POTENTIAL INDUCED DEGRADATION EFFECTS ON CRYSTALLINE SILICON CELLS WITH VARIOUS ANTIREFLECTIVE COATINGS

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ABSTRACT: The first experiences with potential induced degradation (PID) of silicon solar cells have been presented in literature since 1989 [1-4]. It has been shown that PID may cause power losses of more than 30% for modules out in the field. Critical issues on the cell level are the SiN_x anti-reflective coatings (ARC), their deposition method, the emitter thickness and metallization (thus influencing the electrical series resistance). The leakage current was found as an indicator for the intensity of degradation. Moreover, different test methods to prove the stability or susceptibility of samples have been presented.
In this paper we are showing the influence of the anti-reflection coating to provoke PID and the ability of silicon nitrite layers to prevent PID. For each layer structure, at least four different designs have been manufactured and tested for their stability against PID. To do so, it was necessary to find an appropriate test sequence, which would show polarization effects in an adequate time frame, while there is no standard procedure available that addresses this problem for the time being. Furthermore, it has been necessary to develop suitable reference samples to compare the results and to prove the repeatability of the test sequences. The experiment has been divided into two parts: The pre-evaluation has been realized with small one-cell mini-modules to probe the adequate testing parameters and to analyze the leakage currents for various prone samples. During the second part, we also investigated the reversibility of PID - depending on the state of degradation of these samples - to check whether PID is one 100% reversible, or whether the degradation mechanism also shows an irreversible part.

Keywords: PID, Antireflection Coating, Silicon-Nitride, Recovery, Hot-Spot

1 INTRODUCTION

In photovoltaic systems an electrical potential with a polarity negative against ground can build up between the frame and the solar cells within the modules. The actual potential is dependent on the (allowed) string length, the inverter type and the position of the module within the string and may reach 1000V. Observed power losses of photovoltaic systems could be assigned to this potential. The resulting degradation of the system is known as Potential Induced Degradation (PID).

The prevalent model to explain the PID effect states that the potential forces positive charges in form of free positive sodium ions from the glass, to diffuse through the embedding material towards the cell surface area. and the silicon nitride anti reflective coating. It is assumed that sodium ions can accumulate in certain regions of the silicon nitride layer. In case of p-type wafer based silicon cells these charge centers can generate local shunts in the p-n junction [5, 6].

Even though there are several ways to suppress the PID effect at different system levels it is obvious and well known that the silicon nitride anti reflective coating has an important impact on the PID sensitivity.

So, as presented by Pingel et al. [1], simply by increasing the refractive index of silicon nitride, the sensitivity of solar cells to PID could be minimized. Because of that known dependency also the question arises if and how different anti reflective layers could suppress the PID effect.

A major issue of this publication is the impact of the anti- reflective coating on the PID effect. The significant influence of different ARCs on the PID stability of the whole module is demonstrated.

Besides the test series applying different AR-coatings also other results regarding to PID are presented.

- Influence of PID on the hot spot risk of the module.
- Reversibility of PID
- Influence of ambient conditions
- Investigation of acceleration factors dependent on the test conditions

2 EXPERIMENT DESIGN

For the investigations, a standard industrial screen printed, Al-back alloyed mono crystalline p-type Si solar cell was manufactured (by Centrotherm Photovoltaics AG), using a standard cell process. Only the silicon nitride layer, deposited by a PECVD process, has been modified to realize different ARC coatings. 21 cell groups with varied ARC- coating were prepared. In order to increase the comparability and to compensate the different PID speed between cells from the same batch, (which a chess board pattern on an electroluminescence image indicates [7]), 20 cells of the same type were connected in one string. Afterwards, three strings with different cells were connected to one 60 cell module; therefore, each module had three different cell types, which could be independently connected with various analysis devices (see Fig.1) to carry out STC measurements and take electroluminescence images. All modules were also manufactured within a standard module production site with an encapsulant material, which was known to support the PID effect [8]. The cross-linking of the used EVA has been measured in the range between 75% to 77%, which is a decent value for the used material.

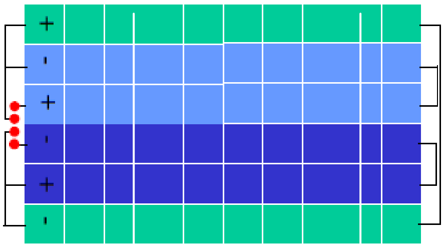

Figure 1: Interconnection scheme of the modules. Each module was realized with three different cell type strings (green, light blue and dark blue).

Besides the use of an encapsulant with known susceptibility for PID also low resistivity wafer material was chosen on purpose. In order to evaluate the relative influence of differing ARCs it is not desirable to produce samples which are PID resistant due to other influencing parameters.

Because there is no official standard released for PID analysis (IEC 62804 under development) yet, the three most common test methods proposals have been adopted to investigate the PID behavior of the different cell concepts.
The test methods are as followed:

1. Climate condition of 85°C with a relative humidity of 85% for 48 hours, PI-Berlin standard [7].
2. Climate condition of 60°C with a relative humidity of 85% for 96 hours (proposal for the IEC standard) [9].
3. Durability test with 25°C with no specific humidity level control for 168 hours (proposal for a simple PID test setup published during PVSEC 2011) [10].

The tests not only differ in their ambient conditions, duration and voltage but also in their contacting scheme. Many of the published tests are based on a contacting (grounding) via the frame of a standard module (e.g. tests 1. and 2. described above). In this case the contacting conditions are dependent on humidity and temperature [11]. Even though the frame grounding may better resemble the actual conditions in the field, for this experiment an even contacting of the surface is preferable, since an increased high voltage stress for cells close to the frame has to be avoided. Therefore the contacting was established by means of a continuous metal contact over the whole glass area. It has to be mentioned that the PID speed is then increased by about a factor of 10.
Investigations with one cell mini-modules also showed that the conventional test voltage of 1000V was too high for an appropriate result resolution for the 85°C and the 60°C climate conditions. Therefore, the voltage for both tests was reduced to 100V. In contrast, during the 25°C pre test run it became clear that a reduction in the voltage would generate nearly no degradation in an appropriate amount of time; therefore this test sequence still ran with the maximum voltage of 1000V. That this is feasible and can be corrected by multiplying the resulting PID speed by 100 was shown by measurements in the past, which worked out that the voltage is proportional to the PID level (Fig. 2) [7], so test results between 25°C and the other examinations are still comparable.

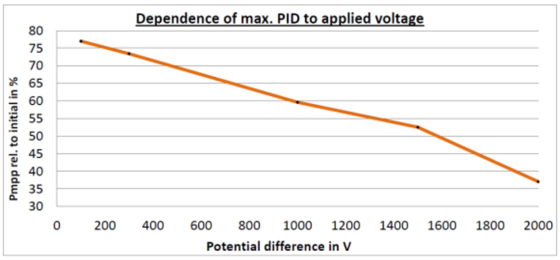

Figure 2: Development of the degradation level due to increasing voltage.

3 EXPERIMANTAL RESULTS

3.1 Comparison of double and triple layer structures

As initially mentioned, it is known from earlier publictions that an increased refractive index comes along with an increased robustness against PID. This was also confirmed during this analysis (Fig. 3).

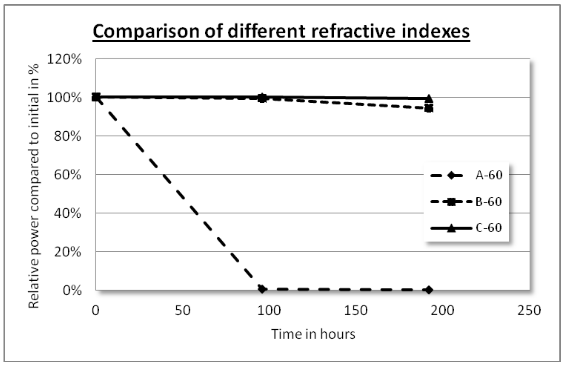

Figure 3: PID results after two cycles of PID/60/85 of cells with different diffractive index (A=2,03; B=2,2; C=2,3).

The disadvantage of an increased refractive index is that it results in lower efficiency at cell level, in particular prior to embedding. Hence, it was a point of interest if it is possible to create double layer structures which can combine the beneficial effects of layers with high refractive index (PID- resistivity) and layers optimized with regard to low optical losses.
Four different double layer cell designs were compared to a standard single layer structure with a refractive index of 2.08 (A). The tested double layer designs consisted of one layer with standard refractive index and one layer with refractive index, varied between 2.2 and 2.5 (G – J).

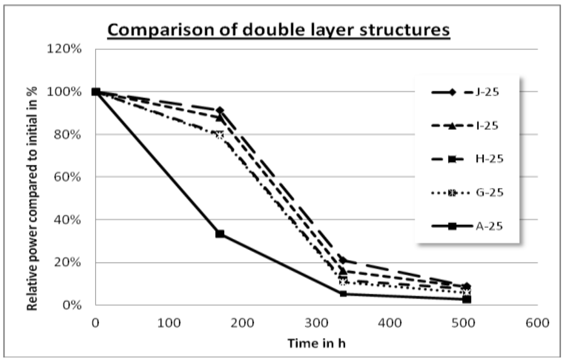

Figure 4: Different degradation behaviour of various double layer (J-G) cells compared to a standard single (A) layer cell.

As shown in Figure 4, applying a second layer slightly increases the stability against PID but does not effectively prevent PID. Also triple layer designs did not show significant improvements (see Fig. 5) either; the degradation is similar to the average degradation of cells with double layer ARC.

The small impact of the multi- layer ARCs is likely due to the limited thickness of the layers with high refractive index, which was restricted in order to avoid undesired optical losses.

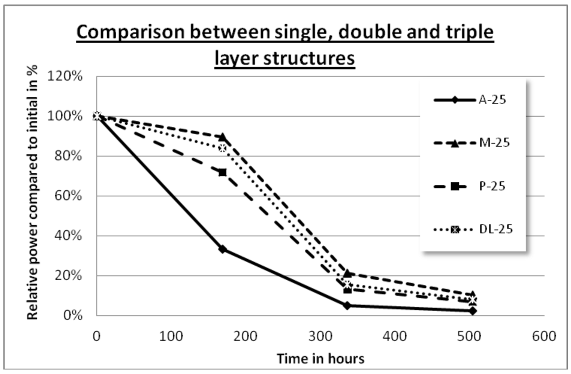

Figure 5: Different PID behaviour of cells with single (A), double (DL) and triple (M; P) ARC layer during the 168h 25°C test method.

3.2 Alternative approaches

There are also other approaches to modify the ARC-coating than the insertion of additional (double, triple) layers with differing refractive index. This may be the use of changed deposition conditions, a pretreatment by radiation (with or without process gas) or an additional gas flow.

The approaches either aim at a suppression of the leakage currents at cell level or at an increased conductivity in order to hinder a charge build up in the ARC.

Several groups, which did include elements of the alternative approaches, were tested in this experimental series.

First two of these groups (N, R) will be compared to the already shown triple layer ARCs at conditions described as test condition 3 (25°C; -1000 V). This example is depicted in Figure 6.

It is obvious that due to these alternative approaches a considerable improvement compared to the multi- layer ARCs could be obtained.

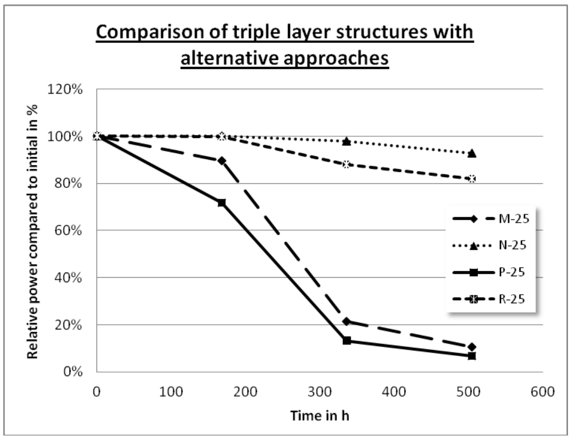

Figure 6: Different PID behaviour of cells with ARCs modified in alternative approaches (N, R) compared to triple layer structures (M, P). Test conditions: 25°C-.; -1000V ; 3 cycles of 168 hours respectively

In the next example (Fig. 7) four of the groups with alternatively modified ARCs are depicted. They are again compared to group M (triple layer, best multi- layer ARC), which was already shown in Fig. 5 and Fig. 6.

The test was carried out at increased temperature and humidity (60°C; 85% rH) with full area contact, and an applied voltage lowered to -100V.

Except from one group again a clear improvement due to the modifications was obtained. Partly also multi- layer structures are included here, which again did not prove to be superior.

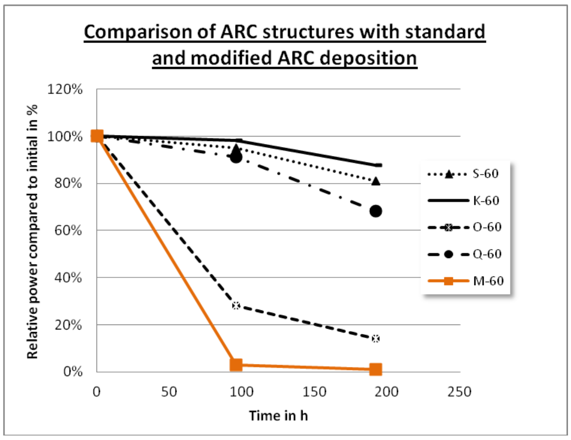

Figure 7: Different PID behaviour of cells with modified ARC deposition, compared with the best performing standard triple layer "M" (see Fig. 5 and Fig. 6). Test conditions: 60°C / 85% rH at – 100V.

Summarizing it can be stated that there are various possibilities to modify the ARC coating and to improve the PID behaviour of the cells.

In future experiments the alternative approaches will be combined and/or modified to further enhance the PID-resistivity.

3.3 Hot spot risk and PID

If we are talking about shunts that can develop in the anti reflective coating in a solar cell, it naturally guides us to the question which influence these shunts have to the cells in terms of hot spot generation. To answer this question, one module was prepared in the way that one string in the module was prone to PID and the other two were stable. The module was initially tested by the IEC 61215 [12] 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. After the initial hot spot analysis no significant difference between the three unequal strings could be seen. The difference in the average leakage current at reverse bias was in the magnitude of around 25%, which is a common result. After 5 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 value. Performing the IEC 61215 hot spot analysis again reveals an increase in the leakage current at reverse bias for the two stable strings about 20%, instead, the prone string showed an increase of leakage current at reverse bias about 1846%. Fig. 8 shows the significant increase of the average current and two leakage currents at reverse bias changes for two stable and one prone cell string.

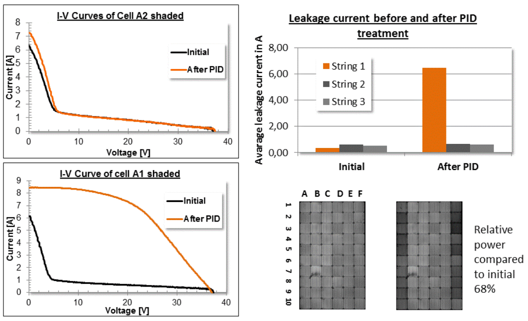

Figure 7: Hot Spot risk analysis before and after PID treatment.

In a second step according to IEC 61215 the cell with the highest leakage current in reverse bias is shaded and stressed for one hour with a sun simulator. In our case every cell was shaded for 30 seconds under the sun simulator and the maximum temperature was determined. The detailed procedure and the difference to the IEC test are presented on this conference by Stefan et al. [13]. In Figure 7 the IR images of the worst performing PID prone (up) and sensitive (down) cells are presented, before and after PID test duration. Comparing the images shows a rapid increase in the maximum temperature of the PID prone cell of around 30K.

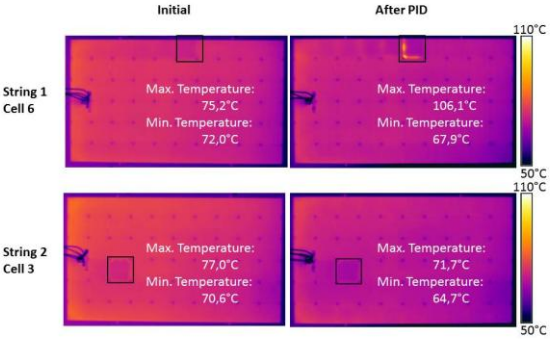

Figure 8: Maximum temperature during a hot spot test of one prone (above) and one stable cell (underneath) before (left) and after (right) PID degradation.

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

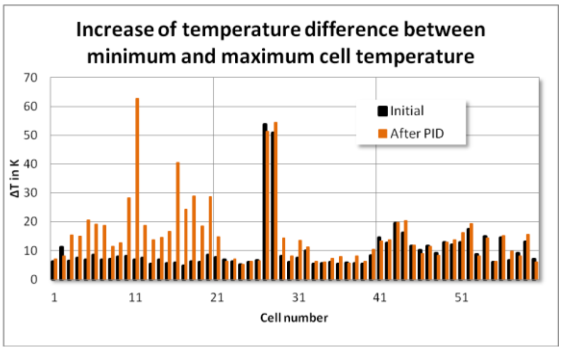

Figure 9: Increase of the temperature difference between minimum and maximum cell temperature of PID prone (1-20) and PID fix (21-60) cells during a hot spot analysis.

These results show that modules, which are affected by PID, don't only have a power drop in addition they have a considerable risk to generate hot spots in the field.

3.4 Acceleration factors between the different test methods

An important step to assess the PID results and therefore the live time estimation under real environment conditions are the activation energy and the acceleration factors. Earlier publications tried to investigate these values, as well [11, 14]. Recently a study about leakage currents during PID stress tests and their relation to the degradation has been published; activation energy of the acceleration factors of various test conditions could be investigated. In our studies it was an issue to see a relation between leakage current and the actual degradation level. Although there was a relation between high leakage currents and prone module concepts, although this seems to be mainly driven by the encapsulate material. The main Problem in looking at the leakage current seems to be that simultaneously to the sodium ion drift, an electrical electron migration takes place, which in summery represents the leakage current. As shown in Figure 9, the progression of the leakage currents of three different modules are in the same range, although the degradation of the modules varied significantly.

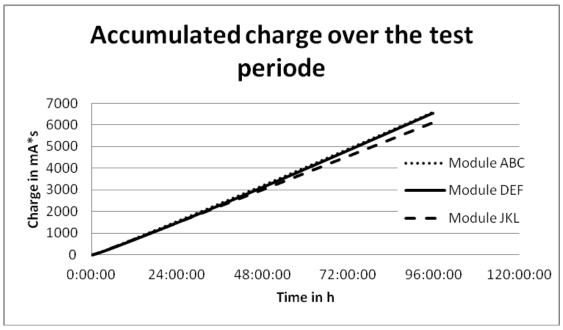

Figure 7: Example of accumulated charges over the time, during a PID stress test. Relative power compared to initial STC measurement of module ABC 66%, module DEF 1% and module JKL 32%. No link could be found between degradation level and accumulated charge.

A former publication about investigating the activation energies regards the normalized power drop of different modules. During our investigations, all modules also showed a non linear degradation progression. The degradation phase could be divided into two parts: the induction phase, where modules even showed a slight increase in their power and followed by a degradation phase, which ended by an asymptotic course against zero. To determine the activation energy, a degradation rate percentage power drop over time was implemented and calculated with the generally valid Arrhenius equation as followed. Whereas $k_{1/2}$ are the degradation rates, R the Boltzmann constant, $T_{1/2}$ the temperature and A the pre-exponential factor

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

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

The activation energy for modules with low, average and high degradation rate was determined for 85°C and 60°C as listed in Table I.

Table I: Determination of different activation energies for different test methods.

Degradation rate	Low	Middle	High
Average activation Energy E_A for 85°C and 60°C in kJ/mol	70.774	54.65	56.14
Average activation Energy E_A for 85°C and 25°C in kJ/mol	82.60	74.77	73.55

The activation energies fit quite well to the degradation rates. A comparison determination of E_A with degradation rates at 85°C and 25°C result in about 20% higher activation energies. These higher values obtained for the activation energy might be explained by the lower relative humidity during the 25°C test cycles, which slows down the degradation rate and therefore increases the activation energy.

As described previously, it seems that for certain module compositions the humidity has a non negligible influence on the degradation behavior. This makes it difficult to determine the acceleration factors, which are due to the assumption related only to the module temperature. Though what is possible is to make a realistic estimation of how fast or slow the different test methods show PID degradation compared to each other. Comparing the climate conditions at 85°C and 85% relative humidity and the method with 60°C an 85% relative humidity, an about four times higher degradation speed could be observed at 85°C. Comparing the 25°C conditions at a non defined relative humidity, which was nonetheless measured and determined with an average value of about 35%, the 85°C showed an about 170times faster degradation. With these values, it is possible to make the following statements:

1. The standard PID test (48h/85°C/r.H.85%) shows the fastest degradation.
2. The test, which is proposed for the IEC 62804 at the moment (96h/60°C/r.H.85%), shows the same results after the double amount of time with regards to 96h.
3. The test, which was published during the PVSEC 2011 (168h/25°C/non defined humidity but in this case about 35%) shows the same results after 50 cycles.

These statements are determined for a fully covered front side with a metal plate and applied with the same voltage.

3.4 Regeneration of PID affected modules

The regeneration of PID charged modules is an important topic, especially for modules, which have been out in the field. The question is, if modules with PID can be regenerated by an opposite potential to their initial power, and whether there are differences between the modules stressed by various climate conditions.

To address these topics, the modules which were degraded by different test cycles in the first run have been recovered with the same amount of time, with the same climate chamber conditions and the same applied voltage. Subsequently, STC measurements and electroluminescence images were made to match the samples. At the end, the modules could be summarized into two groups, modules with a power over 15% and modules with a power under 15% of the initial value after degradation.

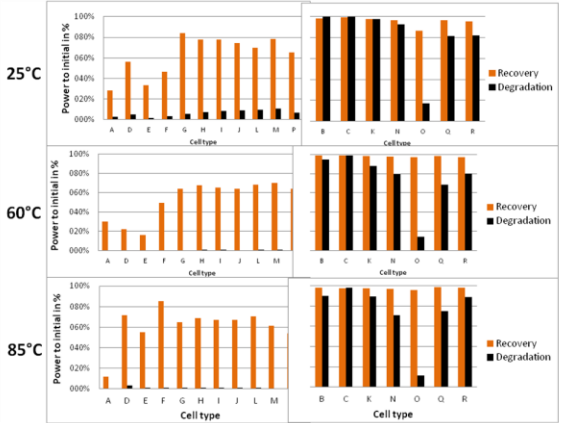

Figure 9: Comparison between PID degradation and PID regeneration of different cell types (A-R) under different climatic condition summarized in two groups, one with power under (left diagrams) and over (right diagrams) 15% of the initial power.

As we can see, all modules with a power left over 15% could be recovered to an average of 97% of their initial value. Modules with a higher power loss could only be recovered to an average value of 59%.

Table II: Average PID level of two groups (below and above 15%) compared with the average recovery level of three different test methods.

Degradation level	Below 15%		Above 15%	
Time of determination	Module power after Deg.	Module power after Reg.	Module power after Deg.	Module power after Reg.
25°C	6.45%	62.95%	81.58%	95.72%
60°C	0.68%	52.70%	74.83%	98.05%
85°C	0.95%	61.48%	74.82%	97.50%

As shown in Table II, the mismatch between the different test methods is negligibly small and mostly driven by the average degradation at the beginning of the recovery process. It seems that nearly all modules remain with a certain percentage of none recoverably degradation. It became particular clear for modules with a high degradation rate and shows the link between degradation level and recovery level.

Analyzing the electroluminescence images a characteristic for every test method could be observed, which was more or less obvious for the different cell types but still recognizable. Every module type shows a different pattern after the recovery phase (see Figure 10). How far the pattern is influenced by the degradation level, humidity, temperature or the exposure time and which pattern would be occur under outdoor conditions could not be finally clarified during this work.

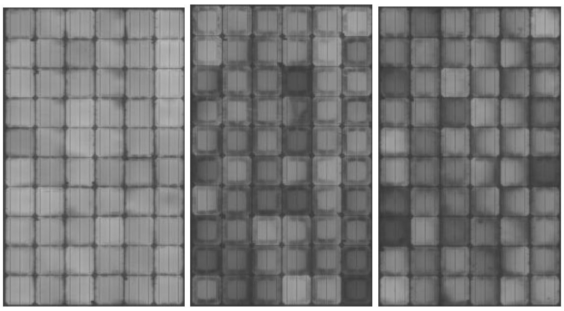

Figure 10: Electroluminescence images of module GHI after recovery at 25°C (left), 60°C (middle) and 85°C (right) show a characteristic electroluminescence pattern.

4 SUMMARY

A major issue of this publication is the impact of the anti-reflective coating on the PID effect. The significant influence of different ARCs on the PID stability of the whole module is demonstrated. In order to directly reveal the relative differences between the groups the sample preparation was, except of the ARC deposition, as much as possible consolidated.

The known dependency of the PID effect on the refractive index triggered an investigation of multi- layer systems. By applying double and triple layer structures the PID effect could be slightly reduced, however obtained improvements are too low to be a practical solution for the PID problem.

Alternative approaches to modify the ARC coating in order to reduce the PID effect were considerably more effective, further experiments will combine and modify the investigated approaches to again enhance the PID stability.

Furthermore, it could be shown that PID affected cells can generate a higher risk of developing hot spots than unaffected cells.

In the course of this work, three common PID test methods have been compared to each other and their acceleration factors have been determined. Briefly summarizing, it was shown that the 85°C test is two times as severe as the 60°C test and 50 times more severe than the 25°C test represented at the beginning. Activation energies could be determined, which are in the range between 82.60 and 56.14 kJ/mol for different modules. Finally, during investigations of the recovery behavior of PID depredated modules it could be shown that modules above a degradation level of 15% can be recovered to a minimum level of 96%. Modules under 15% could at least be recovered to a level of 53%. Finally it was observed that a part of the degradation process is not recoverable and that the percentage of this part is highly dependet on the degradation level the module has been discovered.

5 ACKNOWLEDGEMENT

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