Potential-induced degradation effects on crystalline silicon cells with various anti-reflective coatings

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ABSTRACT

Because potential-induced degradation (PID) can cause power losses of more than 30% for modules out in the field, there has already been an extensive effort placed on avoiding this adverse phenomenon. A key feature at the cell level is the silicon nitride (SiN_x) anti-reflective coating (ARC). Apart from the known dependency of PID susceptibility on the refractive index, the impact of the deposition parameters has also been under investigation. This paper illustrates the influence of different silicon nitrite layers and their ability to prevent PID. A large number of cells and modules were therefore manufactured, differing only in the type of ARC. The modules were subsequently PID tested under three different climatic conditions, and acceleration factors and activation energies were determined from these tests. In addition this paper presents the results of addressing the weak-light performance and the hot-spot risk of panels after PID exposure. Finally, the reversibility of PID was also investigated in relation to the state of degradation of these samples.

Introduction

Depending on the system configuration of solar installations, significant electrical potentials with negative polarity relative to ground can form between the frame and the solar cells within the modules. The actual potential is dependent on the total system voltage, the inverter type and the position of the module within the string, and could theoretically be as high as 1000V. In the past, this potential could be regarded as the root cause of the observed power losses of photovoltaic systems. The resulting degradation of the system is known as potential-induced degradation (PID) [1].

The common model for explaining the PID effect states that the potential causes the diffusion of positive sodium ions from the glass through the embedding material towards the cell. It is assumed that sodium ions can accumulate in certain regions of the silicon nitride (SiN_x) anti-reflective coating (ARC). In the case of p-type wafer-based silicon cells, these charge centres can generate local shunts in the p-n junction [2,3].

> "It is advantageous to address and resolve PID at the cell level."

Even though there are several ways to suppress the PID that occurs in the field, for the sake of flexibility of panel and system design it is advantageous to address and resolve PID at the cell level. The ARC layer (or layers) has been found to be the key feature with respect to the PID sensitivity of the solar cell.

The sensitivity of solar cells to PID could be minimized by simply increasing the refractive index of silicon nitride, as presented by Pingel et al. [1]. But a suitable refractive index for preventing PID is often not ideal in terms of cell efficiency. Consequently, alternative approaches have had to be identified for suppressing the PID effect. For example, this year at the EU PVSEC, Mehlich [4] put forward the possibility of improving cell resistance to PID through several pretreatment steps during the manufacturing process prior to SiN_x plasma deposition. A major issue with this approach is the impact of the anti-reflective coating itself on the PID effect.

The significant influence of different ARCs on the PID stability of the whole module is demonstrated here. Besides the PID test series in which different ARCs are applied, some 'secondary' effects of PID are also presented, specifically the influence of PID on:

- the hot-spot risk of the module
- the weak-light performance

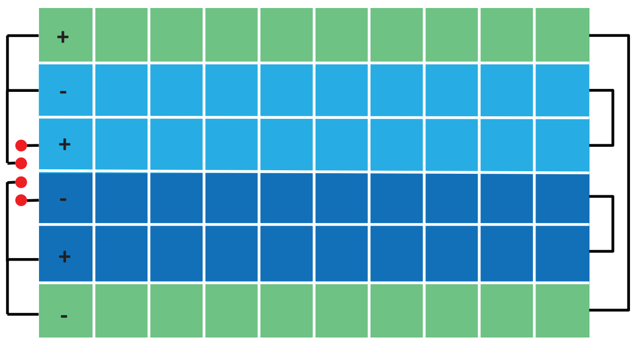

Figure 1. Interconnection scheme of the investigated modules. Each module was realized with three different cell-type strings (green, light blue and dark blue).

Furthermore, PID is discussed in terms of the influence of ambient conditions; in particular, the acceleration factors for different test temperatures (60°C vs. 85°C) are presented, as well as the reversibility of PID.

Experiment design

Standard industrial, screen-printed, Al-back alloyed monocrystalline p-type Si solar cells were manufactured in a single experiment run by centrotherm photovoltaics AG in an industrial environment, resulting in 21 different cell types. In order to increase the comparability and the statistics, 20 cells of the same type were connected in one string. Three strings with different cells were then connected to one module (Fig. 1). All modules were manufactured at a standard module production site, using an encapsulant material which was known to be prone to the PID effect [5].

Besides the use of an encapsulant

with known susceptibility to PID, low-resistivity wafer material was also chosen intentionally. To evaluate the relative influence of different ARCs, it is undesirable to produce samples which are PID resistant because of other influencing parameters.

Since an official standard has not yet been released for PID analysis (IEC draft 62804 is still pending), the three most common test method proposals have been adopted for investigating the PID behaviour of the different cell concepts. The investigated test conditions are as follows:

1. Climatic conditions of 85°C and a relative humidity (RH) of 85% for 48 hours (PI-Berlin standard).
2. Climatic conditions of 60°C and 85% RH for 96 hours (proposal for the IEC standard).
3. Durability test at 25°C with no specific humidity level control for 168 hours (proposal for a simple PID test set-up published during EU PVSEC 2011 [6]).

As well as the different climatic conditions and durations, all modules were created by means of a continuous metal contact over the whole glass area.

Experimental results

Comparison of double- and triple-layer structures

As mentioned earlier, it is known from earlier results in the literature that an increased refractive index is associated with an increased robustness to PID. This was also confirmed during PI-Berlin's analysis (Fig. 2).

> "An increased refractive index is associated with an increased robustness to PID."

The disadvantage of an increased refractive index is that it results in lower efficiency at the cell level, in particular prior to embedding. Hence, it is of particular interest to determine if it is possible to create double-layer structures which can combine the beneficial effects of layers with high refractive index (high resistance to PID) and layers optimized with regard to low optical losses.

Fig. 3 shows a comparison of four different double-layer cell designs (G–J) and a standard single-layer structure with a refractive index of 2.08 (A). The tested double-layer designs consisted of one layer with a standard refractive index and one

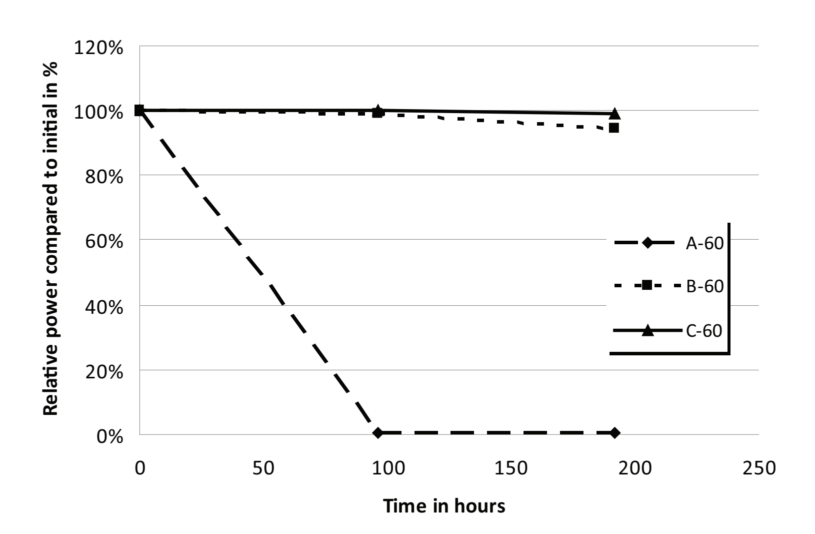

Figure 2. PID results after two cycles of the 60°C/85% test method applied to cells with different refractive indexes (A=2.03; B=2.2; C=2.3).

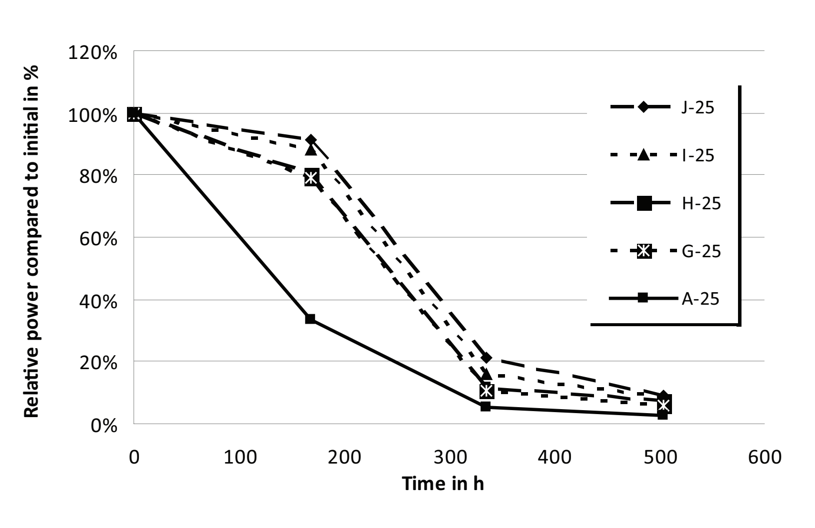

Figure 3. Comparison of the degradation behaviour of various double-layer cells (G–J) compared with standard single-layer cells (A) during the 168-hour/25°C test method.

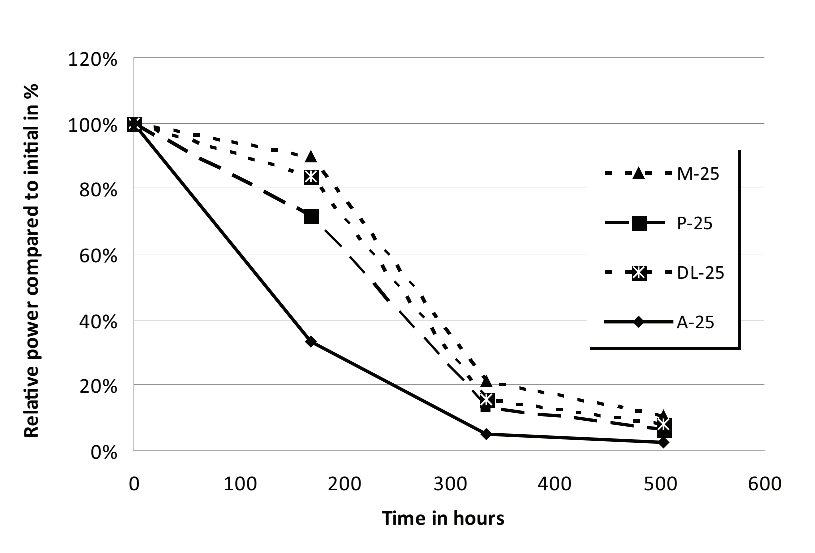

Figure 4. Comparison of the PID behaviour of cells with single (A), double (DL) and triple (M, P) ARC layers during the 168-hour/25°C test method.

PV Modules


UV Exposure degrades
PET over time.

layer with a refractive index ranging from 2.2 to 2.5 (G–J).

As seen in Fig. 3, the application of a second layer slightly increases the resistance to PID but does not effectively prevent it. Nor do triple-layer designs show significant improvements (see Fig. 4) over single-layer ones: the degradation is similar to the average degradation of cells with a double-layer ARC (DL-25). The small impact of multi-layer ARCs is probably due to the limited thickness of the layers with high refractive index, which was restricted in order to avoid undesirable optical losses.

Alternative approaches

In addition to the insertion of additional (double, triple) layers with different refractive indexes, there are other approaches for modifying the ARC. These include the use of modified deposition conditions, a pretreatment by radiation (with or without a process gas), and an additional gas flow. The approaches aim either to suppress the leakage currents at the cell level or to increase the conductivity in order to prevent a charge build-up in the ARC.

Several groups, which included elements of these alternative approaches, were tested in the experimental series. Four of the groups with alternatively modified ARCs are shown in Fig. 5 and compared with group M (best-performing multi-layer ARC – triple-layer), which was illustrated earlier in Fig. 4. The test was carried out at a higher temperature of 60°C and 85% RH because the samples showed no degradation under 25°C conditions. A clear improvement as a result of the modifications was obtained, with the exception of one group. Multi-layer structures are also partly included here, but once again did not prove to be superior.

In summary, it can be concluded that there are various possibilities for modifying the ARC and for improving the PID behaviour of cells. In future experiments, the alternative approaches will be combined and/or modified to further enhance resistance to PID.

Hot-spot risk and PID

It was mentioned earlier that PID can generate local shunts in the p-n junction. This fact leads naturally to the question of what influence these shunts have on the cells in terms of hot-spot generation. To answer this question, one module was prepared in such a way that one string in the module was prone to PID and the other two were stable. The module was initially tested according to the IEC 61215 [7] procedure for determining the hot-spot risk. The key parameter of the risk potential is the level of leakage current at reverse bias of each cell.

No significant difference between the three unequal strings could be seen after the initial hot-spot analysis. The difference

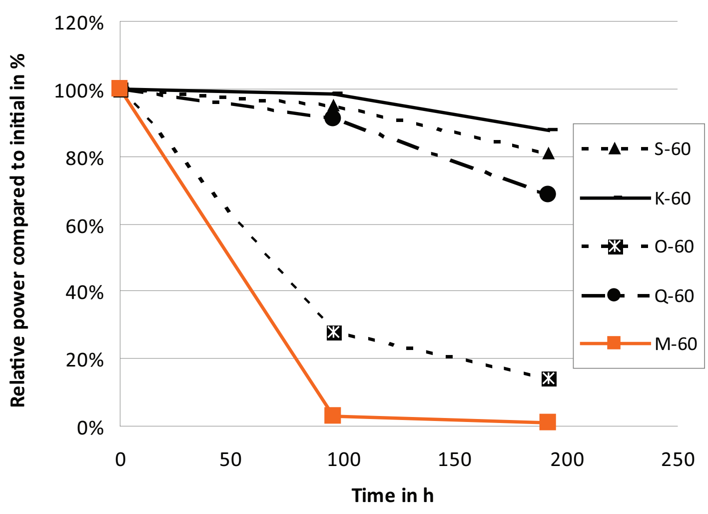

Figure 5. Comparison of the PID behaviour of cells with modified ARC deposition and the best-performing standard triple-layer – M (see Fig. 4). (Test conditions: 60°C/85% RH.)

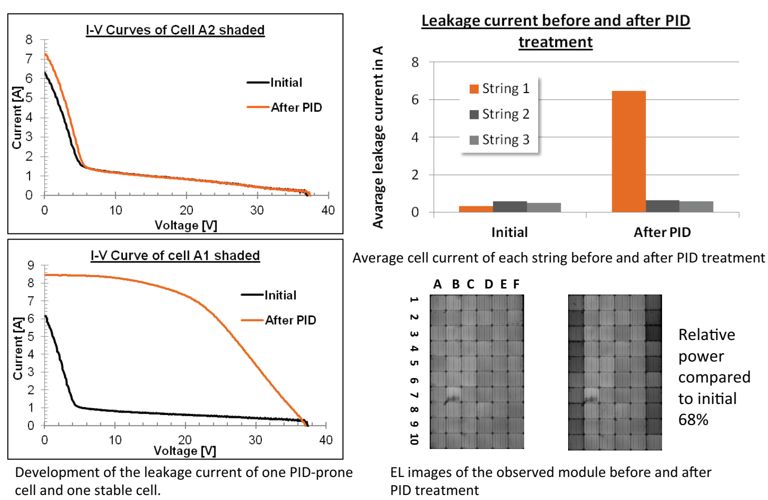

Figure 6. Hot-spot risk analysis before and after PID treatment.

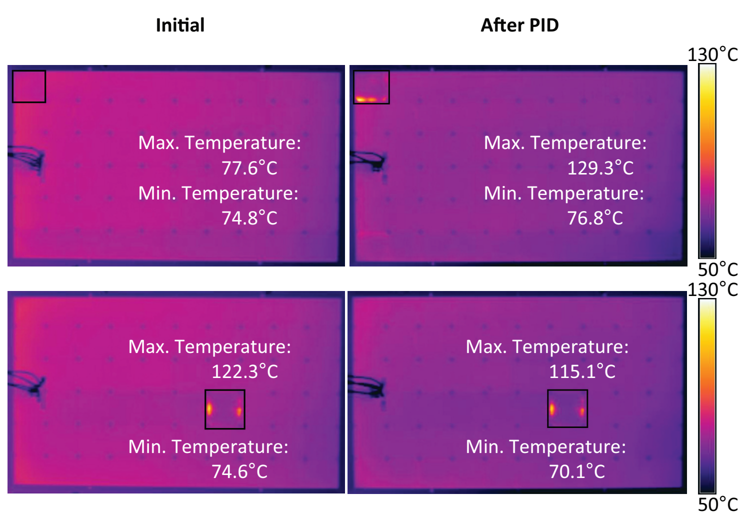

Figure 7. Maximum temperature during a hot-spot test of one PID-prone cell (top) and one stable cell (bottom), before PID degradation (left) and after (right).

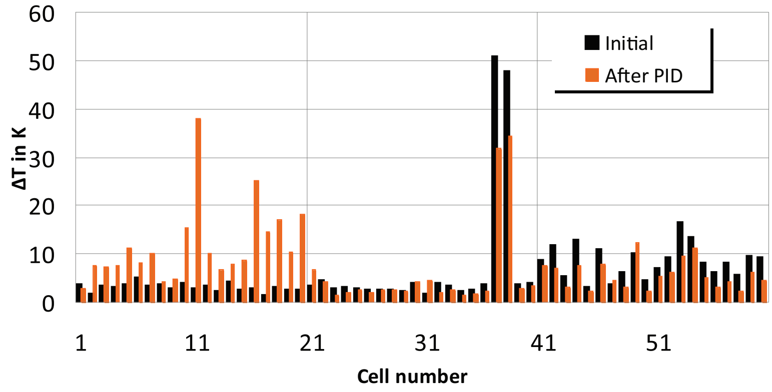

Figure 8. Increase in the temperature difference between minimum and maximum cell temperatures of PID-prone cells (1–20) and PID-stable cells (21–60) during a hot-spot analysis.

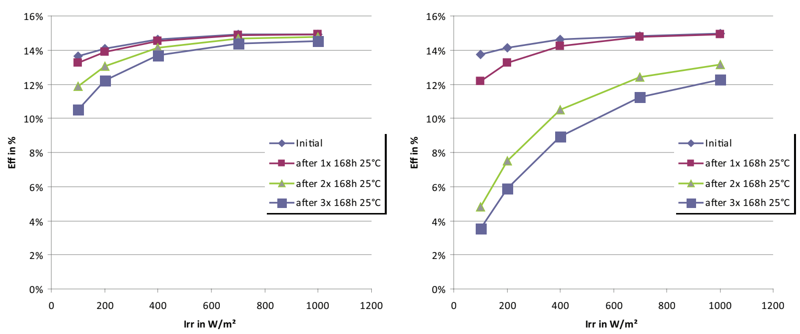

Figure 9. Impact of PID on the weak-light performance of one stable cell string (left) and one prone cell string (right).

in the average leakage current at reverse bias was of the order of around 25%, which is a typical result. After five hours of PID stress, the PID-prone string showed only 68% of the initial power, and the other two strings still showed 99% of their initial values. Performing the IEC 61215 hot-spot analysis again revealed an increase of about 20% in the leakage current at reverse bias for the two stable strings; on the other hand, the prone string showed an increase of about 1846% in leakage current at reverse bias. Fig. 6 shows the significant increase in the average current and two leakage currents at reverse bias changes for the two stable and one PID-prone strings.

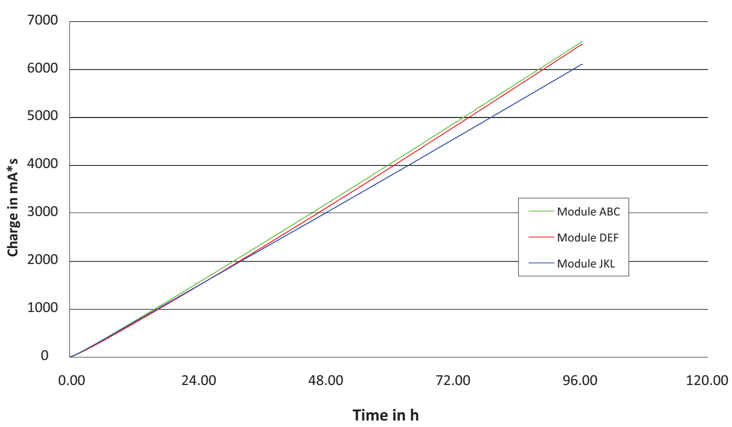

Figure 10. An example of integrated leakage current over time during a PID stress test. Compared to initial STC measurements, the relative powers of modules ABC, DEF and JKL are 66%, 1% and 32% respectively. No link could be found between degradation level and accumulated charge.

In a second step performed according to IEC 61215, the cell with the highest leakage current in reverse bias was shaded and stressed with a sun simulator for one hour. In PI-Berlin's case every cell was shaded for 30 seconds under the sun simulator and the maximum temperature was determined. The detailed procedure and the differences between this and the IEC test were presented by Wendlandt et al. at the 2012 EU PVSEC [8]. The IR images of the worst-performing PID-prone (top) and stable (bottom) cells, before and after the PID test, are given in Fig. 7. A comparison of the images reveals a rapid increase of around 30K in the maximum temperature of the PID-prone cell.

An overview of all 60 maximum cell temperatures before and after the PID treatment is presented in Fig. 8. A significant increase in the temperatures for the PID-prone cells (1–20) can be observed.

These results show that not only do modules which are affected by PID exhibit a power drop, but there is also the risk of them potentially generating hot spots in the field.

Weak-light performance

In addition to standard test condition (STC) power measurements for monitoring the degradation progression during the environmental stress testing, weak-light measurements were recorded after the different degradation steps for every cell type. For a standard module with crystalline silicon cells the efficiency loss, from $1000W/m^2$ to $100W/m^2$, is about 5–10% (according to the internal PI-Berlin database 2008–2012); all tested modules also demonstrated this during the initial determination.

> "Efficiency losses at lower irradiations become more significant for higher degradation rates."

After the first PID cycles some cell strings showed little or no drop in efficiency at $1000W/m^2$, but the change was apparent at weaker irradiances. The reason for this effect is the decrease in shunt resistance which generally happens initially during PID treatment and which has been documented in the literature [1,9]. Efficiency losses at lower irradiations become more significant for higher degradation rates. Fig. 9 shows two examples – one for a comparatively stable module and one for a PID-prone module.

The effect can also be visualized by electroluminescence (EL) images, since low irradiation corresponds to a lower current. Differences in PID can therefore be much better differentiated by EL images

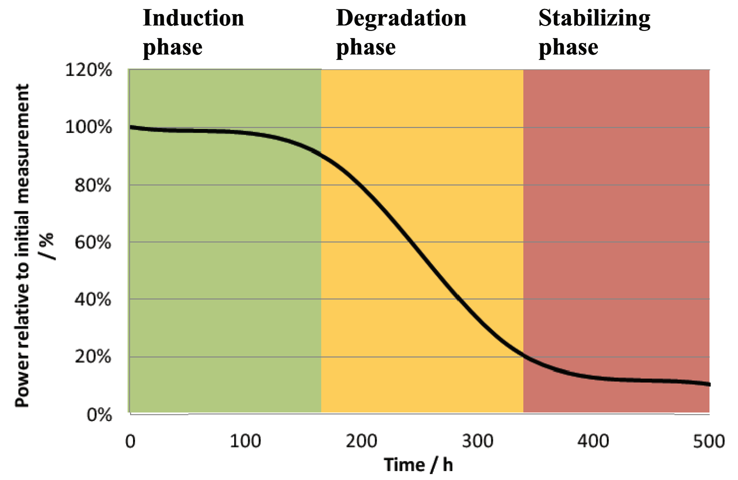

Figure 11. Typical PID degradation progression, consisting of induction, degradation and stabilizing phases.

generated with lower (injection) currents, showing PID-affected cells at an earlier stage, than by images generated with higher currents [10,11].

Acceleration factors between the different test methods

One approach for assessing PID results and which is relevant to lifetime estimations for realistic environments is the determination of activation energies and acceleration factors. A study on leakage currents during PID stress tests and their relation to degradation was recently published [12], and the activation energy of the acceleration factors under various test conditions was investigated. In the studies at PI-Berlin, however, it was found that the relation between leakage current and actual level of degradation is not always straightforward: the relation between high leakage currents and PID-prone module concepts seems to be mainly driven by the encapsulation material. As seen in Fig. 10, the levels of leakage current of three different modules lie in the same range, although the degradation of the modules varies significantly.

All modules showed a nonlinear degradation progression during PI-Berlin's investigations. The degradation phase can be divided into three parts: in sequence, an induction phase (where the module can even demonstrate a slight increase in power), a degradation phase (where the module shows an almost linear degradation progression) and a stabilizing phase (where the degradation process stabilizes at a level which depends on the applied voltage [13]).

To determine the activation energy, a degradation percentage power drop over time was implemented and calculated with the generally valid Arrhenius equation:

$$k_1 = A \times e^{\frac{-E_A}{R \times T_1}} \qquad (1)$$

$$E_A = -\frac{\ln k_2}{k_1} \times R \times \left(\frac{1}{T_2} - \frac{1}{T_1}\right)^{-1} \qquad (2)$$

where k_1 and k_2 are the degradation rates, R is the Boltzmann constant, T_1 and T_2 are the temperatures and A is the pre-exponential factor.

The activation energies for several modules during induction, degradation and stabilizing phases were determined for 85°C and 60°C and are given in Table 1. To calculate the acceleration factors, the time of treatment from those modules whose power levels were located within the degradation phase were compared for climatic conditions of 85°C/85% RH and 60°C/85% RH. From these results, it is possible to make the following statements:

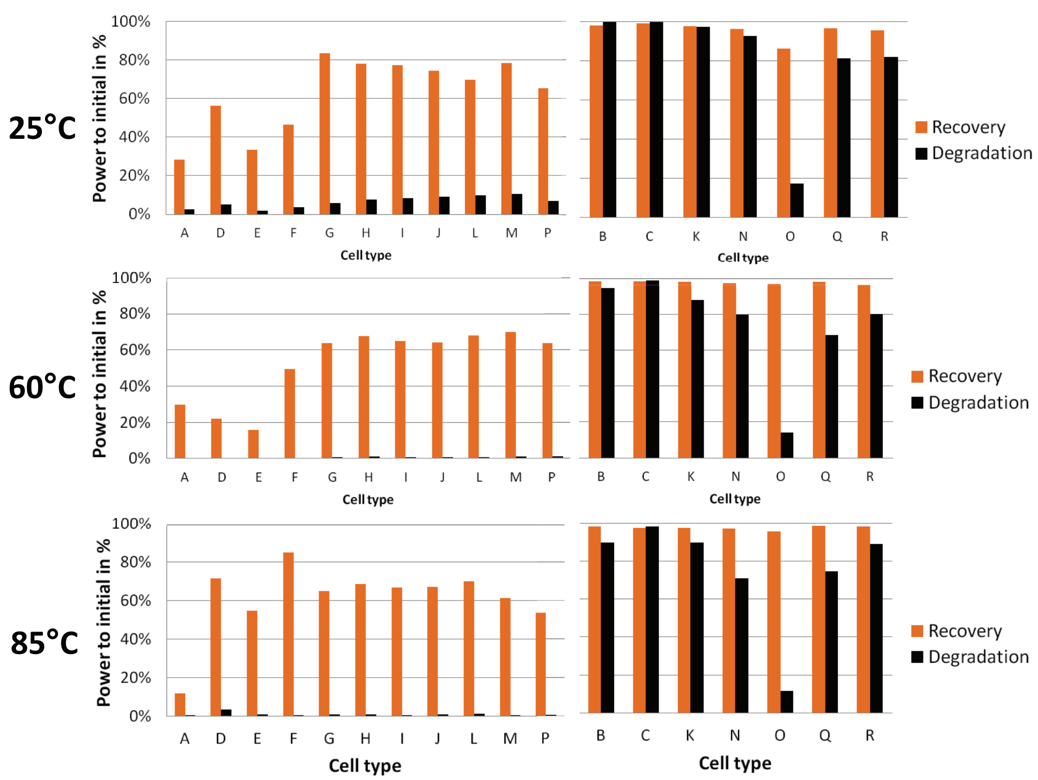

Figure 12. Comparison between PID degradation and PID regeneration of different cell types (A–R) for different climatic conditions, divided into two groups – one with power less than 15% of the initial power (left), and one with power greater than 15% (right).

	Degradation phase		
	Induction	Degradation	Stabilizing
Average activation energy E_A for 85°C and 60°C [kJ/mol]	70.8	54.7	56.1

Table 1. Activation energies for different test methods.

	Below 15% degradation		Above 15% degradation	
Test method	Module power after degradation	Module power after recovery	Module power after degradation	Module power after recovery
25°C	6.45%	63.0%	81.6%	95.7%
60°C	0.68%	52.7%	74.8%	98.1%
85°C	0.95%	61.5%	74.8%	97.5%

Table 2. Average PID level for two groups (degradation level below and above 15%) compared with the average recovery level for three different test methods.

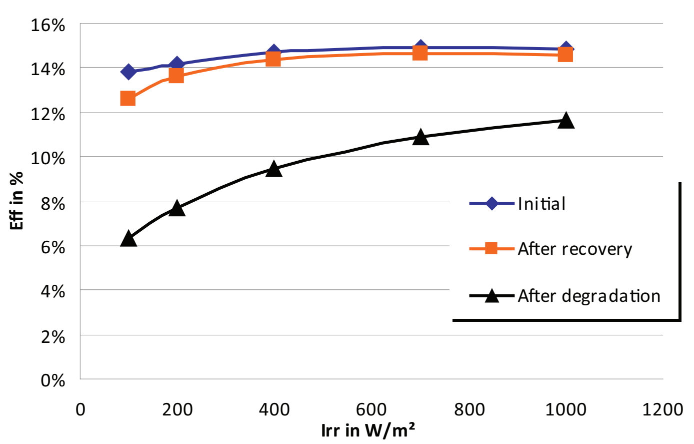

Figure 13. Weak-light performance after different stages of PID.

1. The climatic conditions of 85°C and 85% RH show the most pronounced degradation.
2. Quadrupling the time during climatic conditions of 60°C and 85% RH, which are currently proposed for the IEC 62804 standard, results in the same power degradation.

Regeneration of PID-affected modules

The regeneration of PID-affected modules is an important topic, especially for modules which have been out in the field. The question is, can modules with PID be regenerated by a reverse potential, and are there any differences between the modules stressed by various climatic conditions?

To address these topics, the modules which were degraded by different test cycles in the first run were recovered at the same conditions for the same period of time. STC power measurements and EL images were subsequently taken to compare the samples. In the end, the modules could be divided into two groups: modules with a power greater than 15% of the initial value after degradation, and modules with a power less than 15%. As can be seen in Fig. 12, all modules with a residual power above 15% could be recovered to an average of 97% of their initial values. Modules with a higher power loss could only be recovered to an average value of 59%.

"All modules with a residual power above 15% could be recovered to an average of 97% of their initial values."

Table 2 shows that the difference in the final degree of recovery between the different test conditions is rather small and mostly driven by the average degradation at the beginning of the recovery process. Almost all of the modules could not be recovered to their initial power. It became particularly clear that high degradation levels of modules corresponded to significantly lower recovery levels.

Apart from recovering STC power, another aspect of PID recovery is recovering the shunt resistance, which affects the weak-light performance of modules (see Fig. 13). Even in the case of a more or less full recovery of STC performance, there might be still a reduction in weak-light performance.

Summary

The main topic of this article has been the impact of the ARC on the PID effect – the significant influence of different ARCs on the PID stability of a cell/module was demonstrated. Investigations of multi-layer structures were motivated by the known dependency of the PID effect on the refractive index. The implementation of double- and triple-layer ARC structures was found to reduce, but not completely prevent, PID.

"The implementation of double- and triple-layer ARC structures was found to reduce, but not completely prevent, PID."

Alternative approaches for modifying the ARC by varying certain process parameters for deposition (such as deposition rate, temperature and gas composition) in order to reduce the PID effect were considerably more effective. Furthermore, it was shown that PID-affected cells potentially cause a higher risk of hot spots than unaffected cells, and that PID can have a significant effect on weak-light performance.

Relevant PID test conditions were also compared: an increase in the rate of degradation by a factor of four was determined for 85°C/85% RH conditions relative to 60°C/85% RH. Activation energies were determined and found to lie within the range 56.1 to 70.8kJ/mol for different modules; these are comparable to activation energies determined by other authors [12,14,15].

Finally, during investigations of the recovery behaviour of PID-affected modules, it was demonstrated that modules with a degradation level above 15% can be recovered to a minimum level of 96%. Modules with residual powers less than 15% could be recovered to a level of at least 53%. It was observed that PID is not always fully recoverable and that the extent to which this is possible is highly dependent on the initial degradation level.

Acknowledgements

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Simon Koch joined PI-Berlin in 2007. He studied environmental engineering at the University of Applied Science in Berlin, Germany, and received his diploma degree in 2008. For his diploma thesis Simon worked on defect analysis of silicon solar modules using electroluminescence and photoluminescence imaging, and is now focusing on PID simulation for his Ph.D. thesis.

Juliane Berghold received her Ph.D. in physical chemistry in 2002 from Freie Universität Berlin. She then worked as a research associate on crystalline silicon thin-film technology at Helmholtz-Zentrum Berlin (HZB) until 2006, after which she was director of R&D PV at SOLON. Juliane has been head of R&D at PI-Berlin AG since 2011.

Paul Grunow received his Ph.D. in physics from TU Berlin in 1993 for his work on silicon solar cells at the Helmholtz Centre Berlin. Following a postdoctoral post in Rio de Janeiro in Brazil (UFRJ-COPPE), working on solar thin-film materials, he co-founded SOLON AG in 1996. Together with Reiner Lemoine and others, Paul co-founded Q-Cells AG in 1999, and in 2006 he co-founded PI-Berlin, of which he is a member of the board and senior consultant.

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