Surface Disruption Method With Flexible Glass to Prevent Potential-Induced Degradation of the Shunting Type in PV Modules

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Surface Disruption Method With Flexible Glass to Prevent Potential-Induced Degradation of the Shunting Type in PV Modules

Jaewon Oh, GovindaSany TamizhMani, Stuart Bowden, and Sean Garner

Abstract—Potential-induced degradation of the shunting type (PID-s) has recently been recognized by the industry as a critical photovoltaic (PV) module durability issue. Many methods to prevent PID-s have been developed at the cell and module levels in the factory and at the system level in the field. This paper presents a prospective method for eliminating or minimizing the PID-s issue either in the factory during manufacturing or in the field after system installation. The method uses commercially available, thin, and flexible Corning Willow Glass sheets or strips on the PV module glass superstrates, disrupting the current leakage path from the cells to the grounded frame.

Index Terms—Durability, high voltage, potential-induced degradation (PID), reliability, solar cells.

I. INTRODUCTION

POTENTIAL-INDUCED degradation (PID) is a performance degradation caused by a high negative voltage difference between the photovoltaic (PV) cells and the aluminum frame under humid environmental conditions. PID has a serious impact on the PV system durability over a short period of time [1], [2]. PID caused by junction shunting is specifically referred to as the PID of the shunting type (PID-s) [3], [4]. Although the mechanism responsible for PID-s is not yet fully understood, many scientific studies have suggested that the migration of sodium ions from the PV module glass, such as soda-lime glass, to the cell causes PID-s [5]–[7]. Various methods to prevent or minimize PID-s have been developed and applied at the cell, module, and system levels. These include modification of the antireflece coating on the cell surface to prevent PID-s at the cell level [1], [7], [8]. At the system level, modules affected by PID-s during daytime can be recovered by applying the opposite potential at night [7]; however, 100% recovery cannot be achieved with this method [9]. At the module level, PID-s can be prevented by using alternative module components, such as a new type of encapsulant material or glass. For example, using an ionomer instead of ethylene-vinyl acetate (EVA) as an encapsulant effectively minimizes PID-s because the conductivity of an ionomer is much lower than that of EVA [5], [10]. Selecting module glass with a PID-resistant property, such as absence of sodium or high electrical conductivity, is another simple way to address the PID-s issue [5], [9], [11]. However, the use of such replacement materials could prove to be expensive and/or could result in lower durability or reliability over the long life of PV modules. We have presented an innovative method to prevent PID-s using surface interruption, which does not require changes in the module components [12]. In this paper, we present a simple, reliable, and cost-effective method based on our previous work [12] to prevent or minimize PID-s at the module level in the factory or at the system level in the field (patent pending) [13]. This method uses commercially available, thin, and flexible Corning Willow Glass sheets or strips on the PV module glass superstrates.

II. EXPERIMENTS

Standard 156 × 156-mm² p-type monocrystalline-Si solar cells, which are PID-s-susceptible, were obtained from commercial sources and investigated in this study. Each cell was laminated as a one-cell coupon with the same PV module construction materials and structure (glass–EVA–cell–EVA–backsheet) by using a commercial laminator (NPC LM-110 × 160-s). Typical commercial-grade PV module materials, such as soda-lime solar glass (8 × 8 in²), EVA, and TPE backsheet, were chosen for fabricating the one-cell coupons. To simulate an aluminum frame, aluminum tape with conductive adhesive was attached onto the edges of the coupons. The aluminum tape was not attached onto the top edge due to the presence of the positive and negative leads, as shown in Fig. 1.

To replicate and accelerate the PID-s, three environmental conditions were required: temperature, humidity, and voltage. To simplify the test setup, the high humidity that causes high glass surface conductivity can be replaced with aluminum foil on the module glass and aluminum frame. In this case, no
humidity-controlled chamber is needed. PID-s stress was applied either at 60 °C and 0% relative humidity (RH) or at 60 °C and 85% RH, with an applied voltage of $-600 \text{ V}$ on the cell with respect to the aluminum tape at the edges. The 0% RH condition was used when the glass surface was fully covered with aluminum tape, overlapping the aluminum tape at the edges; the 85% RH condition was used when the glass surface was not covered with aluminum tape. All the one-cell coupons were characterized by light current–voltage ($I–V$), dark $I–V$, and electroluminescence (EL) imaging before and after the PID-s stress tests.

Use of flexible Willow Glass has been demonstrated in a variety of flexible electronic applications including displays, touch sensors, lighting, and PV devices [14]. It is very light, thin ($\sim 100 \mu\text{m}$), and flexible. Because of its unique alkali-free borosilicate composition, the glass was considered to be a good candidate for addressing the PID-s issue.

The Willow Glass sheets were attached onto the glass of the test coupons in three different ways. For the first of these, a square Willow Glass sheet (16 cm $\times$ 16 cm) was placed on the one-cell coupon as shown in Fig. 2(a), and then, aluminum tape was used to cover the whole surface, including the Willow Glass (coupon A). An existence of air gap between the Willow Glass and the one-cell coupon glass is possible due to roughness differences of those glass surfaces, and the air gap could increase an electrical resistance causing less front surface conductivity affecting the extent of PID-s testing. To minimize the possible air gap, a heavy object was placed on the aluminum tape, and an additional aluminum foil was taped tightening both the object and the one-cell coupon. Because the front aluminum covers the whole cell surface, no humidity was needed to carry out the PID-s test. For the second glass attachment method, the square Willow Glass was placed between the front coupon glass and cell (Coupon B). The module laminator was used to encapsulate the Willow Glass. An additional EVA sheet was utilized for this encapsulation, which has the structure (front glass–EVA–Willow Glass–EVA–cell–EVA–backsheets) shown in Fig. 2(b).

In the third glass attachment method, aluminum tape was used to attach a rectangular Willow Glass strip (17.5 cm $\times$ 2 cm) around the edges (coupon C). Only half of the glass strips were covered by the edge aluminum tape, as shown in Figs. 1 (right) and 2(c). Further, various commercially available products were tested as alternative materials for this edge interruption concept. For example, hydrophobic spray (manufacturers A and B) or ionomer were applied to around the edges where the Willow Glass was placed.

Coupons B and C had no aluminum tape on the front surface; thus, 85% RH was used while applying the PID-s stress to these samples. Reference coupons without Willow Glass were also fabricated, and the PID-s setup for these was kept identical to the test conditions employed for a given coupon. Thus, 0% RH was used for reference coupon A, and 85% RH was used for that of coupons B and C.

### III. RESULTS AND DISCUSSION

#### A. Square Sheet Willow Glass for Surface Interruption

As shown in Fig. 3(a) and (b), coupon A showed no PID-s in the area where the Willow Glass film/sheet was placed, whereas the reference coupon experienced PID-s resulting in 20% $P_{\text{max}}$ decrease all over the cell area. The edge of coupon A was, however, observed to be a bit darker (shunting) after the PID-s stress application when compared with its initial state. The dark shunted area of Coupon A caused a decrease of shunt resistance leading to 5% $P_{\text{max}}$ degradation, as shown in Table I. Contact between the front aluminum tape and the gaps between the Willow Glass and edge aluminum tape caused this PID-s progression. Thus, PID-s could be prevented if the gaps were fully insulated from the front aluminum tape under conditions of no humidity (with front aluminum tape covered). To avoid or minimize the humidity ingress issue between the Willow Glass and module glass, the Willow Glass could be fixed with an
interpenetrating bonding material, for example, an ionomer, as indicated in Section III-C.

Because Willow Glass is thin, lightweight, and has acceptable transmittance and exceptionally lower conductivity than common soda-lime glass, it can be applied not only on the front surface of the PV module glass (Coupon A) but underneath the glass (Coupon B) as well as shown in Fig. 2(b). PID-s stressing was carried out on this one-cell coupon (Coupon B) under 60 °C/85%RH, −600 V conditions for 96 h. In addition, a PID-s-free EV A one-cell coupon (with no Willow Glass but commercially available PID-s-free EV A instead of common EV A) was PID-s stressed to compare the PID-s-resistance. Whereas coupon B showed extremely strong PID-s-resistance, the PID-s-free EV A coupon (“Coupon B-2”) suffered from PID-s that resulted in more than a 10% power decrease, as shown in Fig. 4. We also performed a PID-s test for a coupon having a commercially available PID-s-free cell with regular EV A, and even this cell exhibited PID-s with a power loss greater than 30% in 96 h. These alleged PID-s-free EV A and cells would both fail the PID standard [15]. It is possible that the failure of these PID-s-free EVA and cells might be attributed to nonoptimized lamination conditions for those components. Nevertheless, it is suggested that PID-s-free EVA/cells available in the open market should be carefully evaluated when replacing the existing components to safely avoid PID-s.

It was expected that adding an additional EV A layer and the Willow Glass between the solar glass and the cell might result in a decrease in the transmittance. The first row in Table II shows the cell performance loss due to the additional layers in the coupon before PID-s stressing. The data comprising this row were created by measuring I–V performance of nearly identical cells before and after lamination. The decrease of transmittance before PID-s stressing due to the additional layers causes short circuit current (Isc) loss, which results in an efficiency loss (−2% before PID-s). Interestingly, the efficiency (relative) was rather improved from −2% to 1% due to an Isc increase after the 96-h PID-s stress. It is suspected that the test condition (60 °C and 96 h) leads to transmittance improvement of the EV A, which could be caused by better curing of the EV A. In addition, a freshness of the EVA could affect the lamination quality as the manufacturer states in the specification sheet. There were limitations in keeping the EVA fresh in ASU Solar Power Laboratory, since our laboratory was not designed for commercial PV manufacturing. This might suggest that the lamination process should be optimized to minimize Isc loss or even improve Isc when the Willow Glass is applied below the PV module glass.

The method used in Coupons A and B showed great PID-s resistance using the Willow Glass. However, Coupon B method has a few disadvantages in applying them on the PV modules operating in a real field. First, overall output power will decrease

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>CELL PARAMETER BEFORE AND AFTER PID-s STRESS TESTING</th>
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<tbody>
<tr>
<td></td>
<td>Pmax (W)</td>
</tr>
<tr>
<td>Coupon A</td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>3.87</td>
</tr>
<tr>
<td>PID-s 96 h</td>
<td>3.68</td>
</tr>
<tr>
<td>Reference Coupon</td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>3.79</td>
</tr>
<tr>
<td>PID-s 96 h</td>
<td>3.03</td>
</tr>
</tbody>
</table>

![Fig. 3](image)

Fig. 3. EL image before/after PID-s. (a) Coupon A initial. (b) Coupon A after PID-s. (c) Reference coupon initial. (d) Reference coupon after PID-s. PID-s stress applied at 60 °C/0%RH (with aluminum tape front covered), −600 V, 96 h.

![Fig. 4](image)

Fig. 4. PID-s progress under 60 °C/85% RH, −600 V for 96 h. (a) Coupon with the Willow Glass. (b) Coupon with PID-s-free EVA (no Willow Glass).

<table>
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<tr>
<th>TABLE II</th>
<th>CELL PARAMETER RELATIVE DIFFERENCES DUE TO THE ADDITIONAL WILLOW GLASS SHEET AND EVA LAYER</th>
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<tbody>
<tr>
<td></td>
<td>Isc (%)</td>
</tr>
<tr>
<td>Before PID-s</td>
<td>−1.71</td>
</tr>
<tr>
<td>After PID-s 96 h</td>
<td>0.74</td>
</tr>
</tbody>
</table>
Fig. 5. Cross section of typical PV module that shows the resistance of PV module materials affecting PID-s susceptibility.

due to a lower transmittance from additional bonding layer and Willow Glass. Second, cost could be considerably higher when the Willow Glass covering all the cells in a PV module is used on the PV module surface or placed between the module glass and an additional EVA. The Coupon B method requiring large surface area of Willow Glass could lead to marginal or considerable increase in the module manufacturing cost as compared with the other method using alternative encapsulant materials proven to be PID-s-resistant, such as polyolefin [16]–[19] or ionomer [10], [20], due to additional process and materials. In order to address these issues, the amount of these additional materials covering the cells/module should be minimized. These issues are addressed by using edge interruption method using Willow Glass strips, which is presented in Sections III-B and C. The edge interruption method that is used in Coupon C is much more cost effective than Coupon A or B, since the required area of Willow Glass is much less than 10% of the additional material used in Coupon A or B. Moreover, there is no transmittance loss on to the cells, since the strips are applied only around the module edges. Therefore, we anticipate that the Coupon C method should have a higher market penetration, as compared to the Coupon B method.

An illustrative PID-s circuit with high humidity or rain for the field-installed PV modules can be drawn as shown in Fig. 5. The surface interruption method demonstrated in this section is maximized by increasing the $R_{\text{front surface}}$, as schematically depicted in the circuit diagram shown in Fig. 5. Willow Glass above the coupon glass provides an extremely high $R_{\text{front surface}}$, which interrupted PID-s. The Willow glass below the coupon glass also increases the resistance between the front glass and the cell so that PID-s is interrupted. In the literature, it has been reported that PID-s can be prevented/reduced by increasing $R_{\text{glass}}$ [5], [11] or $R_{\text{encapsulant}}$ [10], [16], [21]. An advantage of using the Willow Glass when compared with these PID-s prevention techniques is that there is no need to change potentially PID-s-susceptible PV module materials or cells, which are already used in the module construction. PID-s could be simply minimized or eliminated even after manufacturing the modules, by simply adding the thin flexible Willow Glass in the PV module structure/construction. In other words, Willow Glass can be used as an insulating or PID-s circuit interrupting barrier to block sodium transport to the cells, even if common soda-lime glass is used or PID-s-susceptible cell is used in the module structure.

B. Rectangular Strip Willow Glass for Edge Interruption

Using a conceptual setup, previous researchers of this research group reported that PID-s can be prevented or mitigated by interrupting the surface continuity near the frame edge of the PV module [22], [23]. In this method, the circuit shown in Fig. 5 is conceptually interrupted by a very high value of $R_{\text{edge}}$, thereby preventing PID-s without any transmittance loss to the cells as they are attached away from the cell at the frame edge. To prove this conceptual approach through the use of a physical material as a circuit interrupter, we applied Willow Glass strips/films to a one-cell coupon to increase the $R_{\text{edge}}$. A portion of the Willow Glass strip was fixed by edge aluminum tape [see Fig. 2(c)]; thus, the Willow Glass was in direct contact with the coupon glass. The results shown in Figs. 6 and 7 indicate that PID-s can be physically prevented due to near-edge surface disruption caused by the Willow Glass strips. Coupon C showed nearly no degradation in terms of maximum power ($P_{\text{max}}$), whereas the $P_{\text{max}}$ of the reference coupon showed a power loss of 10% at standard test conditions and 40% at low irradiance, as shown in Fig. 7(c). It should be noted that the bottom of the cell in coupon
C was slightly affected by PID-s, as shown in the EL image in Fig. 6(b). In that area, there was a decrease of about 55% in shunt resistance ($R_{sh}$), as shown in Fig. 7(c). These effects were caused by the unintended conductive path resulting from water ingress between the Willow Glass and the coupon glass during the PID-s stress test. This conductive path can be prevented by avoiding the water ingress with the use of an improved method presented in Section III-C for affixing the Willow Glass at the edges of the coupon glass.

C. Ionomer-Bonded Willow Glass Strip for Edge Interruption

Since the edge interruption method in preventing PID-s was proved to be working, it was expected that any high $R_{edge}$ materials that are interrupting the circuit should work as well. One of the candidates studied was a hydrophobic material, which could interrupt the circuit by repelling water near the coupon edges. The hydrophobic material chosen from two different manufacturers was sprayed around the edges of two coupons, and then, PID-s stressing was carried out at 60 °C/85%RH, −600 V for 5 h. Both coupons exhibited PID-s. This could be attributable to pinholes or cracks in the hydrophobic layer, as shown in Fig. 8. The 85%RH in a weathering chamber is maintained by mist, and the mist could possibly permeate into the pinholes/cracks, which facilitate creating a conducting path to the front coupon glass. It is suggested that the hydrophobic materials for the edge interruption method should not have those defects to effectively prevent PID-s if they are applied to module edges. Electrical insulating spray was also tried to increase the $R_{edge}$. According to the manufacturer of the insulating spray, it is not hydrophobic, but it is used to protect surfaces against weather, moisture, corrosion, oil, alkalies, and acids. The aforementioned PID-s stress conditions were applied to the coupon with the insulating spray, and it was determined that this material also did not work in preventing PID-s. It showed a rather stronger degradation in power than the coupon with the hydrophobic layer. It is suspected that the insulating layer created by spraying also has the pinholes. Another material we found for this edge interruption method was ionomer. The ionomer has a high bulk resistivity and has been known as a good insulation material for PV modules [10]. Ionomer strips the same size as the Willow Glass strips were applied around the one-cell coupon edges using the PV module laminator. After PID-s stressing at 60 °C/85%RH, −600 V for 5 h, the coupon showed only 1% power decrease, while a coupon having no edge interruption showed a power decrease >10%. The ionomer strip was then used as a bonding material in fixing the Willow Glass strip onto the coupon glass. PID-s results of the coupon with Willow Glass bonded by a thin ionomer layer showed only approximately 1% power decrease. As shown in Fig. 9, there are nearly no changes in $I$–$V$ curves and no significant shunting spots based on EL images. It is expected that the Willow Glass strip with ionomer would provide reliable PID-s prevention, since the Willow Glass provides a hermetic good barrier for the well-demonstrated Willow Glass circuit interrupter. In addition, the Willow Glass protects the ionomer from deterioration caused by direct atmosphere exposure, such as UV, humidity, and soiling. However, application of Coupon C method in the field would be challenging as it currently requires a lamination process of Willow Glass strips with underlying ionomer layer. It is, therefore, anticipated that the application of Coupon C method in the field without lamination process requires additional research to successfully implement this method in the field. Nevertheless, this work still demonstrates that the ionomer-bonded Willow Glass strips near the frame edges on the glass surface can prevent the PID-s in the long-term field conditions through the removal of conductive path resulting from water ingress between Willow Glass and module glass.
IV. SUMMARY AND CONCLUSION

In this paper, we present a simple method that uses thin flexible/film Corning Willow Glass on the surface of the glass superstrate to prevent PID-s. Adding a Willow Glass layer onto the glass superstrate effectively minimized or eliminated PID-s. One of the innovative advantages of Willow Glass could be applied onto the glass superstrates of modules not only during manufacturing but in the field by taking advantage of edge disruption as well. Currently manufactured PV modules are expected to mostly contain the PID-s-free cells, but a large fraction of the p-base crystalline silicon PV modules installed over the last ten years might have a potential susceptibility to PID-s. Applying this edge disruption method to those field-installed modules would be a simple and low-cost way to prevent or minimize PID-s progression. The surface disruption method presented in this work was demonstrated to be effective. Further experiments are in progress to apply this method to full-size commercial PV modules.

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Authors’ photographs and biographies not available at the time of publication.