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Accelerated Testing and Modeling of Potential-Induced Degradation as a Function of Temperature and Relative Humidity

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***Abstract*—An acceleration model based on the Peck equation was applied to power performance of crystalline silicon cell modules as a function of time and of temperature and humidity, which are the two main environmental stress factors that promote potential-induced degradation (PID). This model was derived from module power degradation data obtained semicontinuously and statistically by *in-situ* dark current–voltage measurements in an environmental chamber. The modeling enables prediction of degradation rates and times as functions of temperature and humidity. Power degradation could be modeled linearly as a function of time to the second power; additionally, we found that the quantity of electric charge transferred from the active cell circuit to ground during the stress test is approximately linear with time. Therefore, the power loss could be linearized as a function of coulombs squared. With this result, we observed that when the module face was completely grounded with a condensed phase conductor, leakage current exceeded the anticipated corresponding degradation rate relative to the other tests performed in damp heat.**

***Index Terms*—Photovoltaic (PV) modules, potential-induced degradation (PID), silicon, solar cells.**

I. Introduction

POTENTIAL-INDUCED degradation (PID) has been seen in the field to affect power output of some crystalline Si modules [1], [2]. It occurs in conventional front-junction ($n^+/p/p^+$) cells when positive ions, predominantly sodium, are attracted to the cell in negative-polarity module strings [3]. The sodium ions have been associated with junction degradation when they migrate from the cell surface to stacking faults that may intersect the junction [4].

Modeling of PID has taken several forms; for example, correlation between test chamber and outdoor degradation rates with factors of acceleration [5], [6]; modeling and extrapolation of leakage current [3], [6]–[8], which is easily measured during PID testing but not yet clearly correlated with power degradation; placing modules in a chamber at various conditions, examining the degradation and using derived constitutive equations to estimate field degradation with typical meteorological year data [9]; and shunt resistance monitoring in a chamber to estimate the conditions in the natural environment for onset of PID [10]. However, complete modeling is very difficult because of variable factors such as stress history [11], [12], recovery of PID that may occur in hot dry periods [6], [13], and the effect of ionization by light to neutralize charge in silicon nitride [14]. Further, publications with PID modeling using constitutive equations have generally been semiproprietary and difficult to evaluate objectively and reproduce experimentally.

In this paper, we obtain semicontinuous statistical data of the power degradation and leakage current by *in-situ* monitoring of modules undergoing PID in an environmental chamber. This allows application of accelerated degradation models [15] based on the Peck (or power law) [16] and exponential models [17] as a function of time, which have been used to model temperature- and humidity-induced corrosion phenomena in semiconductor components with applied voltage. A benefit of the approach is that after the applicability of the accelerated degradation model is understood, durations of subsequent tests can be reduced because of our ability to extrapolate module power as a function of time using the model. This methodology allows predicting "soft failures," the time to various degradation levels, and degradation curves in the time, temperature, and relative humidity (RH) space, as opposed to just "hard failures" as with fixed or predefined power loss limits of Arrhenius-lognormal lifetime models. Peck and exponential models are applied in standards of the Joint Electron Device Engineering Council [18] and SEMATECH [19]. These are explored here for characterizing PID and proposed as a platform for eventually combining with other PID rate-controlling factors for a complete PID model. This type of model may also be used to compare the results of stress tests performed at different levels and conditions, for example, differing temperatures and differing surface conductive mediums, such as with various humidity levels and condensed-phase conductor electrodes (water or metal foils). With the model, one can calculate the PID rate of one module type for the conditions at which another module type may have been tested for comparison purposes. Finally, the accelerated stress testing procedure, degradation model, and parameters are derived and can be applied as module testing framework for rating durability of crystalline silicon PV modules for PID sensitivity.

Leakage current, or total coulombs transferred from the active cell circuit under high-voltage bias to ground, has been

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TABLE I
CONDITIONS AND SAMPLE COUNT

Temperature (°C)	Relative Humidity (%)	Sample Count
60	85	5
72	85	5
85	85	5
60	95	3
60	100	2

related to degradation of modules as early as the Jet Propulsion Laboratories studies in the 1980s [20]. Some more recent studies also relate leakage current to PID [3], [13]. However, many convoluting factors make it difficult to draw dependable relationships between leakage current and degradation by PID in an arbitrary set of modules [9]. It may nevertheless be meaningful to examine leakage current in a set of modules of a given type in well-controlled experiments. We, therefore, explore what relationships can be drawn between leakage current, the environmental conditions, and degradation rate.

II. PROCEDURE

Twenty 250-W-class (60 crystalline Si cell) modules of near-sequential serial numbers were obtained. The modules were constructed of conventional front-junction (n^+/p/p^+) silicon nitride-coated multicrystalline silicon cells, soda-lime glass, ethylene vinyl acetate encapsulant, and stabilized polyester backsheets with anodized Al frames. These modules displayed significant PID resistance compared with some previous modules studied [6], [11], [14], but degradation could still be measured. They were divided into five groups for stress testing in a damp-heat chamber with -1000 V applied to the active cell circuit (shorted leads). The module frames were grounded. At the 85% RH condition, modules were tested at 60 °C, 72 °C, and 85 °C (five replicas per condition), whereas at the 60 °C condition, 85%, 95%, and 100% (condensed phase) RH conditions were applied (varying number of samples per condition); see Table I. Samples at the 100% RH condition were tested in a simulated manner, with foil on the face weighted down by a rubber mat in the environmental chamber at 95% RH. The foil was electrically connected to the frame and to ground. In separate testing, we found that leakage current was repeatable and statistically indistinguishable whether modules had electrolyte fluid or foil on the surface when in the chamber under these conditions.

An electrical power supply was used to drive forward-bias current up to 10 A through the modules to measure dark *I–V* curves. A switching network was used to switch modules intermittently in 4-h intervals between the high-voltage bias and the dark *I–V* curve traces, providing semicontinuous monitoring of the module power degradation and near-continuous leakage current monitoring. A computer controlled the sequencing of the measurements, test conditions, and data logging. Maximum power ($P_{\max}$) was extracted by use of the superposition technique—specifically by displacing the dark *I–V* curve measured on the module during the course of PID from the first quadrant to the fourth quadrant by the short-circuit current and finding the maximum in the *I–V* product. Normalized module power ($P_{\max}/P_{\max\_0}$) was obtained from the dark *I–V* curves taken at stress temperature to estimate standard test condition (STC, 1000 W/m^2, 25 °C) $P_{\max}$. The method was previously described and validated by obtaining semicontinuous STC $P_{\max}$ degradation curves for five various silicon module types within 1.5% (relative) error [21].

The classic Peck and exponential models in the form that are used for modeling time to failure (TTF) are, respectively:

$$\mathrm{TTF} = A_0 \cdot f(V) \cdot e^{\frac{E_a}{kT}} \cdot RH\%^{-B} \tag{1}$$

$$\mathrm{TTF} = A_0 \cdot f(V) \cdot e^{\frac{E_a}{kT}} \cdot e^{-RH\% \cdot B} \tag{2}$$

where E_a is the thermal activation energy; A_0 is a preexponential; *B* is the exponent associated with *RH* (*RH*, taken in percent); and *k* and *T* have their usual meanings in Boltzmann statistics, where their product is in units of eV in this study. *f*(*V*) is a function of the applied voltage, which was constant throughout this analysis.

Because degradation as a function of time was obtained, we may use an accelerated degradation model instead of a lifetime model with a fixed predefined failure level. Linear fitting to the degradation stage of the PID data is achieved if the time is scaled to the power of 2 (t^2), as previously shown for PID data of various other crystalline silicon PV module types [6], [21]–[23]. Whereas (1) is given as a TTF, a rate equation can be written as its reciprocal. Linearizing the degradation of the normalized power with respect to t^2, the resulting form of the accelerated degradation model applied is

$$\frac{P_{\max}}{P_{\max\_0}} = 1 - A \cdot e^{\frac{-E}{kT}} \cdot RH\%^{B} \cdot t^2. \tag{3}$$

The term "1" is inserted because at $t = 0$, the normalized power is 1 per our convention. The detailed monitoring of modules enables development of a model for PID as a function of arbitrary time, temperature, humidity, and leakage current. Later, in this paper, leakage current is considered, and the exponential model is applied to achieve optimal fitting of the parameter space for coulombs, temperature, humidity, and time.

III. RESULTS AND DISCUSSION

A. Module Power Degradation Modeling

Normalized power degradation curves for the five conditions tested are shown in Fig. 1. Several phases of the degradation curve can be seen most clearly for the 60 °C, 85% RH condition: a period of incubation, followed by degradation in power, a point of maximum power loss, and, in some cases, a period of relative stability or recovery. Interestingly, the higher stress temperatures did not result in noticeably different maximum degradation for the 85% RH condition. However, progressively increased RH led to more extensive degradation associated with total grounding of the module face, frequently evident in electroluminescence images that show more spatially uniform degradation when using Al foil grounding, for example.

For PID power modeling, only the degradation part of the curves in Fig. 1 was analyzed. Additional techniques would

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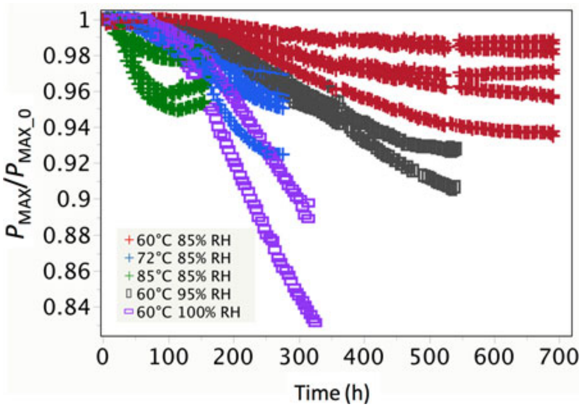

Fig. 1. Normalized power degradation of modules by PID in an environmental chamber as a function of temperature and humidity. −1000 V was applied to the cell circuit.

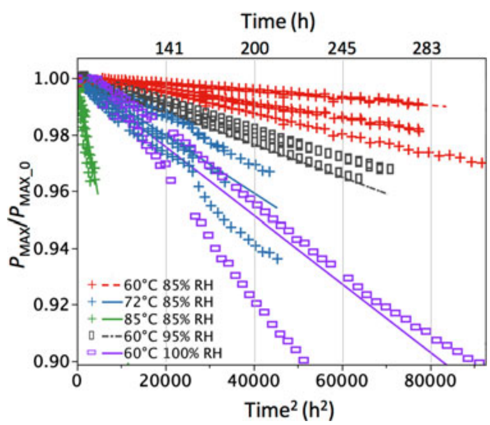

Fig. 2. Normalized power loss by PID as a function of temperature, RH, and stress time. Lines of fit are the result of application of the Peck model on a time-squared basis.

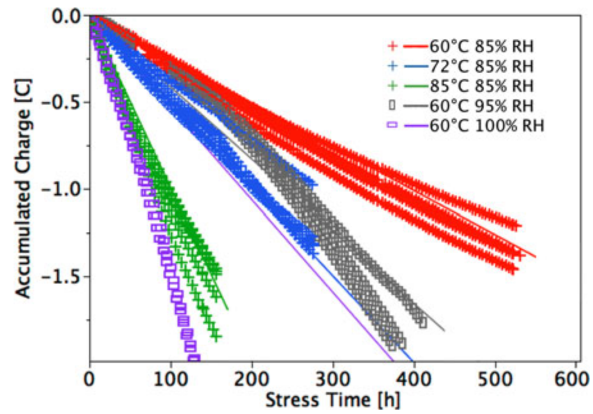

Fig. 3. AC (coulombs) as a function of time with exponential model fit. Data and model-fitting curves are included for the 60 °C/100% RH (condensed phase) condition; however, the data for this condition are not modeled. The rate of AC for the 60 °C/100% RH condition exceeds predictions based on the model using the data obtained at less than 100% RH.

be required to model the power degradation leveling off and any recovery processes. It can be seen that linear fitting to the normalized power in the degradation stage is achieved if the data are scaled to the power of 2 (see Fig. 2). Using the method of least squares, the dataset was fit using the Peck model in the form of (3) with $E = 1.76$ eV, $A = 2 \times 10^{-8}$ h^{-2} and $B = 14.24$. When linearizing on the time-squared basis, it can be mathematically shown that the exponential factor E is twice that of the activation energy ($2{\cdot}E_a = E$) found using the Arrhenius-lognormal lifetime model. An activation energy $E_a = 0.85$ eV was experimentally determined using the Arrhenius method [23] considering only the 85% RH condition, which is in reasonable agreement with 1.76 eV/2 = 0.88 eV found in this analysis. The advantages of the linearization method, however, merits modeling according to (3) with use of an accelerated degradation model.

Linearizing the module power degradation on the time-squared basis permits the extrapolation of module power degradation from shorter tests once the linear relationship is confirmed for the particular module design under study. According to the results in Fig. 1, the confirmation should include testing at the lowest RH condition of interest to measure the extent of the linear degradation region that can be modeled; otherwise, the maximum extent of degradation may be overestimated. Further, the linearization method enables the development of multistress accelerated degradation models such as that given in (3). A key outcome of establishing applicability of this accelerated degradation model for the module power degradation data is that much less data will need to be collected to describe the PID rate of other module types undergoing such stress tests in the future. Moreover, the acceleration model can be used to predict module PID rate and TTF for different module "soft failure" criteria (such as 1%, 5%, or 20% power degradation) for a range of given temperature and humidity conditions. With this, module PID durability can be rated in terms of mean TTF for different power degradation levels as well as for different environmental conditions. If the accelerated degradation model can be combined with a similar multistress PID recovery model, it should be possible to estimate module PID in the field based on temperature, humidity, voltage, and other rate-controlling factors such as illumination and stress history when they become better understood.

B. *Module Leakage Current Modeling*

The total quantity of charge determined from the leakage current of the modules undergoing PID versus time is found to be approximately linear with time (see Fig. 3). In some cases, the curve has a small concavity upward and, in others, downward because of moderately decreasing or increasing leakage current, respectively, over the course of the stress test. Applicability of the Peck and exponential models was tested with these data. Best fitting of the accumulated charge (AC) data was achieved with the exponential model in the form:

$$\mathrm{AC} = A{\cdot}e^{\frac{-E_a}{kT}}{\cdot}e^{RH\%{\cdot}B}{\cdot}t \quad (4)$$

with the exclusion of the 60°C 100% RH condition, which did not fit with the balance of the dataset. When this discontinuity

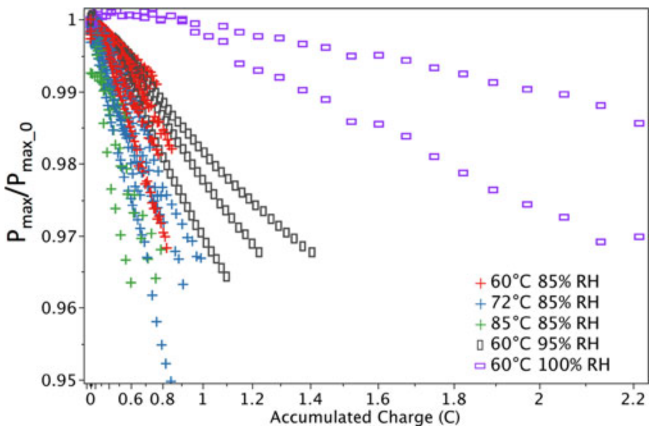

Fig. 4. Normalized STC $P_{\max}$ as a function of AC in coulombs, linearized by plotting the *x*-axis scaled as coulombs squared. While the 100% RH condition exhibits elevated AC because of elevated module leakage current, the modules stressed under this condition exhibit subnormal degradation on an AC basis.

became apparent, the data of the 100% RH condition were excluded for modeling of the AC. The determined model parameters are $A =$ -12 422 C/h, $E_a = 0.563$ eV, and $B = 0.0496$. The thermal activation energy component here, calculated independently, is similar to that of the Arrhenius fitting for leakage current considering only the 85% RH condition data, 0.559 eV. This is in the low end of the range given in other studies [3], [7], [8], [24]. The deviation of the leakage current data of the 100% RH condition from the rest of the dataset is likely associated with the change of the grounding from adhered water molecules on the glass in the 85% and 95% RH cases to the condensed phase with much higher conduction.

Now that we have seen the time-squared correlation with power and the time-linear correlation with AC; we can observe the power to AC relationship. To view it linearly based on the above understanding, the normalized power of all the tested modules is plotted versus charge on an axis scaled to coulombs squared in Fig. 4. Considering all but the 100% RH condition, the spread in AC spans from 0.3 to 0.8 C (267% range) at 0.99 fraction power remaining and increases from there with further degradation.

This extent of correlation may be useful, but it must be recalled that this dataset is for a group of very similar modules. There is no expectation of such grouping when comparing different kinds of modules. For example, increased silicon nitride conductivity associated with higher index of refraction would lead to a more conductive module laminate, potentially increased leakage current, but decreased PID rate [24]. Increased electrical connection of the cell metallization grid or interconnect ribbons to the front glass can potentially increase leakage current but bypass PID-causing ionic conduction at the surface of the silicon cells. While increased heat and humidity increase coulombs transferred, which was related to increased PID rate for the module type tested (see Figs. 3 and 4), module design factors can affect leakage current and PID rates differently.

The 60 °C 100% RH condition does not correlate with the other stress conditions—there is significantly increased AC relative to the degradation in view of the other modules in the dataset. This suggests that the completely grounded module surface leads to a leakage current increase, but the PID rate saturates. The system voltage provides the electromotive force for Na^+ ions moving in the module package to the cell surface; however, the process may be rate limited by voltage-independent sodium diffusion to the junction within the cells where the semiconductor layer is nearly equipotential. Sodium shows the highest diffusivity and solubility in silicon among the alkali metals [25] and has been found at stacking fault defects at sites where PID was observed [4].

IV. Summary

Higher temperature did not increase the maximum extent of PID, whereas higher humidity did. Power degradation was linearized by plotting on a time-squared basis. This may provide mechanistic information about the rate-controlling process. A form of the Peck (power law) model was successfully applied to characterize the degradation process with time, temperature, and RH. With this accelerated degradation model, performance can be characterized with short-duration experiments when the degradation process is linear when viewed on a time-squared basis. An exponential model was used to model accumulated coulombs, excluding the 100% RH condition data, which could not be modeled continuously with the other data because of the substantially higher conductivity of the condensed phase. Degradation in power was also examined as a function of accumulated coulombs and stress condition. An approximately linear grouping of curves of normalized power plotted versus coulombs squared was observed for the PID tests in noncondensing damp heat. The results, however, showed that beyond a certain surface conductivity, the PID rate does not increase. Analyses relying on leakage current when module surfaces are wet or conductive beyond a certain threshold may, therefore, not be directly applicable for inferring the PID rate.

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