Light-induced degradation newly addressed – predicting long-term yield loss of high-performance PV modules

Module degradation | Light-induced degradation has long been recognised for its negative effects on the performance of crystalline silicon solar cells. Researchers from Fraunhofer CSP explain how with the advent of advanced materials and cell technologies such as PERC, new tests and standards are required to minimise the impact of the phenomenon on plant reliability

Light-induced degradation - a reoccurring issue

In addition to installation and maintenance costs, long-term energy yield is most important for the operation of PV power plants. The long-term yield is determined by both module efficiency and long-term performance. Thus, modules have to pass several standardised tests to fulfil well-defined reliability criteria. While standard tests are suited for the latest technology at their time, new technologies often require new tests for long-term reliability assurance.

Long-term power degradations, such as light-induced degradation (LID), are basic menaces for economic PV system operation. LID is an important degradation phenomenon effecting solar cell and module efficiency. It can cause an efficiency loss up to 15%rel under illumination in the first years of module operation. Manufacturers have achieved control over this defect in standard crystalline silicon solar cells with aluminium back surface field, keeping LID below 3%rel [1]. In general, the LID sensitivity of solar cells can be limited by using an adapted, optimised solar cell production process.

However, these cell processes respond sensitively to variations in the silicon material used for cell production (e.g. contaminations from crystallisation processes). Furthermore, the measures to prevent LID reduce the process parameter window leaving less room for other optimisations. LID also seems to be a serious issue for new high-performance solar cell technologies: lab tests and field data analysis have shown light-induced degradations of 3-5%rel for mono-crystalline passivated emitter and rear cell (PERC) solar cells and 7-15%rel for multi-crystalline PERC-cells [2]. The degradation rates depend strongly on environmental and operation conditions such as temperature or electrical operating point (MPP, VOC, ISC). In contrast to previously known types of LID, the degradation process in PERC cells may last much longer (over several years).

Hence, the growing market for latest technology modules, particularly PERC, demands a critical review of existing standard tests. Improved LID assessments for PV modules are required based on realistic, accurate and reliable accelerated life testing procedures.

Fraunhofer Center of Silicon Photovoltaics CSP supports the industry by applied research in this field. It provides research services from testing and quantifying the LID sensitivity of cells and modules, over root cause analysis, to optimisation of the passivation process for LID mitigation.

LID occurs for all cell technologies

The phenomenon of of solar cell degradation caused by illumination has been under investigation for more than 40 years [3]. Different chemical processes reducing the solar cell efficiency are known. Often, they are induced by a shift in the Fermi level due to an increase in excess carrier concentration. As the increase in excess carrier concentration is related to the incident irradiation, this process is quite generally termed light-induced degradation (LID). However, the same effect occurs by inducing a current to an unilluminated solar cell which as well causes an increase in excess carrier concentration.

Well known LID mechanisms are the activation of boron-oxygen complexes

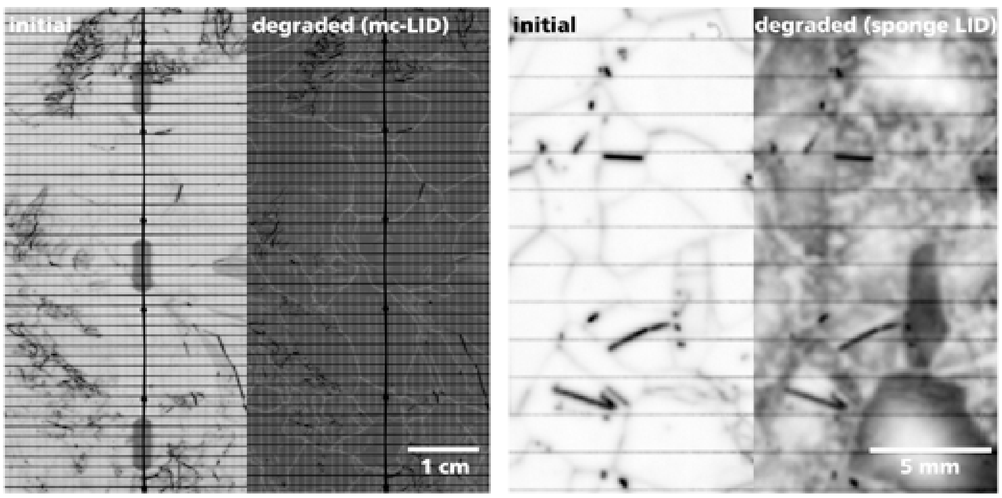

Figure 1. Light beam-induced current mappings of a mc-LID sensitive PERC solar cell before and after degradation (left) and of a sponge-LID sensitive solar cell (right). The different lateral appearance allows the determination of degradation type. The cells were processed in an intentionally modified cell process leading to high LID sensitivity

(BO-LID) and the dissociation of iron-boron (FeB-LID) pairs [4, 5]. However, also other metal contaminations as chromium and copper cause LID [6, 7]. Recently, two new LID defect types were detected: sponge LID on "high performance multi" (HPM) and mc-LID (also termed "LeTID") on multi-crystalline PERC [8, 9]. A distinction of these different LID mechanisms is possible by the degradation rates, the subsequent regeneration process, the material impurities of the wafer material and the lateral appearance (example shown in Figure 1).

Boron–oxygen complex activation (B–O LID)

Light-induced degradation has first been reported on monocrystalline boron-doped Cz silicon solar cells, which suffer up to 10%rel in efficiency under operation. At elevated temperature regeneration occurs subsequent to the degradation [10], increasing the cell efficiency again until the initial efficiency is partly or entirely regained. The defect mechanism as well as the kinetic behaviour has been under investigation for several decades now. However, still the scientific discussion is ongoing. Currently, there are several explanations for this LID effect. The main and most prominent explanation is a formation of so called B-O complexes under light or carrier injection [7]. This B-O degradation is also the most prominent LID and often meant by the general term 'LID'. Depending on the material and the operating location during field operation the degradation may take months until saturation.

Iron–boron pair dissociation (FeB LID)

The defect formation of FeB-LID is well understood. In the dark, positively charged iron atoms link to the negatively charged boron atoms due to Coulomb interaction. These complexes have shallow energy levels and do not reduce the cell efficiency. The shift in the Fermi level under illumination causes the neutralisation of the iron ions, which consequently separate from the boron atoms. Interstitial iron causes a much higher charge carrier recombination under solar cell working conditions [5]. Thus, the dissociation of iron-boron pairs causes a severe efficiency loss in iron-contaminated cells within the first minutes of illumination.

mc-LID or LeTID

mc-LID was first noticed on p-type mc-Si PERC solar cells leading to an efficiency loss of up to 15%rel. Standard Al-BSF and mono-Si PERC cells are less affected. In contrast to other LID mechanisms, it occurs at elevated temperatures above 50°C only. Therefore, Hanwha Q CELLS suggested the name light-and-elevated-temperature-induced degradation (LeTID) [2]. mc-LID differs from the above discussed mechanisms by occurring on much longer time scales as it takes days in the lab and years during operation. Subsequent to the degradation, regeneration sets in. However, during field operation the regeneration will not start in the 20-year warranty period. It is believed that a metallic impurity causes the degradation. However, the root cause of degradation is still under investigation. Recently, a high Cu concentration was detected with element analysis at mc-LID sensitive mc-PERC cells, indicating that Cu plays a role in mc-LID [11].

Sponge LID

Sponge LID is a fairly new degradation mechanism with the root cause still being a topic of research. It can occur on HPM-Si material. This new wafer type with small grains but only few dislocations leads to an efficiency gain of about 2.5%rel. Sponge LID can over-compensate this gain and saturates within a day in the lab, inducing an efficiency loss of up to 10%rel [8]. Under outdoor conditions the degradation takes a few weeks.

Effect of LID in the field under operation

For conventional Al-BSF modules, light-induced degradation typically occurs within the first year in the field with a power reduction in a range from 0.5% to 3%. With respect to module warranty, module manufacturers often simply subtract the anticipated power loss from the initial power measurement and label it accordingly. Nevertheless, for PERC modules much higher losses of between 7%rel and 15%rel were reported [2]. There are also PERC modules showing very low LID losses (1%rel) by modification of the wafer growing recipe and the solar cell production as LID strongly depends on the material and solar cell manufacturing process parameters.

Typically, not all cells within a module are affected equally (see Figure 2). However, one can show by electric simulations that even few degraded cells can decrease the performance of the PV module considerably (see Figure 3). This is based on the fact that the current in a cell string is limited by the current flow through the degraded cells. Thus the module current and therefore the module power (at MPP condition) are significantly affected even if only few cells in a module are degraded. Based on field data, it has been found that these power losses can be directly translated into yield losses if the appropriate temperature and illumination conditions are taken into account.

LID testing

Testing and standards on module level

Light-induced degradation affects the efficiency of PV modules during their complete lifetime. Therefore, quantifying LID is an important task for yield

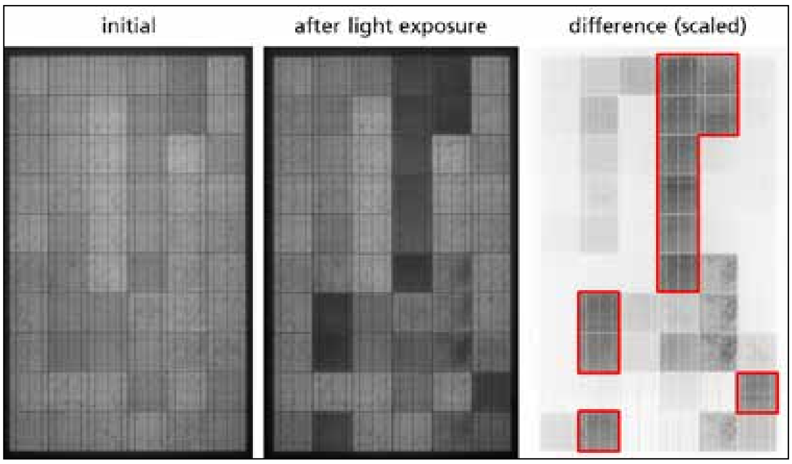

Figure 2. Electroluminescence images of a module before light soaking (left), after 20 hours of illumination with AM1.5 (middle) and the difference between the two – scaled and inverted (right)

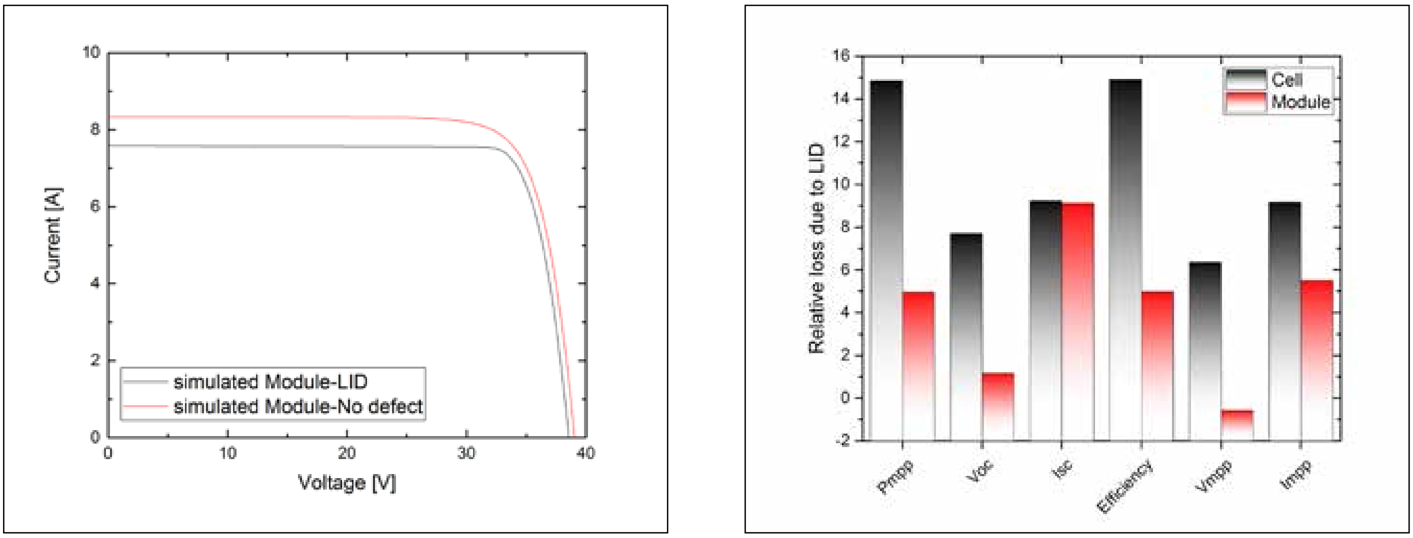

Figure 3. Electric simulations of module parameter losses when 12 cells in a 60-cell standard module show significant LID. Left: IV-curves of a module before and after LID. Right: Relative changes in electrical characteristics of cell and module after light induced degradation

simulations and cost-effectiveness of PV systems. The LID stabilisation test is used for two purposes: first for initial stabilisation in order to check the manufacturing label values by flash testing; and second for assessment of LID after final stabilisation. According to norm (IEC 61215-2:2016) final stabilisation is not required for crystalline PV modules anymore. This made sense for standard crystalline BSF modules since the LID effect was considerably small and occurred during the first hours of operation. However, this is not always the case for specific LID types in PERC technology modules with their particular degradation kinetics. Therefore, Fraunhofer CSP highly recommends the application of final stabilisation tests in LID testing of modules.

The LID stabilisation test consists of a sequence of light exposure intervals of equivalent irradiance dose (>5kWh/m^2). During light exposure the module performs at its maximum power point (MPP) and is kept at constant temperature (50±10)°C. After each interval the module is flashed. If the difference in module power of the last three flashes is smaller than a threshold value defined by the norm the stabilisation is regarded to be finished and the accumulated total irradiance dose required is determined. If not, the procedure is repeated and the next light exposure interval is applied. If the performance loss succeeds 5% after stabilisation the module failed the standard test. However, already a degradation of 5% would have a drastic impact on the levelised cost of energy (LCOE). Thus checking for LID before the investment is even useful when installing certified modules.

Requirements of testing PERC technology modules

There are two problems arising when the degradation rates are small. At standardised conditions (50°C, MPP) it could take up to 1,500 hours (two months) until maximum degradation is reached [2]. This is much more time- and material-consuming (e.g. lamps) than for standard back contact cells with test durations of about 60 hours and makes this test hardly affordable. Since the degradation is slow, it may happen that within the last three intervals of light exposure the difference in power is small enough such that "stabilisation" is detected while in fact it is not reached yet. This way, the measured power loss is underestimated.

Fraunhofer CSP therefore suggests LID indoor testing at elevated temperature (80°C) and under open circuit voltage (VOC). Both effects accelerate the degradation and compensate the effects mentioned above. However, a quantitative correlation with outdoor performance based on acceleration factors and temperature dependence is the subject of ongoing research.

Outdoor LID tests can be performed in a similar way. The irradiance is measured by a reference cell mounted next to the module. The module performs at its maximum power and only irradiance levels above 500W/m^2 are considered for calculating the total irradiance dose required for stabilisation according to norm. Again, open circuit conditions and a thermal isolation of the modules for achieving higher module temperatures can accelerate the degradation significantly. Accordingly, for reproducible and comparable outdoor LID evaluation the definition of standardised test conditions is mandatory.

Fraunhofer CSP is working on these R&D issues beyond standard norm testing within various projects. In particular, various light-soaking chambers as well as a module-level LED sun simulator are used to expose PV modules to various light wavelength, temperature and operation conditions. The LID behaviour of PV modules is characterised through I-V measurements and also through quantum efficiency measurements at module level.

Degradation tests during operation

Testing the long-term reliability of PV installations is not only a task for R&D departments. Also plant owners can evaluate the reliability of their modules during operation. Knowledge of current problems and possibilities for rectification are important for risk mitigation as well as increased yield and production feedback. Thus, low-cost and precise module-level monitoring is needed, for early detection of LID and other performance-reducing issues during operation of a plant.

For these investigations the voltage is usually measured at inverter or string level in a PV system. Yet, voltage measurements from a string during

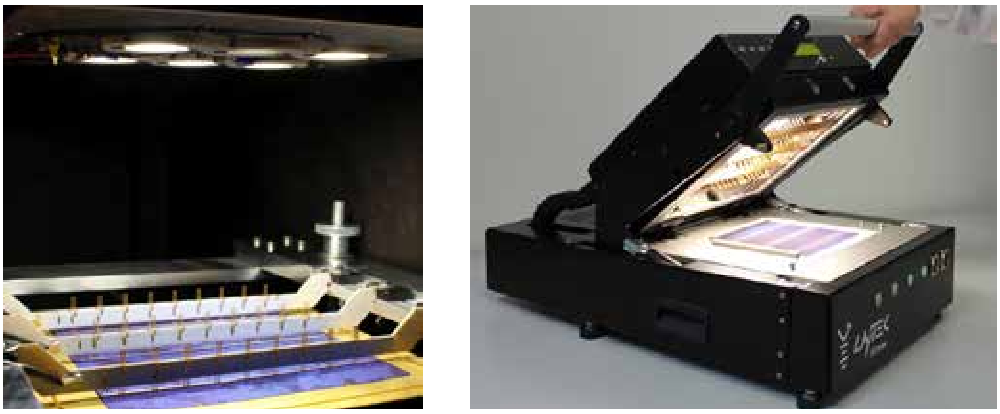

Figure 4. Left: LED-based test set-up at Fraunhofer CSP. Right: Commercially available LIDScope by LayTec AG

operation can be precise, but they are insufficient to detect and evaluate losses that occur on single modules. String voltage is the average of all voltages of strings which are connected to the same MPP tracker. An average voltage value gives no insight into the location and nature of a problem. An alternative for a more detailed evaluation is the SunSniffer technology.

The SunSniffer technology has been in field use for seven years. Its core is a sensor in each junction box and it is seamlessly integrated into PV systems, with data transmitted via powerline communication, thus no additional cables are required. It measures temperature and voltage in each module with ±1% accuracy. In combination with the power measurement data of the strings and the data of irradiation sensors, these data are analysed by an artificial intelligence algorithm. As result, the deviations are recognised and specific patterns can be detected and assigned to certain types of errors [12]. Measurements are made in intervals down to 30 seconds. However, these intervals are non-static, as the system calculates and determines the concrete interval necessary.

LID is detected by its specific voltage and temperature pattern and is automatically recognised. Still more investigation is needed to ensure detection at its earliest appearance. To further improve automated detection, the complex LID pattern needs to be scrutinised more deeply. Permanent module-precise measurements and their analysis enable continuous refinement of these filters and further comprehension of this phenomenon. For scientific reasons, it would be beneficial to have all modules with PERC cells being measured on a constant basis in order to better understand and maybe even find indications to solve LID. Plant owners would benefit equally.

Degradation tests on cell level

LID tests can already be performed at an early stage of production by investigating the solar cells. This is important for accelerated solar cell developments and quality control during module production. At Fraunhofer CSP, LID test set-ups are developed allowing quantitative and user-friendly LID reliability tests (see Figure 4). These set-ups are suitable for accelerated LID testing as well as simulating field conditions. Two set-ups have been developed based on (1) advanced LED techniques and (2) electrical carrier injection. Both carrier injection by light or by electrical currents lead to the same effect. Using advanced LED techniques, IEC standard module test conditions can be applied to solar cells, mini-modules, or individual components. The second set-up is optimised towards a robust LID test for mass-production circumstances. Electrical carrier injection offers a reliable, robust and controllable degradation procedure that is easily operable and independent from environmental influences. The system is commercially available from Laytec AG, the LIDScope (Figure 4, right).

Mitigation strategies

There are several strategies to mitigate LID: (i) selecting proper wafer material; (ii) optimising solar cell and module production; and (iii) introducing a production step to avoid LID.

Selecting proper wafer material

Most LID defects can be traced back to the wafer material [7]. Hence, a proper choice of wafers can minimise light-induced degradation. For example, to mitigate B–O-related degradation it’s important to choose wafers with reduced boron and/or oxygen concentrations. Degradation effects in multi-crystalline silicon solar cells (FeB-LID or mc-LID) can be reduced using wafer material with fewer metal contaminations.

Optimising solar cell and module production

Adaption of the solar cell process can lead to a reduction of various LID types [13]. For example, optimisation of firing conditions reduces the extent of degradation on mc-Si PERC cells. Subsequent

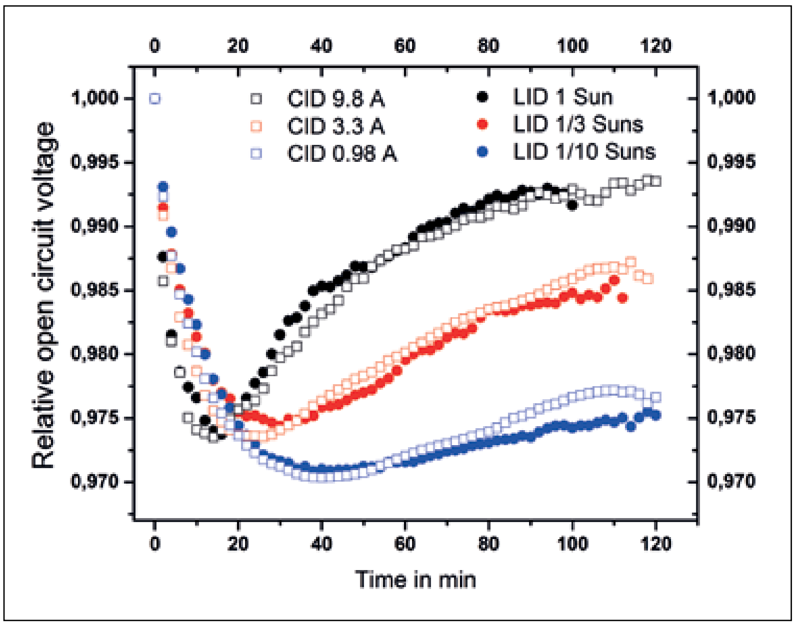

Figure 5. Comparison of LID and CID for different intensities at 140°C on boron-doped Cz silicon solar cells showing B-O LID [16]

treatments can also be carried out, such as illuminated annealing or a second firing step. However, these approaches are lavish and have several disadvantages i.e. no complete avoidance or avoidance to an unknown extent and negative influences on the solar cell efficiency and other parameters.

Introducing a production step to avoid LID

A promising technique is so-called regeneration, which is a subsequent process step within the solar cell production that passivates the LID defects [14, 15]. Typical degradation-regeneration curves are shown in Figure 5. The passivated defects are stable under field conditions. Generally, light and elevated temperature is used to perform regeneration. Several furnace manufacturers, such as centrotherm photovoltaics AG and Despatch Industries, have introduced solutions to the problem. These regeneration processes have the disadvantage that an individual cell treatment and an in-situ process control are not possible. Fraunhofer CSP has investigated an alternative method with more process flexibility. This process is based on an electrical current-induced regeneration for industrial application [16]. The regeneration process can be carried out using forward biasing and increased temperature (Figure 5). The key is a correct control of both temperature and carrier injection. This process is assumed to be more flexible, controllable, scalable and cost efficient than current methods.

Summary

LID is a critical topic for plant owners, since it can permanently reduce the efficiency of modules by up to 15%rel. Particularly high-performance solar cells are affected, as unresolved LID types have been detected on new material and cell processes. However, this degradation effect can be reduced or even avoided by optimising the cell process or passivating the LID defects. To achieve that Fraunhofer CSP is working on root cause analysis of new LID phenomena and on optimisation of passivation methods. However, LID tests throughout the value chain, as well as dedicated LID test standards in module quality control, are advisable to guarantee long-term reliability of photovoltaic installations. ■

Authors

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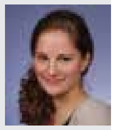

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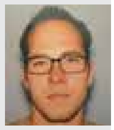

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