Potential-induced degradation (PID) of bifacial PV modules incorporating PERC+ technology

Kai Sporleder, Volker Naumann, Stephan Großer, Marko Turek & Christian Hagendorf, Fraunhofer Center for Silicon Photovoltaics CSP, Halle, Germany

Abstract

The market share of bifacial solar modules is rising, because of the additional power yields of up to 20% per year, which reduce the levelized cost of electricity (LCOE). Many manufacturers have bifacial PV modules in their portfolios, with a majority of them employing bifacial passivated emitter and rear cell (PERC+) technology. In this paper, it is shown from the results of studies that rear-side-related potential-induced degradation (PID) effects can occur in addition to the conventional front-side shunting type (PID-s). Two types of rear-side PID are described – polarization-type degradation (PID-p) and corrosion-type degradation (PID-c) – which can both lead to severe power losses: up to 50% from the rear-side contribution, and around a 10% loss in overall front-side performance. To assess and distinguish these PID effects at an early stage in PV module production, a novel test scheme at the cell level, which combines illumination with high-voltage stress, is proposed. Additionally, a new method is presented for a quantitative evaluation of the rear-side PID on the basis of spectral measurements using LED solar simulators, which is also applicable to outdoor assessment of PV power plants. These new findings on rear-side PID for bifacial PERC+ solar cells thus also require the establishment of a new standardized test routine for solar cells and modules in order to ensure equal test conditions for the quantification of expected power losses in the field.

Introduction: bifacial PERC technology and new types of degradation

The idea of bifacial solar cells dates back to the 1960s [1] and describes the ability of solar cells or modules to convert light from both the front and the rear side into electrical energy. About 10 years ago, technological concepts were introduced to manufacture and mass produce the passivated emitter and rear cell (PERC) in a bifacial design – the so-called *bifacial PERC*, or *PERC+*. For PERC+ cells, bifaciality is achieved in an adapted cell process, whereby a full-area rear-side metallization is replaced with screen-printed metallization; thus, the rear side becomes translucent [2].

In 2020 bifacial solar cells are predicted to reach a market share of around 20%, and it is envisaged that the market share will grow steadily to around 60% within the next ten years [3]. Bifacial PERC is expected to play a key role, because it can conveniently be produced on existing PERC production lines, since production capacity is available and is anticipated to grow further [3,4]. With the introduction of PERC+ technology, new degradation mechanisms have come under the spotlight during the last few years. In this paper, the origin and importance of potential-induced degradation (PID) of bifacial PERC solar cells will be explained.

> "With the introduction of PERC+ technology, new degradation mechanisms have come under the spotlight during the last few years."

For PERC+ cells, bifaciality is achieved by omitting the full-area metallization at the rear side of the solar cell in favour of local contacts. However, without this metallization there is no electromagnetic shielding of the rear side, making it vulnerable to rear-side PID. This phenomenon has been confirmed by reports in a number of scientific publications in the last two years, on laboratory tests with commercially available bifacial PERC solar cells. Two different rear-side PID mechanisms have so far been distinguished. The first – *PID-p* – is due to a polarization effect at the rear interfaces; this effect results in a non-permanent reduction in the field-effect passivation and is mostly reversible. The second mechanism – *PID-c* – is due to corrosion of the silicon; to a large extent, this is irreversible and results in permanent and localized structural damage to the passivation layers.

PID: a short history

Depending on the polarity of the voltage and on the type of solar module, potential-induced leakage currents through encapsulating module layers can cause various degradation phenomena. For thin-film modules, it has been known since 2003 that transparent conductive oxides (TCOs) based on tin oxide can corrode under conditions of increased humidity and temperature, if the active layer is at negative potential compared with the grounded module frame [5].

In 2005 a 'polarization effect' was reported for solar modules with back-contacted n-type crystalline silicon solar cells [6]. These modules showed a degradation in performance when they were at a positive potential relative to the module frame. It was assumed that the degradation was based on a field effect that causes deterioration of the electrical surface passivation of the solar cells. This is what is referred to as *polarization-type degradation*, or commonly *PID-p*.

Other degradation phenomena relate to corrosion of anti-reflective layers, cell metallization and cell connectors, which were also found to be associated with leakage currents through electrical potentials in 2010 [7]. Finally, in the same year a substantial reduction in the power output of solar modules with p-type solar cells was reported [8,9]. This significant degradation of solar modules, referred to as *potential-induced degradation*, occurs in PV systems where the solar cells are at a negative potential compared with the module frame. In this case, a strong reduction in the shunt resistance, well below 1Ω, in the affected solar cells has been observed.

Through microstructural investigations, the degraded performance was able to be attributed to a large number of nanoscopic shunts in the affected solar cells, which was then called *PID-s* [10]. An accelerated, yet realistic, test for PID-s on solar cells was developed at Fraunhofer CSP, and test set-ups for the approach became commercially available, e.g. the PIDcon testing tool by Freiberg Instruments [11].

The drop in the parallel resistance due to the PID-s shunts is, however, reversible. After reducing the potential difference, the solar cells heal slowly; this regeneration can be accelerated by increasing the temperature and applying a reverse voltage [8,12].

In subsequent years, a number of countermeasures against PID-s were developed and implemented in state-of-the-art modules and PV systems. Because of the high relevance to reliability and the increasing number of bifacial crystalline silicon solar modules, current PID research activities are now focusing on the investigation of PID effects on the rear side.

PID – a new threat for the rear side?

For standard PERC solar cells, there is no risk of PID affecting the rear side. The passivating layers and the silicon are shielded by the fully metallized rear side. However, for PERC+ cells, the electrostatic shielding due to this metallization is missing, and cells are exposed to the same high-voltage conditions on the rear side that are known to cause PID on the front side. Thus, the rear side can also suffer from PID.

The fact that the rear side can be affected by PID was reported in various publications in 2018 and 2019 [13–15]. In these works, p-type mono PERC+ cells were investigated, with the result that similar high-voltage stress conditions on the rear side also led to performance losses because of PID. The performance losses described in these publications ranged from 12% after 40h [13], 10% to 13% [16], and up to 50% [15].

From all these published results, it is clear that PID stress can severely damage the back side of bifacial solar cells, thus reducing the overall cell performance. However, the results are difficult to compare quantitatively, and conclusions regarding yield losses cannot directly be drawn, as the test conditions were not identical: test times between 24h and 136h, temperatures of 50°C, 60° and 85°, and voltages of 1,000V and 1,500V were used in the studies. It is therefore important to identify and specify unique test conditions, i.e. by means of a standardized test procedure for rear-side PID, similar to the existing test norms for front-side PID.

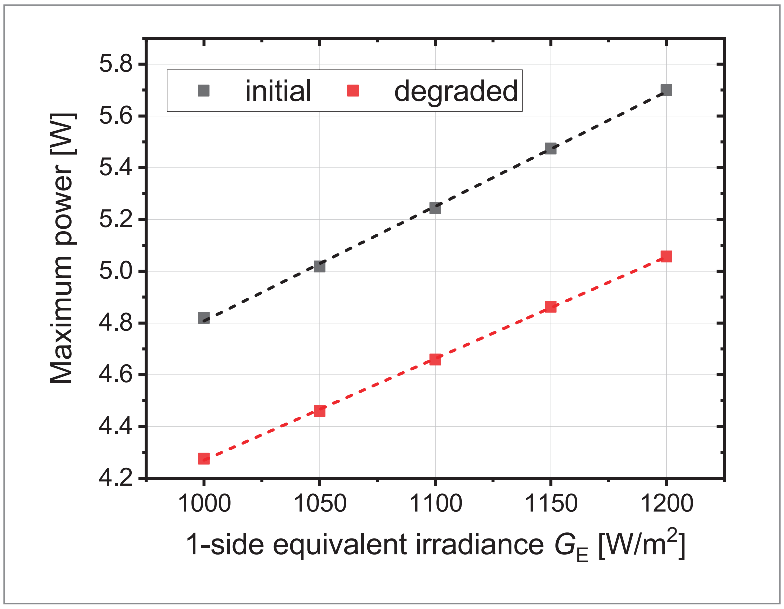

Figure 1. Power (P_{max}) of a mini-module as a function of the one-side equivalent irradiance G_E.

Two different degradation mechanisms are currently known in the scientific literature for PID at the rear side: 1) a degradation due to depolarization of the passivation layers, abbreviated *PID-p*; and 2) a corrosive PID type, referred to as *PID-c*.

PID-p of the polarization type assumes that the field-effect passivation of the AlO_x layer is depolarized by charge compensation because of an accumulation of positively charged ions in the rear-side AlO_x passivation layer [13]. This interpretation was developed according to the findings of Swanson et al. [6].

The second currently known PID effect is due to corrosion of the Si below the passivating AlO_x and SiN_y layers. By analysing just the *I–V* curves, it is not possible to distinguish whether the high potential causes just a depolarization or an irreversible corrosion. This differentiation can be accomplished by using spatially resolved methods: microscopic regions of up to 2μm in size showing corrosion can be detected by means of laser beam induced current (LBIC) or electron beam induced current (EBIC) methods [14].

Another fundamental difference between PID-p and PID-c can be related to the recovery behaviour of degraded cells or modules under light exposure. Alternatively, the high-voltage stress test can be performed under simultaneous illumination. If the degradation is caused by corrosion (PID-c), the performance of the stressed sample cannot be recovered by illumination. However, in the case of PID-p a complete healing can be achieved [17,18]. More importantly, if the PID test is performed

"PERC+ cells are exposed to the same high-voltage conditions on the rear side that are known to cause PID on the front side."

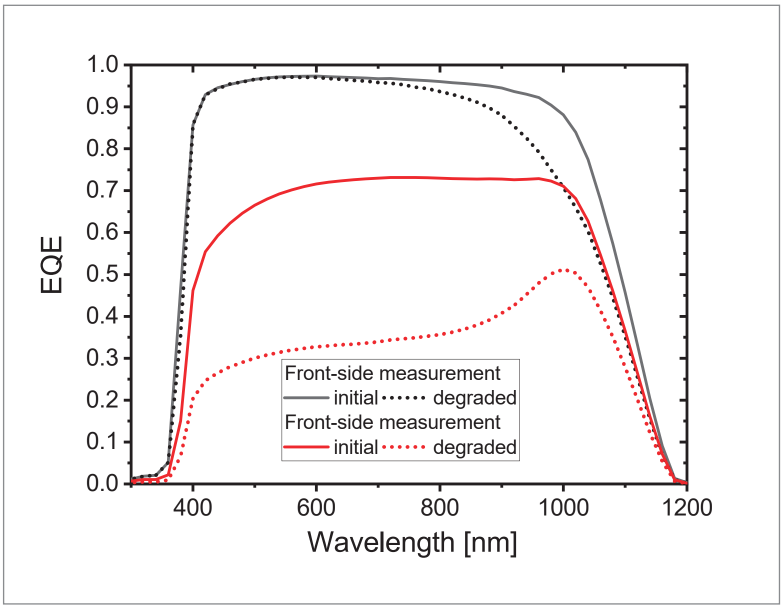

Figure 2. External quantum efficiency (EQE) of a bifacial PERC one-cell module. Compared with the initial state (solid lines), the measurements in the degraded state (dotted lines) have reduced EQE signals in certain wavelength ranges as a result of PID.

"Spectral features serve as a criterion for distinguishing rear-side PID from front-side PID."

under simultaneous illumination, PID-p can even be suppressed. This implies that for a PV park, polarization-type degradation (PID-p) is probably not critical, assuming that a rear-side light intensity exceeding 10W/m² is sufficient to suppress PID-p [17]. This is not the case, however, for corrosion-type degradation (PID-c), which causes damage to the cells in field conditions.

In the light of these findings, an accelerated PID test is proposed for the rear side, whereby illumination together with the high-voltage stress is simultaneously applied in the test set-up. Furthermore, to test for PID at the rear side a new standard ought to be developed which includes these combined test conditions. On the basis of the results obtained at Fraunhofer CSP, the authors propose that the standard should feature a high-voltage stress of 1,500V at elevated temperatures around 85°C, combined with an illumination of 1–5% of normal test intensity.

As an example, Fig. 1 shows the power of a mini-module as a function of the one-side equivalent irradiance G_E. The measurements were carried out before and after a PID test. In the test configuration, a voltage of 1kV was applied across the full-area metallic electrode on the back of the module opposite the grounded solar cell. The front of the module was also connected to the ground. In this special configuration, a single-side PID assessment is possible in such a way that shunting-type PID (PID-s) of the front side is avoided. Power losses of around 11% under standard test conditions are thus caused by rear-side PID as a result of the degradation of the rear side only.

Classification and quantification of different types of PID

The major impact of all types of PID in an advanced stage is the reduced power of the solar cells and modules. During quality assurance tests or product development, the power under standard test conditions is typically determined using solar simulators. As the cells within a single module are usually not affected equally by PID – visible, for example, as a checkerboard pattern in luminescence imaging – it is essential that the light field from the solar simulators used is of high lateral uniformity for a reliable power analysis. Reliability can be ensured, for example, by the use of the Fraunhofer CSP uniformity test sensor, which is made of identical materials to those of the modules under consideration, but with all cells individually connected to an integrated measurement electronics. This allows a simple, fast and accurate assessment of the lateral properties of the solar simulator light field.

Nevertheless, while conventional measurement systems reliably yield the power losses after a stress test, it is not possible to identify the specific type of PID. In particular, for a failure identification and optimization of the production process, it is of critical importance whether the front side or the rear side of the solar cell is affected.

It has been shown that the two types of PID, PID-p and PID-c, exhibit a distinct characteristic change in the spectral response of the cell (see Fig. 2). A spectrally resolved external quantum efficiency (EQE) analysis was carried out for the one-cell module, both in the initial state and after the PID stress test. In the degraded state, an increase in carrier recombination is observed for wavelengths above 700nm when measured with the sunny side up. This is reflected in a reduced EQE signal at larger wavelengths. While the absorption of the incident light depends on the wavelength, electron hole pairs are still created throughout the entire depth of the cell, including the degraded rear surface of the cell.

With the module flipped over, i.e. the rear side is now the sunny side during the EQE measurement, PID-related carrier recombination dominates the near-surface regions and thus leads to a characteristic and severe drop at wavelengths below 900nm. A peak in the rear-side EQE in the 900 to 1,100nm wavelength range indicates that an increase in bulk recombination due to rear-side PID is negligible. These spectral features are characteristic for rear-side degradation and thus serve as a criterion for distinguishing rear-side PID from front-side PID.

Using a recently developed rapid quantum efficiency test based on LED solar simulators [19], this classification and distinction of the PID type can easily be combined with the power test under standard test conditions. Furthermore, the spectral information provided by a more advanced test set-up using LED solar simulators results in far more reliable estimation of yield than a single measurement as described in the test norm for measurements under standard test conditions.

In a simplified version, the usage of LED solar simulators allows the illumination to be controlled using either short or long wavelengths only. As can be seen from the inlay in Fig. 3, the short-circuit current I_{sc} of a module is significantly reduced by about 20% for long-wavelength illumination; on

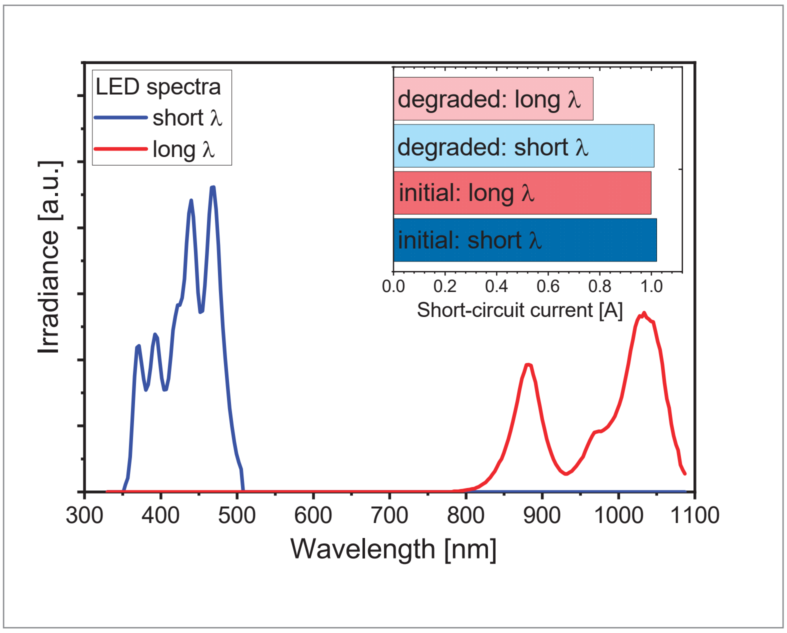

Figure 3. Two spectra of an LED solar simulator for rapid rear-side PID testing, representing the short-wavelength range (blue line) and the long-wavelength range (red line). The inlay shows the resulting short-circuit current of a bifacial one-cell module for the two indicated spectra in the initial and degraded states. While there is almost no change in the current for the short-wavelength spectrum, the long-wavelength spectrum clearly shows the rear-side degradation.

Figure 4. LED-based solar simulator at the Fraunhofer CSP PV park. Using different coloured LEDs, an initial diagnosis of the type of PID can be made.

"The new types of PID associated with PERC+ solar cells need to be tested using an adapted new test standard which includes the simultaneous application of illumination and high-voltage stress."

the other hand, the I_{sc} is not reduced when using short wavelengths. Thus, this simplified version of a spectral measurement can clearly reflect the increase in carrier recombination at the rear surface of the solar cell due to rear-side PID.

The indoor-testing schemes applicable to quality assurance or to R&D can also be transferred to a quick outdoor assessment. As the first outdoor LED solar simulators are now commercially available, similar measurement approaches can be implemented in a field inspection of PV modules, resulting in a more defined failure classification and in the ability to distinguish between rear-side PID and front-side PID (see Fig. 4).

Conclusions

With bifacial PERC, or PERC+, technologies, new degradation mechanisms related to high-voltage stress of the cell rear side can occur. There are two PID effects which can affect the rear side of a bifacial solar cell and reduce a PV module's power in a significant way. The first of these, polarization-type PID (PID-p), is reversible and can be suppressed by illuminating the solar cells; thus, the implications for field operation are less significant. The second, corrosive-type PID (PID-c), leads to permanent structural damage of the passivation layer of the solar cell; it is not reversible and also occurs under illumination. The new types of PID associated with PERC+ solar cells need to be tested using an adapted new test standard which includes the simultaneous application of illumination and high-voltage stress.

All three PID types – PID-s, PID-p and PID-c – result in a power loss of the cell. In order to distinguish between the various types, spectral measurements are necessary, which – in a simplified version – can even be performed using LED solar simulators. As PERC+ technology becomes more widespread, it is essential that new test schemes are established, i.e. high voltage combined with illumination, new test devices, and adapted characterization tools and procedures, in order to classify and quantify the PID effects.

References

[1] Mori, H. 1966, "Radiation energy transducing device", U.S. Patent 3.278.811.
[2] Dullweber, T. et al. 2016, "PERC+: industrial PERC solar cells with rear Al grid enabling bifaciality and reduced Al paste consumption", *Prog. Photovolt: Res. Appl.*, Vol. 24, No. 12, pp. 1487–1498.
[3] ITRPV 2019, "International technology roadmap for photovoltaic (ITRPV): Results 2018", 10th edn (Mar.) [https://itrpv.vdma.org/en/].
[4] Dullweber, T. et al. 2016, "Industrial silicon solar cells applying the passivated emitter and rear cell (PERC) concept – A review", *IEEE J. Photovolt.*, Vol. 6, No. 5, pp. 1366–1381.
[5] Osterwald, C. et al. 2003, "Electrochemical corrosion of SnO_2:F transparent conducting layers

in thin-film photovoltaic modules", *Sol. Energy Mater. Sol. Cells,* Vol. 79, No. 1, p. 21.

[6] Swanson, R. et al. 2005, "The surface polarization effect in high-efficiency silicon solar cells", *Tech. Digest 15th Int. PVSEC*, Shanghai, China.

[7] Hacke, P. et al. 2011, "Characterization of multicrystalline silicon modules with system bias voltage applied in damp heat", Report No. NREL/CP-5200-49344, National Renewable Energy Lab (NREL), Golden, Colorado, USA.

[8] Pingel, S. et al. 2010, "Potential induced degradation of solar cells and panels", *Proc. 35th IEEE PVSC*, Honolulu, Hawaii, USA.

[9] Berghold, J. et al. 2010, "Potential induced degradation of solar cells and panels", *Proc. 25th EU PVSEC*, Valencia, Spain, pp. 3753–3759.

[10] Naumann, V. et al. 2014, "Explanation of potential-induced degradation of the shunting type by Na decoration of stacking faults in Si solar cells", *Sol. Energy Mater. Sol. Cells,* Vol. 120, pp. 383–389.

[11] Freiberg Instruments, PIDcon testing tool [https://www.pidcon.com/en/pid-testgeaete.html].

[12] Pingel, S. et al. 2012, "Recovery methods for modules affected by potential induced degradation (PID)", *Proc. 27th EU PVSEC*, Frankfurt, Germany.

[13] Luo, W. et al. 2018, "Elucidating potential induced degradation in bifacial PERC silicon photovoltaic modules", *Prog. Photovolt: Res. Appl.,* Vol. 26, No. 10, pp. 859–867.

[14] Sporleder, K. et al. 2019, "Local corrosion of silicon as root cause for potential induced degradation at the rear side of bifacial PERC solar cells", *physica status solidi (RRL)*, Vol. 13, No. 9, 1900163.

[15] Carolus, J. et al. 2019, "Physics of potential-induced degradation in bifacial p-PERC solar cells", *Sol. Energy Mater. Sol. Cells,* Vol. 200, 109950.

[16] Sporleder, K. et al. 2019, "Root cause analysis on corrosive potential-induced degradation effects at the rear side of bifacial silicon PERC solar cells", *Sol. Energy Mater. Sol. Cells,* Vol. 201. 110062.

[17] Luo, W. et al. 2018, "Investigation of the impact of illumination on the polarization-type potential-induced degradation of crystalline silicon photovoltaic modules", *IEEE J. Photovolt.,* Vol. 8, No. 5, pp. 1168–1173.

[18] Sporleder, K. et al. 2019, "Potential-induced degradation of bifacial PERC solar cells under illumination", *IEEE J. Photovolt.,* Vol. 9, No. 6, pp. 1522–1525.

[19] Turek, M. et al. 2019, "Spectral characterization of solar cells and modules using LED-based solar simulators", *Sol. Energy Mater. Sol. Cells,* Vol. 194, pp. 142–147.

About the Authors

Kai Sporleder studied medical physics at Martin Luther University Halle-Wittenberg, Germany. In 2015 he joined Fraunhofer CSP, focusing on defect diagnostics and electrical characterization of silicon solar cells. Since 2017 he has been carrying out research work for his Ph.D. on potential-induced degradation at the rear side of bifacial solar cells.

Dr. Volker Naumann studied physics in Halle, Germany. He began working at Fraunhofer CSP in 2008, and has been involved in research on diagnostics and microstructure analysis since 2010. He received his Ph.D. in physics, with a thesis on PID root cause analyses, from Martin Luther University Halle-Wittenberg in 2014. He is currently a researcher in the Diagnostics and Metrology group at Fraunhofer CSP, where he leads the Surface and Layer Characterization team.

Dr. Stephan Großer studied physics and received his Ph.D. in the field of surface science from the Martin Luther University Halle-Wittenberg in 2008. He joined the Fraunhofer CSP in 2011, where he leads a team that focuses on microstructure characterization of materials and devices. His research interests lie, in particular, in the localization, target preparation and root cause analysis of defects and contaminations.

Dr. Marko Turek studied physics at Dresden University, and received his Ph.D. in the field of condensed matter theory from the University of Regensburg. At Fraunhofer CSP he leads the team involved in the electrical characterization of solar cells and modules. His research focuses on the loss analysis of solar cells, advanced characterization methods, and the development of new test methods and devices.

Dr. Christian Hagendorf is the head of the Diagnostics and Metrology research group at Fraunhofer CSP. He obtained his Ph.D. at Martin Luther University Halle-Wittenberg in the field of surface and interface analysis of semiconductor materials. Joining Fraunhofer CSP in 2007, he established a research group which focuses on defect diagnostics and metrology in crystalline and thin-film PV.

Enquiries

Kai Sporleder
Diagnostics and Metrology
Fraunhofer Center for Silicon Photovoltaics CSP
Otto-Eissfeldt-Strasse 12
06120 Halle, Germany

Tel: +49 345 5589-5070
Email: kai.sporleder@csp.fraunhofer.de