# POLARIZATION EFFECTS AND TESTS FOR CRYSTALLINE SILICON CELLS

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ABSTRACT: Polarization or the potential induced degradation effect (PID) on crystalline silicon moduls is an alarming failure mode on modern crystalline silicon cells meeting high system voltages [1-4]. It can cause power losses in the vicinity 30% and more. Known parameters for PID on the cell level are high electrical resistivity of the $SiN_x$ anti-reflective coating via low refractive index and increased thickness and low emitter depth.
In this work we investigate the Polarization effect in regards to degradation speed on different encapsulants and module designs and with a special focus on selective emitter cells. The aim is a better understanding of the effect to propose appropriate test procedures for crystalline silicon cells and modules. For this purpose, different cells and modules have undergone various test sequences comparing different module materials and components.

Keywords: Polarization, crystalline silicon cells, selective emitter, PID

## INTRODUCTION

Initially, Sunpower [1] and Evergreen PV modules [2] have shown Polarization effects at crystalline silicon cells. During the last years NREL [3] described several module defects caused by voltage stress, and investigated resulting leakage currents that have been expected to indicate PID. It was a common believe, that these effects only occur for special cell and module designs but not affecting the whole silicon solar industry. In 2010, Solon SE showed that there is also a Polarization effect on standard mono and poly crystalline cells. Among others the influence of different encapsulants and various configurations of the silicon nitride layers could be verified and a test procedure for crystalline modules was proposed [4].
Since mid-2010 more and more returns from the field arrived at PI-Berlin’s lab showing power degradations caused by Polarization. During our research we even found Polarization effects on CIGS modules which is published in [5].
Cells became more prone to potential induced failures during the last five years. Although the effect is not clear on the microscopic level yet, one can say, that it is a consequence of improvements in cell and module design. As an independent testing institute it is our ambition to develop adequate test procedure for crystalline silicon cells and modules for PID stability.
In this work we try to find a quick test procedure on the cell and module level. On cell level we tested different encapsulates and the PID behavior of the latest upcoming cell generation - cells with selective emitters. The role of the sodium ions in the Polarization effect is still unclear, but during the investigations on the cell level it soon became clear that it is necessary to have a look on the whole module, or to be more precisely the cell interaction with the module materials and the environment. Therefore, stress sequences with different working conditions have been evaluated with the aim of a reproducible test method which includes all relevant parameters. Finally, a quick Polarization test sequence has been developed to help module and cell manufactures to check their different products.

## SAMPLES WITH DIFFERENT ENCAPSULANT MATERIALS

The goal of the first experiments has been to find an encapsulate material which is able to polarize cells as fast as possible. In the experiment three different encapsulating materials have been evaluated in terms of their behavior during PID-provoking test runs. Selections of cells from the same batch have been laminated to glass-EVA-cell-EVA-backsheet samples. The test run has been performed in a climate chamber with a temperature of 85°C and a relative humidity of 85%, which corresponds to the damp heat conditions according to the standard IEC 61215 [6]. The front surfaces of the samples were fully covered with a copper foil and were connected to the positive pole of a power supply of 200 V, the cell contacts were connected to the negative pole. The results in Table 1 show the average cell power values with different module materials applied, before and after the voltage stress. It is to determine that PVB and EVA encapsulants promote the Polarization process whereas silicon laminated samples hinders the PID effect.

Table 1: Overview of the average initial cell power of samples with different encapsulant materials and their power after a 48 h PID tests sequence with 200V.

| Material | Average initial cell power [W] | Average cell power after 48 h PID stress [W] | Deviation [%] |
|---|---|---|---|
| EVA | 1.71 | 0.15 | -91.35 |
| PVB | 1.71 | 0.01 | -99.31 |
| Silicone | 1.65 | 1.62 | -2.08 |

At a first sight samples with silicone encapsulants seem to be excellent, but test-to-failure sequences revealed that severe degradation starts after 190 hours and reached a degradation rate of 90% after 240 hours.
PVB laminated samples show the highest susceptibility regarding PID. Despite the fact that PVB laminates are slightly more suitable for our PID-revealing tests than EVA laminates, all following tests will be performed with EVA materials due to the high availability and their wide spread use in the solar industry.

THE ROLE OF TRANSITION FROM THE ENCAPSULANT AND THE CELL SURFACE

Figure 1 shows the sandwich test-setup which has been used for several test sequences. The aim was to find a test method with little preparatory work and the possibility to extract the polarized crystalline cells after the treatment for further research. A sandwich consisting of two glass plates, two EVA sheets, and a silicon solar cell have been pressed together and laminated.

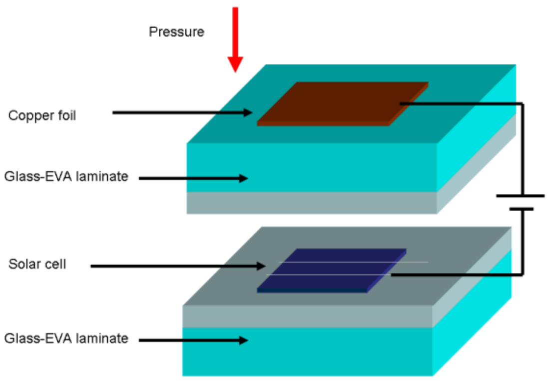


Figure 1: Schematic test-setup with two glass-EVA laminates and a crystalline silicon cell in between. Both glass plates have been pressed together to simulate a laminated module. The outside surface of the front glass has been equipped with copper foil. The foil and the cells contacts have been connected to a laboratory DC power supply and have been stressed with a voltage of -200V at 50°C at 20% RH.

After 48 hours of stress the cells have shown characteristic patterns of inhomogeneous Polarization in electro-luminescence images. During continuation of the voltage stress the indication of PID in electro-luminescence images unexpectedly disappeared.
The sandwich pressure has been performed via module clamps (adjusted to 6 Nm via a torque wrench). For higher pressure values most of the cells cracked and thus have not been not useable any more for further studies. At 6 Nm the EVA-cell-interface has been connected unequally, contacting predominantly the grid and bus-bars and resulting in sporadic PID effects. Moreover, EVA's rate of chemical crosslinking and its adhesion properties changes significantly under the given climatic conditions. After the failed sandwich tests the cells have been laminated with EVA as described above and have been tested for PID. All cells have shown degradation effects as expected.
To find out the role of the EVA-cell-interface regarding PID mechanism, further investigations have to be carried out. For the time being, it is inevitable to prepare laminated samples for further studies and PID analysis. Therefore, all following samples are prepared with standard EVA and standard float glass applying unified soldering techniques and lamination conditions.

CELLS WITHOUT ANTI REFLACTION COATING

During the test sequences two theoretic models emerged for explaining the PID effect. All models are based on the fact that mobile sodium ions can diffuse from the front class to the cell surface due to a force caused by potential induced stress. The velocity of the positive charged ions are mainly influenced by the encapsulate material, the temperature, the humidity and the applied voltage. When sodium ions reach the $SiN_x$-ARC (Anti-Reflective-Coating) various options occur: On the one hand the charged ions concentrate on the surface of the layer building up an electric field leading to an anti-passivating effect resulting in an increasing surface recombination rate. On the other hand the sodium may diffuse into the bulk and act as a donator atom. This leads to a rising concentration of sodium ions in the emitter, so the negative doping will be neutralized, the p-n-junction will be diminished, so the photovoltaic effect of the cell.
To study these theories cells with and without any $SiN_x$-layer have been laminated and tested for 48 hours at dry heat conditions (85°C and 20% RH). None of the samples without $SiN_x$-layer showed a Polarization effect after 48 hours. However, a slight increase in performance due to a passivation effect was shown in the past by [7, 8]. The $SiN_x$-coated reference sample shows losses in performance of more than 90%.

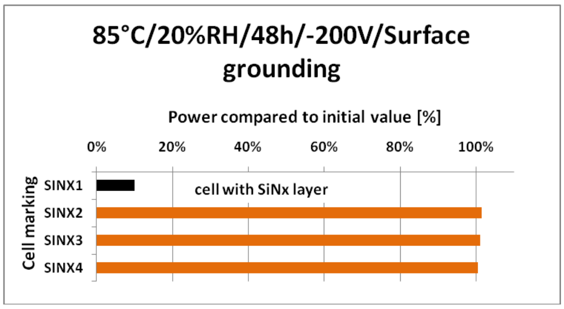


Figure 2: Cells without $SiN_x$-ARC show no degradation of performance due to PID stress test.

To underline the role of sodium in the PID mechanism, a polarized sample and an untreated reference have undergone a TOFSIMS-analysis (Time-of-Flight Secondary Ion Mass Spectroscopy) up to a total depth of 1µm. Figure 3 visualizes the result and shows a ten times higher concentration of sodium ions on the polarized cell (Probe 1, Position 1) compared to a low concentration of sodium in the unaffected reference cell (Probe 2).

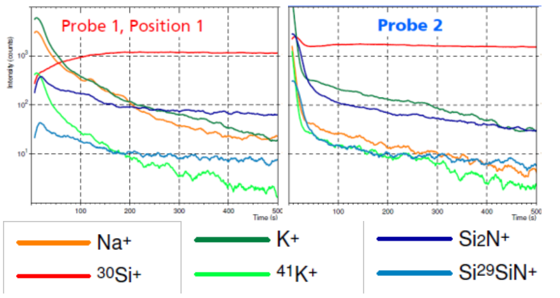


Figure 3: TOFSIMS profiles of a polarized cell (Probe 1) and an unaffected reference cell (Probe 2) for various elements.

On the one hand it is to determine that a $SiN_x$-layer promotes the Polarization of crystalline solar cells. It needs to be investigated if no $SiN_x$-layer also means no Polarization effects. On the other hand the TOFSIMS-results indicates an ionic movement into the bulk. Difficulties and uncertainties in interpretation of TOFSIMS results are given through two decisive disadvantages of the measurement itself:

- Various sputter rate for different elements [9].
- An inaccurate depth profile on probes with an uneven surface.

In summery the experiments show that the $SiN_x$ layer is the deceive region and that $Na^+$ ions are emigrating towards the cell by applied voltage.

CELLS WITH SELECTIVE EMITTER

After the previous test runs a standard test sequence on cell level was implemented with the following approach:

- Soldering and laminating the cell with a standard EVA, glass and back sheet.
- Initial I-V measurement in accordance with IEC60904-1 before PID.
- Full-area coverage of the module front surface with a metal foil.
- Temperature of 85°C.
- Relative humidity of 85%.
- Applied voltage of -200 V between the cells and the metal foil.
- Treatment of 12 hours.
- Final I-V measurement in accordance with IEC60904-1.

The actually newest cell technology available on the marked, cells with selective emitters, have been tested and compared to cells with homogenous emitter in a first test run. The goal was to study the influence of thinner emitter on the Polarization behavior.

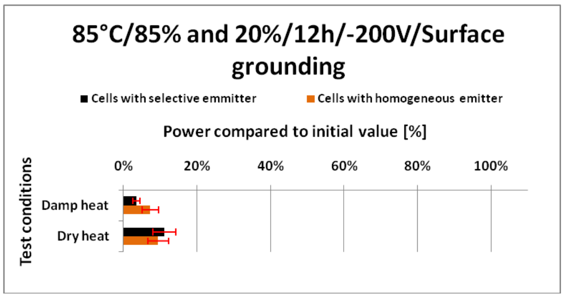


Figure 4: PID susceptibility comparison of crystalline silicon cells with selective and homogenous emitter. Both test runs, at damp heat (85°C/85%RH) and dry heat (85°C/20%RH) conditions, showed no significant differences between both cell concepts.

In figure 4 it is shown that selective emitter cells don't show a remarkable difference in regards to susceptibility for Polarization compared to standard silicon cells. It was also found that cells of a same emitter technology show a wide range of sensitivity in Polarization. This fact creates general problems for analyses not only on cell level but also on module level, which has been described by [4] and becomes visible by the checkerboard pattern (see figure 7) on PID affected Modules. Even adjacent cells with the same crystalline cell pattern, concluding with the same process history, behave different under potential induced stress. In this case further researches have to be done in the future.

MODULE LEVEL

PID VELOCITY INFLUENCED BY HUMIDITY

As mentioned above PID effects have to be considered in a wider context. For this reason entire modules have been stressed under various test conditions with the aim to study all different influence factors with the aim of and to develop a standard PID module test procedure.
A selection of different module types has been evaluated at dry heat and damp heat conditions. All modules were frame grounded and stressed with a voltage of -1000V. As seen in figure 5 the modules' performances dropped just slightly after 48 hours at dry heat conditions with a low scatter from average.

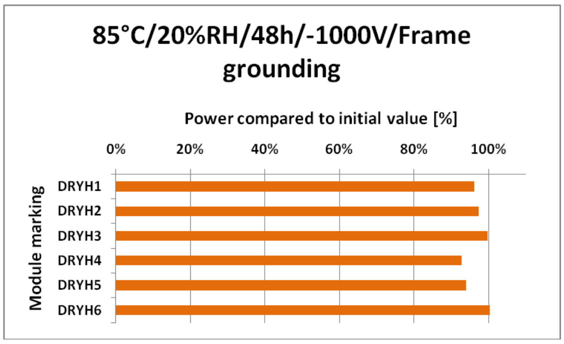


Figure 5: Nearly no power distribution was determined after 48 hours stress test with a relative humidity of 20%. Only a slight mismatch between the single module types is observed.

With an increase of the rel. humidity up to 85% at 85°C a significant drop in performance is observed for almost all tested module types. The rate of degradations varies over a wide range and is different for all module types as seen in figure 6.

It is to determine that the humidity has an important influence of the ability of modules to develop characteristic sign of PID. For a rapid test procedure the presence of a remarkable humidity is inevitable.
It is to be expected that no condensed water comes up during the tests and thus no extensive contact on the glass surface occurs. Two effects about the interaction with humidity are conceivable. Either humidity penetration supports the sodium transport or the humidity realizes a better contact situation during the test cycle on the front surface due to condensation. An interaction of both effects is likely.

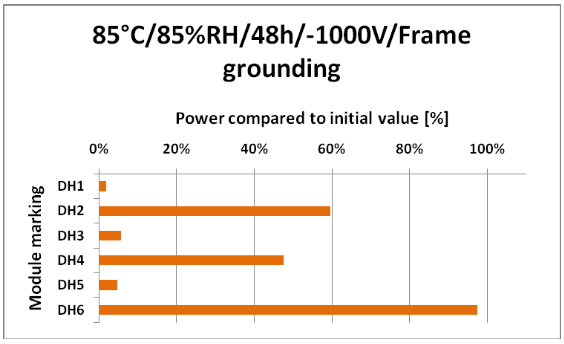


Figure 6: After adding humidity to the test sequence all modules show power distributions. The mismatch between the modules becomes significant for each module type.

During the next step two possible grounding situations, the influence of full surface grounded modules and frame grounded modules were investigated and compared to likewise frame grounded field returns. All of the examined modules grounded this way showed distinct Polarization development from the frame to the modules' center with preferred PID affected cells on the lower rows in field module. Modules with a full surface grounding show no noticeable direction of degradation but it highlights the different behavior of cells recognizable in the so-called chessboard pattern.

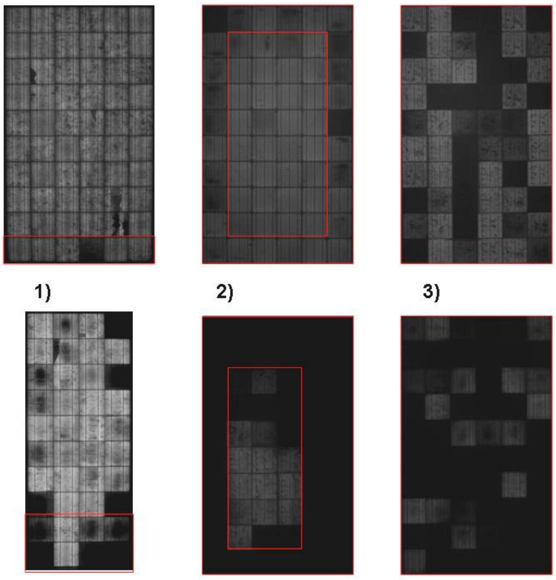


Figure 7: Different contact situations during test sequences compared to field returns.

1) frame grounded field modules: PID mainly on lower cells
2) frame grounded test modules: PID on cells near to frame
3) full surface grounded modules: random distribution of affected cells (chessboard pattern) caused by the different PID cell susceptibility.

According to natural grounding situation in field all following analyses were done with frame groundings and implemented in the internal standard test sequence.

VOLTAGE DEPENDENCE OF MODULES WITH CRYSTALLINE SILICON CELLS

As a result of prior tests a voltage dependence of PID has been observed. To investigate this relation several modules were connected to a power supply and burdened with different voltages over periods of several hundred hours. In figure 8 it is seen that the degradation of some modules start even at small voltage level. Regardless of the voltage level itself the modules' degradation processes stabilize on a certain levels which seem to be characteristic for each module type. With plotting degradation rate over the voltage level a linear and characteristic correlation can be found.

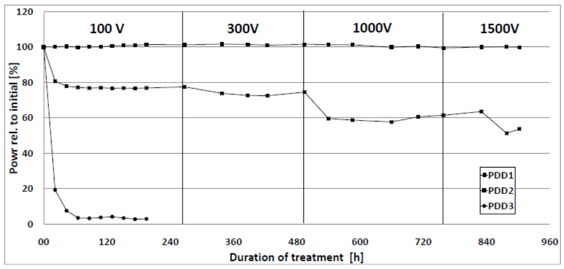


Figure 8: The susceptibility to PID varies significantly over a wide range of modules. Some modules show a rapid loss in performance at a very low voltage level (PDD3) whereas other modules don't even show degradation tendencies at voltages beyond the 1000V mark (PDD1). A voltage dependency could be determined as shown with PDD2, which shows a saturation state at every voltage level.

An interpretation of the voltage dependency might be capacitive effects. Ionic migration caused by a certain electric force according to an applied voltage leads to a saturation of electric charge keeping all forces in thermodynamic equilibrium. These electrical charges influence the semiconducting properties as described above.
For the standard test method the maximum system voltage written on the label will be used.

STANDARD PID TEST

Table 2: Overview of the first test results after the developed test sequence. The first index of the module number indicates the module type, the second number gives the consecutive number. Class A classifies modules with power drops below 5%, B between 5 and 30% and C all modules with a power deviation above.

| Module number | Initial power [W] | Power after 48h PID stress [W] | Deviation to initial value [%] | Class |
|---|---|---|---|---|
| PID01 | 229.62 | 230.90 | 0.56 | A |
| PID02 | 230.57 | 231.96 | 0.60 | A |
| PID11 | 195.15 | 189.59 | -2.85 | A |
| PID21 | 189.93 | 178.02 | -6.27 | B |
| PID31 | 247.14 | 174.19 | -29.52 | B |
| PID41 | 237.12 | 122.71 | -48.25 | C |
| PID51 | 213.76 | 104.30 | -51.21 | C |
| PID52 | 219.08 | 104.05 | -52.51 | C |
| PID53 | 212.37 | 97.64 | -54.02 | C |
| PID54 | 210.35 | 95.95 | -54.38 | C |
| PID55 | 215.27 | 96.30 | -55.26 | C |
| PID61 | 216.13 | 86.60 | -59.93 | C |
| PID71 | 191.24 | 69.89 | -63.45 | C |
| PID81 | 149.12 | 46.51 | -68.81 | C |
| PID91 | 226.49 | 1.11 | -99.51 | C |

Taking into account all test results and experiences a PI-Berlin standard test sequence was implemented as listed:

- I-V measurement in accordance with IEC60904-1 before PID.
- Initial electroluminescence analysis due to the PI standard
- Grounding of the module as described in the manual (via frame).
- Temperature of 85°C.

- Relative humidity of 85%.
- Applied voltage of the maximum system voltage given by the label between the cells and the frame.
- Degradation period of 48 hours.
- Final I-V measurement in accordance with IEC 60904-1 within four hours after finishing the test.
- Final electroluminescence analysis to evaluate the PID spread.

For assessing the tested objects the modules will be classified in three PID quality categories A, B and C. A classifies modules with power drops below 5%, B between 5 and 30% and C all modules with a power deviation above.

## JOINT PID TEST

This publication found an accurate analysis method for Polarization including all gathered experiences of the last years. Many questions in regards to PID's physical and chemical mechanism as well as to a variety of environmental impacts remain unanswered and need to be investigated in the future. Up to now, all different factors have not been sufficiently studied and it is too early to establish a general industry guideline or an international standard. Therefore, the three German IEC-accredited test institutes Photovoltaik-Institut Berlin, TÜV Rheinland Energie und Umwelt GmbH and VDE Prüf- und Zertifizierungsinstitut GmbH (in co-operation with Fraunhofer Institute for Solar Energy Systems) and three German PV manufacturers Q-Cells SE, SCHOTT Solar AG and Solon SE developed an easy method avoiding any need of expensive equipment to check solar modules of their PID reliability [10]. All parties concerned agreed the following test method:

- Temperature of 25°C.
- I-V measurement in accordance with IEC60904-1 before PID.
- Full-area coverage of the module's front surface with aluminum foil or water.
- A voltage of -1000 V applied between the cell matrix (via the junction box) and the front surface.
- Degradation period of seven days.
- I-V measurement in accordance to IEC60904-1 within four hours after finishing the test.
- A maximum of 5% of $P_{mpp}$ degradation shall be allowed.

A Round-Robin test [9] has shown the comparability of the test results among the participating institutes and the PV manufacturers. As this is just a quick check the parties agreed together in a further development in the test method.

## CONCLUSION

It was shown that the Polarization or PID effect only occurs when encapsulant and silicon nitride layer are attached to each other.
The examination clarifies whether a cell shows a Polarization behavior or not. In a first test run a comparison between cells with selective and homogenous emitter were tested and no significant differences have been observed.
After several comparative tests with different environmental conditions two test sequences for single cell laminates and modules have been developed.
For assessing modules a classification into three PID quality categories A, B and C are defined. Class A for modules with power drops below 5%, B for degradation rates between 5 and 30% and C for all modules with a power deviation above.

All presented tests can only give an answer of the question: Is the tested object susceptible against Polarization or not. None of these tests can give a statement about the life time of any tested object. As described in this paper a verity of factors influencing the Polarization speed and in outdoor conditions some of the factors are changing minutely or are strongly dependant on the climate region. Furthermore modules show a self-curing effect [4] which makes it even more difficult to give a forecast of the modules behavior.

## OUTLOOK

Future studies will analyze the self-curing effect of different module types under typical operating conditions of modules in the field, more studies about cells with selective emitter will be carried out and investigations about defects created by positive potential against ground will be published. Moreover, reversible Polarization effects are observed at CIGS modules and will be published in future works as well. But first of all our main focus is to establish a common test sequence on module level which can be used as a template for an international standard.

## AKNOWLEDGEMENT

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