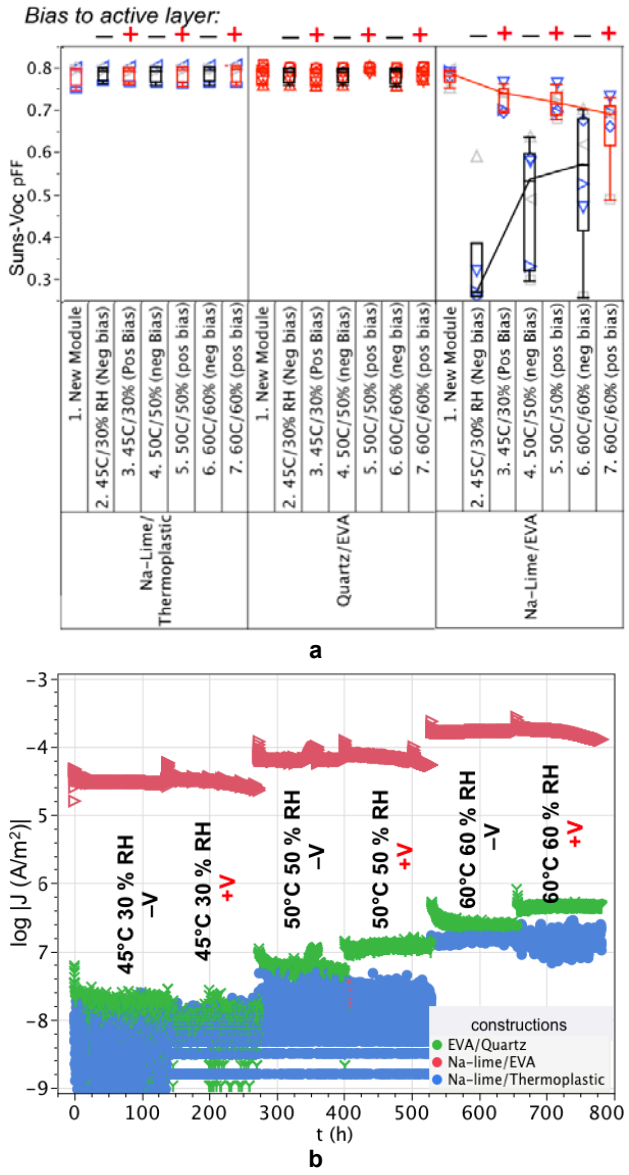

Figure 4. (a) Loss of pseudo fill factor (pFF) after 130-h RH segments of alternating –/+1000 V bias applied to the active layer for three mini-module constructions, stepped through increasingly higher temperature and RH levels. Data are fit with quartile box plots and group medians are connected. Different point styles/colors are to track the samples. (b) Leakage-current density for the three constructions showing the current to be higher by three orders of magnitude for the EVA/soda-lime glass construction that exhibits PID. They however show reduced PID at higher stress levels despite the increased leakage current.

At issue is the appearance that PID degradation is history-dependent, and the observation that subsequent higher temperature, RH, and leakage current combinations do not lead to greater degradation. Also, considering that partial PID recovery with thermal annealing is observed [6], it cannot be assumed that a module that is subjected to an extent of charge transported continuously will exhibit the same power degradation as one that experiences that same leaked charge accumulated intermittently over high-humidity days and days of bright sunshine. Based on Fig. 4, it would appear that a continuously applied stress would lead to the most severe degradation per coulomb leaked.

Acceleration Factors

We compared the electric charge leaked (in coulombs) of chamber-stressed modules described in Fig. 3 to similar modules fielded at the same system voltage (–600 V, scaled logarithmically with irradiance) in Florida, over a 3-month period (from February to April) as a basis to determine the acceleration factor (Fig. 5). We note that the acceleration factor at 25°C in chamber is near unity—a day in chamber at 85% RH has the same leakage current as a day in the field. It appears that fielded modules see periods of wetness where leakage current is significantly higher than that at 85% RH in chamber in addition to periods of dryness, which balances out to the equivalent of a 24 h period at 25°C, 85% RH in chamber. Because we know that modules can recover from PID degradation to some extent by thermal treatment [6], and we observe non-linear relationships between stress level, leakage current, and PID, we speculate and must yet verify that the module degradation in the field could be less than that of a continuous chamber stress test done at a given acceleration factor using coulombs as a basis. A more accurate understanding of the acceleration factor for PID is anticipated with more extensive field data.

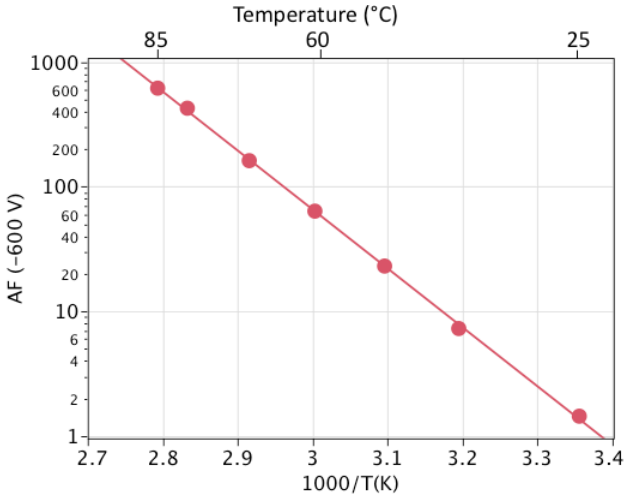

Figure 5. Acceleration factor for leakage current in a chamber as a function of temperature at 85% RH compared to a similar module fielded in Florida with simulated –600 V system voltage, measured for a 3 month period. Time to achieve the equivalent coulombs leaked is used as the metric for the ratio.

Ionic Transport

Sodium migrated from the glass has been seen to accumulate at the transparent conductive oxide layer of a-Si modules in negative bias [12]. We have previously shown high Na concentration and increasing Cu levels in the surface and sub-surface area of the cell after negative bias is applied to the mc-Si active layer of modules in 85°C/85%RH by secondary ion mass spectroscopy (SIMS) [13]. Auger electron spectroscopy indicates precipitation of sodium at the surface of the cell, on the silicon nitride, and at locations such as defects in the silicon nitride (see Fig. 6). It is believed that various metal ions in addition to Na from the large holding volume of impurities, the soda lime glass, are electrostatically attracted to the surface. The active layer at –600 V can act as a source of electrons such that the ions are chemically reduced and electrodeposited. It is however not yet clear which species causes the p/n junction, typically 0.2 -0.3 μm below the silicon surface, to exhibit shunting by the PID mechanism.

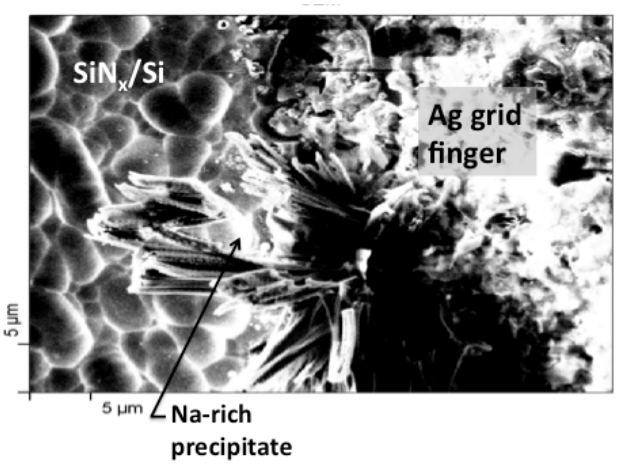

Figure 6. A sodium-rich precipitate (confirmed by Auger electron spectroscopy) deposited on a mc-Si cell in a module subjected to 1000 h of 85°C/85% RH damp heat with –600 V applied to the active layer.

SUMMARY AND CONCLUSIONS

As standardized module performance tests do not adequately evaluate for the durability of modules to system bias, we suggested stress factors, levels, and methods for testing based on the stresses that fielded modules see. Module leakage current is highest in the morning associated with dew and remnant precipitation from the night. Over the course of a day, the magnitude of the leakage current moves opposite to module temperature, despite the higher conductivity of glass and the encapsulant, because the module dries out and leaves no surface humidity to complete the circuit to ground. Modules in continuously wet climates are expected to show the greatest system voltage-related degradation considering the observation that wetness is the most important environmental factor for elevated leakage current and the relationship between module leakage current and power degradation. For a new module with surface maintained at 85% RH, the leakage current was found to be Arrhenius with temperature in the range of 25° to 85°C, suggesting a constant mechanism for leakage current-related degradation throughout this range; however, as humidity is allowed to permeate the encapsulant with time, it is expected that additional electrolytic corrosion mechanisms will become active. A number of methods to ground the module surface were considered, each with their particular advantages depending on the situation and experimental needs; however, conventional environmental chamber testing at 85% RH with nameplate-rated system bias applied to the active layer has the benefit of being able to measure multiple modules with uniform humidity and safety. Initial estimates of acceleration factors in chamber tests were calculated as a function of temperature based on leakage current observed in similar modules mounted in Florida. This must, however, be moderated by the fact that module power degradation was measured to not be strictly a function of net coulombs leaked to ground. These results, in combination with those in the literature, suggest that a constant stress with humidity and system voltage will be more damaging than that stress applied intermittently or with periods of recovery comprising hot and dry conditions or alternating bias in between. Further, observations of Na migration leading to electrodeposition on the cell surface in a negatively biased module were made.

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