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Effects of Photovoltaic Module Soiling on Glass Surface Resistance and Potential-Induced Degradation

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Abstract — **The sheet resistance of three soil types (Arizona road dust, soot, and sea salt) on glass were measured by the transmission line method as a function of relative humidity (RH) between 39% and 95% at 60°C. Sea salt yielded a 3.5 orders of magnitude decrease in resistance on the glass surface when the RH was increased over this RH range. Arizona road dust showed reduced sheet resistance at lower RH, but with less humidity sensitivity over the range tested. The soot sample did not show significant resistivity change compared to the unsoiled control. Photovoltaic modules with sea salt on their faces were step-stressed between 25% and 95% RH at 60°C applying -1000 V bias to the active cell circuit. Leakage current from the cell circuit to ground ranged between two and ten times higher than that of the unsoiled controls. Degradation rate of modules with salt on the surface increased with increasing RH and time.**

Index Terms — **dust, photovoltaic modules, potential-induced degradation, sea salt, soiling, soot, surface resistance.**

I. INTRODUCTION

Environmental factors affecting rate of potential-induced degradation (PID) in conventional front (n^+/p) junction conventional cells include temperature, humidity (both internal and external to the module) [1,2], illumination [3], voltage potential of the active cell circuit [4], recovery history [5,6], and system grounding configuration [4]. Soiling on the module face that can change its conductivity has received relatively little direct attention in terms of controlled experiments. However, it has been observed that modules by the sea exhibit elevated leakage current [7]. Conductivity over the face of the active cell circuit—whether it be the encapsulant, glass, or a ground conductor over the whole glass face—influences the nature of the degradation because of the path to ground [8]. It is anticipated that some soil types deposited on module glass will cause decreased surface resistance, leading to extension of the potential of a grounded module frame more effectively across a glass surface. Screening tests of various soil types would inform which soils could potentially have the greatest influence on PID and raise awareness for photovoltaic (PV) power plant developers in those environments with the most impactful soil types.

In this work, three soil types were tested for sheet resistance on glass: Arizona road dust, soot, and ASTM D1141-98 sea salt. Based on the outcome, sea salt, which had the greatest impact on reducing sheet resistance at elevated relative humidity (RH) levels, was deposited on modules to examine the leakage current from active cell circuit to ground and the PID rate relative to control modules with unsoiled glass as a function of relative humidity at 60°C.

II. EXPERIMENT

Square 413-cm^2 Starphire (low-iron) untextured glass was used for soil deposition to determine its electrical resistance. Particle coatings were applied in a similar technique as described in [9]. Glass coupons were weighed prior and post soil deposition to determine the mass loading. Simulants of common soils, including Arizona road dust (A2 fine grade, Powder Technology, Inc.), sea salts (ASTM D-1141-52, Lake Products Co., Inc.), and soot (in-house formulation, consisting of 92% carbon black [Vulcan XC-723], 5.3% diesel particulate matter [NIST Catalog No. 2975], 2.8% unused 10W30 motor oil, 0.1% β-pinene [Catalog No. AC13127-2500, Acros Organics]) were suspended in deionized H_2O, at a ratio of 3.3 g/275 mL. Water was selected as the carrier solvent to avoid any compatibility concerns with the electrical contacts on the glass. Deposited non-aqueous mass loading was 2.75 ± 0.87 g/m^2.

3M Electrically Conductive Aluminum Tape #3302 was used for conductor stripes in transmission line method (TLM) patterns. The TLM methodology to extract sheet resistance of a layer is described in Schroeder [10]. Sheet resistance in units of ohms per square (Ω/□) was chosen as the electrical resistance parameter to characterize soiling because of the generic applicability of the results for surfaces of arbitrary area and because of the ability to determine sheet resistance independent of contact resistance. The stripe dimensions (length x width) were 15.25 cm x 1 cm, and the spacing between the edges of the different conductor stripes were 0.25, 0.50, 1.5, and 2.0 cm. A board containing multiple probes was used to make contact to the conductor stripes, and 100 V was applied between the adjacent stripes while monitoring current with separate probes to determine resistance. The resolution of the apparatus at 60°C and 39% RH is 5×10^{-9} A, but surface conductivity of the probe holder board at 95% RH led to a background current of 1.5×10^{-8} A. The probe apparatus and sample were placed within an environmental chamber to determine the sheet resistance of the soiled glass as a function of relative humidity stepped in increments from 39% to 95% with 1.25 h dwells at each level and 60°C, a typical peak open-rack module temperature [11]. Repeat measurement cycles on samples were not performed because of visible corrosion of the contact metallization and ion migration.

Testing on full-size modules was performed on two pairs of 60-cell conventional (n^+/p) multicrystalline silicon 240-W class module types. One of each module type had salt placed on the glass face and frame; the other in the pair was used as a control with clean glass surfaces. An aqueous solution of 20% by weight ASTM D1141-98 sea salt was applied in two spray/dry cycles with 25 g/m^2 total dry mass loading and inserted into an environmental chamber for stress testing at 60°C, stepping the relative humidity at levels of 25% 65%, 85%, and 95%, with -1000 V applied to the shorted module leads. Leakage current was monitored and degradation of maximum power ($P_{\max}$) at standard test condition (STC) was semicontinuously monitored using dark current-voltage curves measured *in-situ* in the environmental chamber at stress temperature using our previously developed method [12].

III. RESULTS AND DISCUSSION

Calculated sheet resistances obtained for the three deposited soils and the unsoiled glass control module are given in Fig 1. The resistance between the contact stripes for the TLM analysis with which this figure was developed appeared constant at the lower intervals but tended to decrease during the hold times at higher relative humidity. The variability is speculatively attributed to time-dependent reactions considering the humidity, constituents of the test sample, and electrochemical reactions. Repeat experiments on given glass samples showed corrosion of the aluminum contact stripes similar to aluminum module frames that show corrosion after stress testing with bias [13]. For the TLM measurements, a corresponding threshold in current was observed on reaching each relative humidity level, so these initial values were used for the TLM calculations. Time-dependent effects on surface resistance therefore remain open for further study.

To the extent we could resolve, the unsoiled glass sample used as a control had steady sheet resistance with time up to and including the 67% RH level at about 6×10^{10} Ω/□. However, this is significantly above that specified by vendors of the glass used, 10^6 Ω/□– 10^8 Ω/□ range [14]. On the other hand, solar PV glass manufacturers have also specified 10^{10} Ω·cm bulk resistance [15] or 3.1×10^{10} Ω/□ for the 3.18-mm-thick glass sheet resistance. The resolution provided by the instrumentation is therefore believed to be on the order of the sheet resistance of the clean glass or better. The primary source of noise in the TLM measurements is inconsistent contact resistance under the various contact stripes on a given sample.

Systematic decreases in sheet resistance can be seen for the various samples with increasing relative humidity (Fig. 1). Arizona road dust showed lower sheet resistance compared to the control at lower relative humidity and with comparatively less humidity sensitivity over the range tested. Elevated leakage current independent of humidity would suggest increased PID in a low-humidity environment. The soot sample did not show significant conductivity over the unsoiled control; on the other hand, different soot and other carbon-containing compounds may have differing results. Sea salt yielded a 3.5 orders of magnitude decrease in resistance on the glass surface when the relative humidity was increased from 39% to 95%.

Because of sea salt's important effect on glass surface sheet resistance, this material was chosen for examination of the effects on leakage current and module PID rate of two module types referred to as A and B and compared to controls of each type with no soiling. Leakage current measured on the modules with salt were a factor of two to ten times higher than the modules without sea salt (Fig. 2). The greater leakage current of full size module samples with salt over those without salt compared to the TLM samples in Fig. 1 may be due to the greater mass loading of salt on the modules. Time-dependent increases on the leakage current are not seen at lower RH within the time frame of each RH level step; however, at the 85% and 95% levels, the modules with sea salt applied show significant increase in leakage current as a function of time. This increase may be due to corrosion of aluminum, ion migration, and changing chemistry on the glass surface, which was observed after samples were stressed. Those samples without salt tend to be more stable, or sometimes have decreasing leakage current versus time at each RH stress level.

PID rate of the two modules at the last 3 h of each RH level is reported in Fig. 3. Just as the leakage current of the modules with salt increased more significantly over their controls toward the end of the dwell at the 85% and 95% RH conditions, the measured PID rates were at their maximum at the end of the dwells. At the 25% and 65% conditions, the intrinsic behavior of the individual variation in the modules seems to have dominated over the soilant.

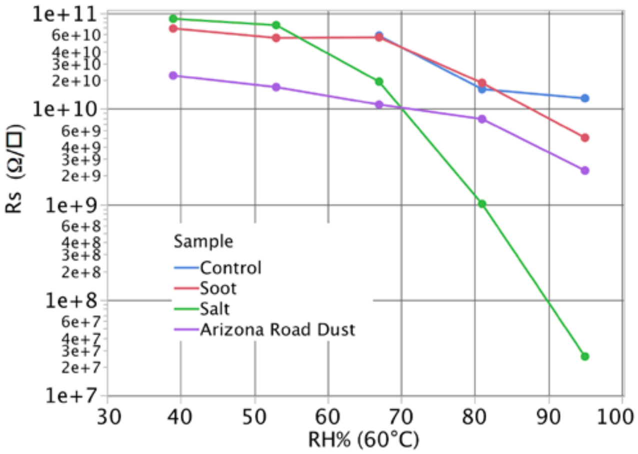

Fig. 1. Sheet resistance of various soils as on glass and an unsoiled control as a function of relative humidity at 60°C.

PID rate may correlate on a given module type with leakage current [2], and leakage current was also found to increase here when the PID rate increases (see Figs. 2 and 3). It is expected that if dwell time at each level were extended, the leakage current and PID rates of the salt group modules would be even greater than their corresponding control modules. Dwell time was practically limited by the finite life of the module and the desire to maintain the module at more comparable states between each RH stress level.

Electroluminescence images of module type A obtained by subtracting pre- and post-stress testing states with and without salt on the surface are given in Fig. 4.

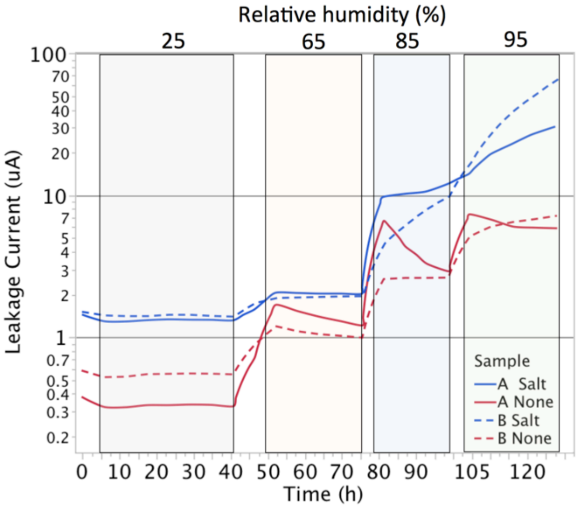

Fig 2. Leakage current measured from two pairs of module types, one in each pair with sea salt on the surface. Modules were stressed at four relative-humidity level steps as shown, 60°C, and –1000 V.

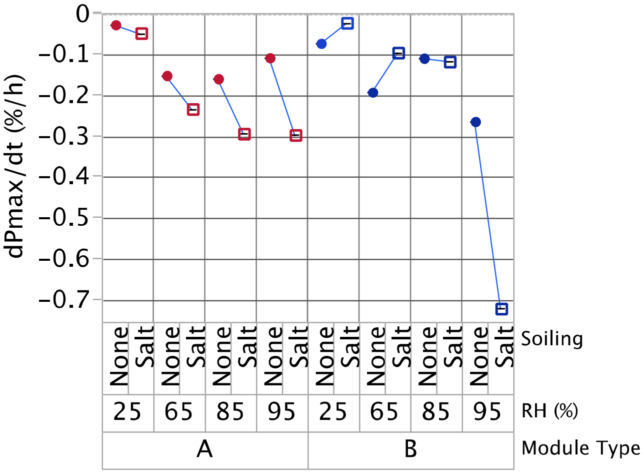

Fig. 3. Potential-induced degradation rate of maximum power for two module types (A and B) with and without sea salt applied at 60°C as a function of relative humidity at the end of the dwells shown in Fig. 2. Connecting lines are drawn to show the trends.

Electroluminescence images are not shown for sample type B, which exhibited similar, but less distinguishable effects. A small effect of the salt and increased degradation can be seen in Fig 4a based on the increased cell darkening because of the degraded p-n junction associated with PID compared to that of the clean control module in Fig. 4b. Despite the salt that increased the conductivity on the surface and measurably increased the leakage current, the degradation still remains primarily concentrated at the module edges near the frame. This suggests that the ionic current flow, generally considered to be Na^+ motion toward the cells in the case of negatively biased cell circuits, is primarily concentrated at the edges. These experimental results are consistent with modeling results, which show that for modules with packaging having relatively low bulk resistivity in the front face, the ionic leakage preferentially flows to the cells at the module edges for a wide range of front-surface lateral resistances [16]. High glass and encapsulant volume resistivity would lead to more even distribution of leakage current across the face—associated with a more constant voltage potential between the external glass surface and the active cell circuit of the module—but lower net current magnitude [17].

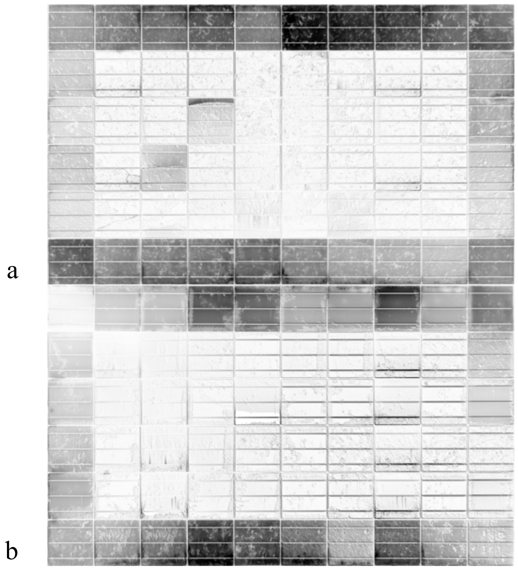

Fig. 4. Subtractive electroluminescence images taken at 4.1-A forward-bias current on module type A with salt; (a), 73.3% power remaining; (b) without salt, 84.7% power remaining. Degraded areas appear dark.

IV. SUMMARY AND CONCLUSIONS

Soiling is frequently implicated as a factor promoting PID in the natural environment. To develop an understanding of which soiling environments accelerate PID, three soiling types were examined for surface sheet resistance by the TLM method as a function of relative humidity. The soot sample showed little difference compared to the clean glass control. Arizona road dust showed a decreased resistivity at low relative humidity, but relatively little humidity dependence. Sea salt showed an important decrease in resistivity starting at the 67% RH level and 3.5 orders of magnitude lower sheet resistance at 95% RH.

In examining sea salt on 60-cell crystalline silicon commercial modules, we found time-dependent increases in leakage current at 85% and 95% relative humidity leading to increased PID. These results show significant PID risk in soiling environments that have salt. Because of this result, examination of other soil types and further investigation into time-dependent effects are indicated.

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