Potential-Induced Degradation-Delamination Mode in Crystalline Silicon Modules

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Abstract

A test sequence producing potential-induced degradation–delamination (PID-d) in crystalline silicon (c-Si) modules was tested and its results were found comparable under visual inspection to cell/encapsulant delamination seen in some fielded modules. Four commercial modules were put through this sequence: 85°C, 85% relative humidity (RH), 1,000 hours (h) damp heat, followed by an intensive PID stress sequence of 72°C, 95% RH, and -1,000 volts (V), with the module face grounded using a metal foil. The 60-cell c-Si modules exhibiting the highest current transfer ($4.4 \cdot 10^{-4}$ A) exhibited PID-d at the first inspection after 156 h of PID stress. Effects promoting PID-d are: accelerated loss of adhesion due to damp heat, sodium migration further reducing adhesion to the cells, and gaseous products of electrochemical reactions driven by the applied system voltage. An International Electrotechnical Commission (IEC) technical specification to evaluate for PID-d is anticipated.

Introduction

Various delamination modes have been seen in crystalline silicon (c-Si) photovoltaic (PV) modules deployed in the field. Some of these delamination modes are understood, such as those resulting from volatile organic compounds from ethylene vinyl acetate (EVA) leading to bubbles [1]. Degradation or failures associated with potential-induced degradation (PID) have been known to take a number of forms, including polarization, charge developed over the cell face causing carrier recombination [2], and shunting (PID-s), where sodium ions are transported by voltage potential to the cell, diffusing into defects causing junction recombination losses and shunting of the junction [3]-[5].

Corrosion can also lead to delamination. This effect has been extensively studied in transparent conductive oxide (TCO) layers of thin-film modules, such as SnO_2F and ZnO [6]-[8]. In the case of voltage bias applied over a TCO-coated glass such that the electric field points to the TCO, Na^+ ions migrate toward the TCO-glass interface and accumulate. In the presence of humidity, reaction products of the sodium, TCO, and water lead to blistering and cracking of the TCO.

Sometimes delamination over the Si cell surface is associated with the metallization [9]. There have been reports of grid finger blossoming, the appearance of rainbow-like diffraction patterns on the gridlines, and expanding brown regions on grid lines [10]. The blossoming appears as cell/encapsulant interface delamination and some extent of grid finger corrosion extending from the bus bar or the cell edge. The phenomenon was reported on cells with both Ti-Pd-Ag-passivated silver (tri-metal) and printed silver metallization. This developed on cells in modules that were forward biased at 100 milliampere (mA) while exposed to an 85°C, 85% relative humidity (RH) environment for 180 days [10]. In our work exploring PID, we found that mini-modules that had previously been subjected to 1000 hours of damp heat at 85°C/85% RH showed this type of delamination when subsequently subjected to a PID test at 72°C/95% RH with a negative bias of 1000 V for up to 196 hours [11]. We have observed visually similar degradation in fielded Arco Solar and Siemens M-55 modules [11]. We continue to find these defects both in older [12][13] and recently installed modules in the field.

International Electrotechnical Commission (IEC) technical specification (TS) 62804-1, the "Photovoltaic (PV) Modules – Test Methods for The Detection of Potential-Induced Degradation Part 1: Crystalline Silicon" describes methods to measure the module design's ability to withstand degradation from system voltage effects that manifest in relatively short term. The testing in IEC TS 62804-1 does not purport to examine for delamination or electrochemical corrosion. Developing a test method to examine for corrosion and resulting delamination to ensure such failures will not occur in the field remains an open item for c-Si modules. Therefore, this study further explores how to test for the PID-delamination mode in commercial c-Si modules.

Experiment

Four silicon-based PV module types (60-cell c-Si or multicrystalline [mc]-Si) of 250 W class were purchased on the open market in multiple replicas. All modules were processed through the following test sequence:

1. IEC 61215 damp heat, 85°C, 85% RH, 1,000 h in the open-circuit condition
2. PID stress: 72°C, 95% RH, -1,000 V, and surface-grounded by foil on the front glass (up to 292 h).

The voltage bias of -1,000 V was applied to the cell circuit for Step 2, and current transfer to ground was monitored using a leakage current sense circuit described previously [14].

Results and Discussion

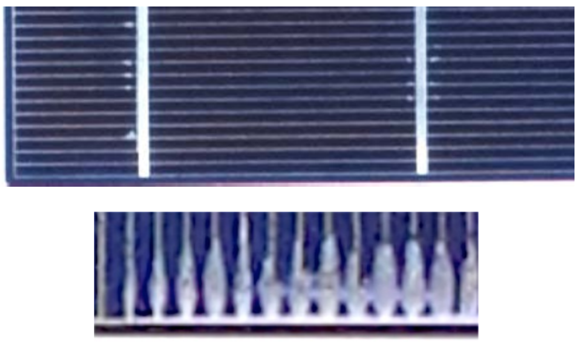
The results of the stress sequence on four types of silicon-based commercial modules are summarized in Table 1. The delamination and power loss indicated in the table refer to that observed during the PID stress part of the sequence. Delamination was seen in one of the four module types (#3). Power loss was seen in three module types, including the type that exhibited delamination; neither delamination nor power loss was seen in one module type (#4). The module type that exhibited neither power loss nor delamination had the lowest characteristic current transfer over the course of testing and the module that exhibited delamination had the greatest.

Table 1. Results of Stress Tests on Four Commercial Modules

Module #	Delamination	Power Loss	Current (A) (-1,000 V)	Current Density (nA/cm^2) (-1,000 V)
1	No	Yes	$6.4 \cdot 10^{-5}$	4.9
2	No	Yes	$2.6 \cdot 10^{-5}$	1.8
3	Yes	Yes	$4.4 \cdot 10^{-4}$	16
4	No	No	$7.9 \cdot 10^{-7}$	0.027

Current leaking from the active cell circuit to ground over the course of the PID stress test was largely stable for all four module types. Delamination induced by the stress testing in module #3 is shown in Figure 1a after 156 h of the PID stress and again after 292 h of PID stress (Figure 1c). Figure 1b and Figure 1d show examples of visually similar delamination from the field. They are Arco Solar and Siemens Solar modules. Siemens Solar acquired ARCO Solar in 1990 so they may share common module construction. There are several reports of these module types exhibiting such delamination in the field [12][13][15]. To our knowledge, this observed delamination has not been previously attributed to system voltage stress effects. We are proposing that it is PID-delamination (PID-d). Comparing Figures 1a and 1b, modules respectively degraded by stress testing and field exposure, in both images we can see delamination occurring at the grid fingers, frequently at some small distance from the bus bar.

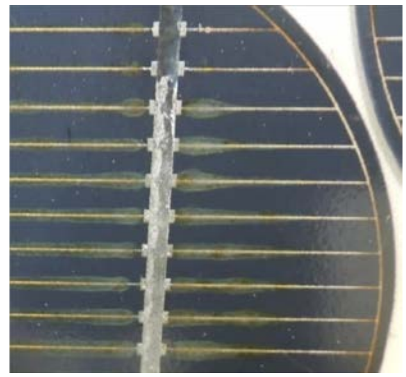
Stress Test Results



IEC 61215 85°C, 85% RH, 1,000 h followed by 72°C, 95% RH, -1,000 V with grounded foil on surface, 156 h PID stress.

(a)

Field Equivalent

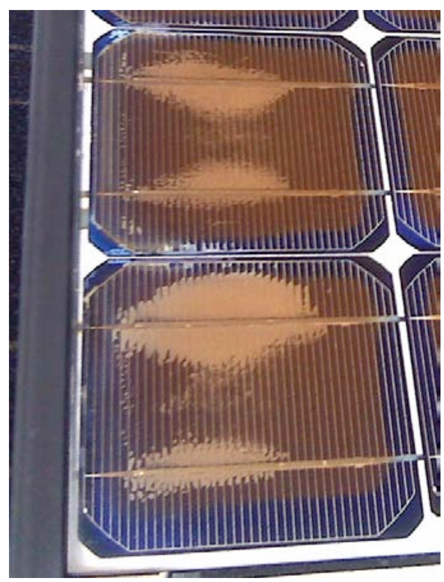


An Arco Solar module exhibiting delamination at the grid fingers in an unknown field configuration.

(b)

IEC 61215 85°C, 85% RH, 1,000 h followed by 72°C, 95%, -1,000 V with grounded foil on surface, 292 h PID stress.

(c)



Siemens M55 module exhibiting delamination in a field-test system at Sandia National Laboratory.

(d)

Figure 1. Images of delamination in accelerated stress testing of module type #3 (a, c) with applied stress conditions as shown, and in the field (b, d). The signature delamination in the plume form can be seen in regions in all samples. Extensive but comparable delamination is seen in (c) and (d).

They both exhibit delamination in the shape of a plume. The module in the field also shows discoloration of the grid fingers because of extended field exposure effects, such as condensation in the delaminated regions. Figures 1c and 1d, obtained respectively from stress tested and fielded modules, show more extensive delamination. Both exhibit delamination around the bus bars. The chamber-tested module (Figure 1c) exhibits significantly more delamination around the cell edges. The fielded module exhibits some there as well, but in Figure 1d, we see more delamination where there is encapsulant browning.

Various electrochemical degradation processes on cells and modules under voltage bias stress have been examined before [7][16]-[18]. The effect seen depends on the polarity of the applied bias :

- **Cell positive relative to the frame:** Corrosion is characterized by loss of cell metallization and the formation of cathodic dendrites; the dissolved cell metallization ions migrate to the frame where they deposit as dendritic crystallites. The metallization ions also react with the encapsulant, clouding and discoloring it [16].
- **Cell negative relative to the frame:** Less obvious characteristics to the naked eye, but microscopic examination reveals the formation of anodic corrosion salts and the evolution of gas bubbles at the cell's metallization-silicon interface. This results in metallization delamination and consequently increased cell series resistance [16].

The rate at which the reactions occur is proportional to the leakage current which in turn is controlled in large part by the ionic conductivity of the module insulation [16]. The magnitude of the current increases with humidity in the EVA by approximately one-half order of magnitude as the equilibrium relative humidity goes from 30% RH to 95% RH. The extent of humidity absorbed in the encapsulant required for gaseous formation has yet to be determined.

The cell circuit in this work was biased negatively whereby gas evolution can occur. This gaseous evolution has been attributed to cathodic gas evolution (i.e., hydrogen in aqueous systems)[17].

Factors anticipated to contribute to delamination are:

- IEC 61215 damp heat stress test results in the literature may, depending on the formulations used, reduce adhesion strength. For example, adhesion strength of EVA bonding to backsheet reduces by a factor of 10 or more in damp heat [19].
- PID stress, with negative-voltage bias applied to the cell circuit attracts Na to the cell [4], which decreases adhesion between the cell and the encapsulant [20].
- Humidity in combination with voltage potentials can lead to electrochemical reactions. Depending on the pH, water can dissociate with electrical potential on the order of 1 V [21] with products such as H_2 or other byproducts depending on the materials in the system. The generated gases can cause bubbles and delamination.

The current transfer shown for the conventional cell modules (considering modules #1 and #2) is in the mid 10^{-5} A range. This compares to conventional cell modules of similar dimension (1.6 m^2) in the field that exhibit peak current transfer in the mid 10^{-6} A range in Florida [22] and Gran Canaria [23]. Therefore, there is approximately a factor of 10 acceleration in current transfer considering the present PID-d stress test procedure compared to the maximum current measured in the field for typical modules. On the other hand, module #3 shows an order of magnitude higher current transfer than typical modules, so the current transfer in the field would be anticipated to be up to an order of magnitude higher as well. It is conceivable that this module type might show PID-d in the field and it will be deployed to test this. However, the current transfer in the field is not necessarily uniform over the module face. PID degradation is frequently concentrated on the lower edge of modules where moisture and soiling accumulate, suggesting greater current transfer there. The rate of current transfer may be a relevant metric because, for the delamination activated by gas formation from electrochemical processes, the rate of gas evolution may have to exceed the rate of out-diffusion of the gas from the module package. The stress conditions applied herein are a starting point for the development of a standardized test for examination of the PID-d mode.

Summary and Conclusions

A PID stress sequence was found to produce the delamination akin to cell/encapsulant delamination seen in some fielded modules. Based on visual inspections, we attribute such delamination seen frequently in ARCO and Siemens Solar modules to the PID-delamination (PID-d) mechanism that was reproduced in one of four presently shipping commercial module types. That module type exhibited high current transfer under negative system voltage bias because of low module package resistivity. Factors driving the delamination are believed to be damp heat, Na accumulation at the cell surface further reducing adhesion, and gaseous byproducts of electrochemical processes driven by the applied negative voltage potential to the active cell circuit.

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