Towards a test standard of light and elevated temperature-induced degradation

Module degradation | Understanding of LeTID remains incomplete, although its effects on PV power plant performance are recognised as being potentially significant. Tabea Luka, Friederike Kersten, Matthias Pander, Max Koentopp, Marko Turek, Werner Bergholz and Thomas Pernau of the LeTID Norm consortium outline progress towards developing a standardised test for the defect, a key step in minimising its impact

In a PVEL survey of 2018, light-induced degradation (LID, LeTID) was identified as the defect that causes the greatest concern among investors implying severe financial risks [1]. One reason is that the defect is still relatively new and not entirely understood due to its complexity. To reduce these risks, the LeTID Norm consortium is working on a standard to test the LeTID sensitivity. To this end, the consortium brings together the experience of research cell manufacturers, research institutes, test facilities and PV power plant operators. Thus, the proposed test standard is based on a better understanding of the defect that is causing LeTID combined with practical applicability of the test procedure.

Light-induced degradation – the current scientific knowledge

The phenomenon of illumination leading to a loss of solar cell efficiency has been under investigation for more than 40 years. Several mechanisms causing such a degradation have been studied, including the activation of boron-oxygen-defects (BO), the dissociation of iron-boron-pairs (FeB), the degradation due to copper (Cu-LID), sponge-LID, and light and elevated temperature-induced degradation (LeTID). It is well known that all these defects are activated by charge carrier injection i.e. by illumination or current injection equivalently [2]. While most of these mechanisms are activated within minutes (FeB) or days (BO, Cu-LID and sponge-LID) during operation, it takes years until the LeTID degradation reaches its maximum [3]. Due to the significantly different timescales it is relevant to determine LeTID apart from the other LID mechanisms to estimate the overall losses during operation. A separation of LeTID is feasible as this degradation can only be observed above 50-60°C implying testing times of the order of weeks. Quite generally, the kinetics strongly accelerate with increasing temperature [2]. However, high temperatures over 75°C reduce the degradation extent, since the regeneration which occurs subsequently to the degradation is even more accelerated (see Figure 1). At a relatively low temperature of 25°C, a degraded cell exhibits a recovery of the degraded cell parameters under illumination. This recovery differentiates from the regeneration observed at elevated temperature, as it results in an instable state, which degrades again at an elevated temperature treatment [4].

Investigations have also shown that the cell process strongly affects the degradation. The higher the temperature of the firing process step (the last high temperature step in cell manufacturing), the stronger the degradation [5]. Slower cooling rates after reaching the peak temperature during firing step can reduce LeTID [6]. Furthermore, pre-annealing before the firing step or post-annealing after the firing step can reduce LeTID [7]. It was also shown that thinner wafers [8] and gettering steps for metallic impurities reduce LeTID [9]. During the last years, several publications showed that a high hydrogen content introduced into the silicon from the silicon nitride passivation layer of a PERC cell leads to faster and stronger LeTID [10,11].

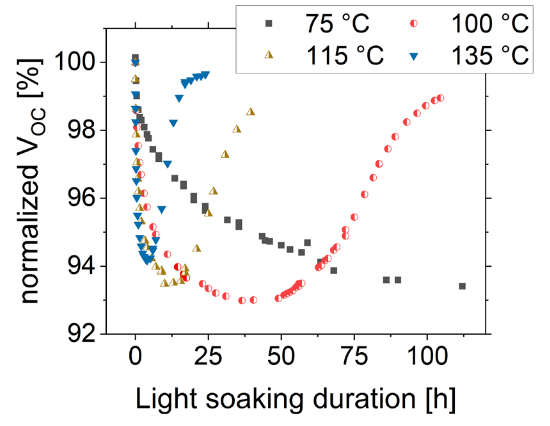

Figure 1. Typical LeTID degradation and regeneration behavior of the normalised open circuit voltage (V_{oc}) of solar cells during illumination equivalent to one sun at 75°C, 100°C, 115°C and 135°C

At the moment, there is no common model for the cause and description of LeTID. Due to the strong influence of hydrogen on LeTID the UNSW has presented a "three-bucket/four-state model", which assumes that hydrogen is the only LeTID causal agent [12]. Schmidt et al. assume that 3d transition metal impurities are the main causal agent. In this model, the assumed state after firing is that the interstitial metal impurities are paired with hydrogen atoms and are assumed as recombination inactive [13].

Within the LeTID Norm project a model has been developed assuming that 3d transition metal impurities dissolving from metal-silicon-precipitates paired with hydrogen cause the degradation (see Figure 2). In this model, the well-known property of Co, Ni and Cu to form metastable platelet precipitates even after the fastest cooling to room temperature is used [14]. Since Co, Ni and Cu are common common impurities in PV wafers and

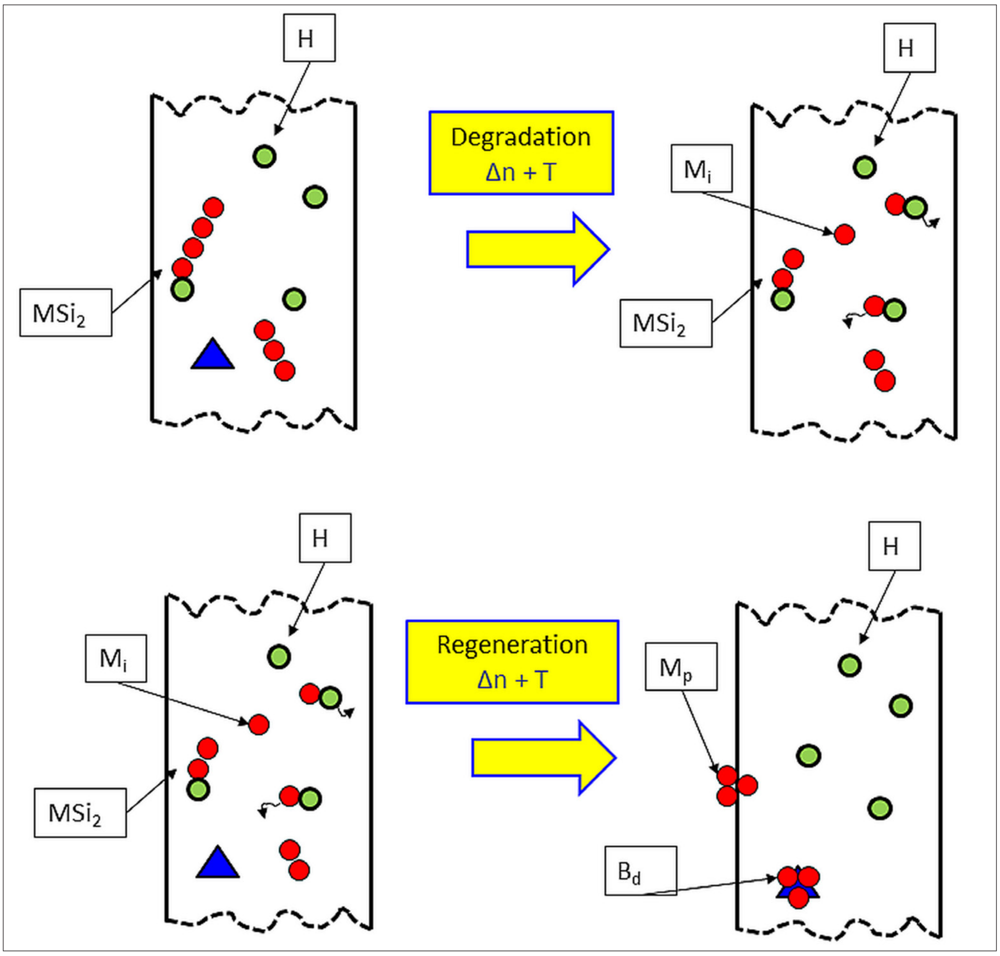

Figure 2. Schematic representation of the LeTID model suggested by the LeTID Norm consortium

cells, in typical concentrations up to or more than 10^{13} cm^{-3}, the presence of such platelets of the type MSi$_2$ is certain. The dissolution of the precipitates at LeTID conditions and the diffusion of the now dissolved metal impurities (recombination active!) to the sinks (recombination inactive!) is used to explain the observed degradation and later recovery of the lifetime and therefore the cell parameters, as depicted in Figure 2.

Test procedures and test setups

As LeTID is still not fully understood and thus cannot be ruled out entirely, quantifying LeTID is an important task to assure at most minor losses due to LeTID and thus reduce the risk of investors. Furthermore, from a process development point of view, it is essential to separate LeTID from other known degradation types such as iron related FeB-LID or oxygen related BO-LID. The dissociation of FeB pairs happens under carrier injection and at temperatures which is used for LeTID stress, therefore before measurement of the IV-characteristics at room temperature, storage of the devices in the dark long enough for the FeB pairing to be completed is needed to avoid the impact of this additional degradation mechanism. As for the BO-complexes, a suitable pre-conditioning is needed to clearly separate LeTID from BO-LID.

Testing throughout the value chain

LeTID-related reliability tests are relevant throughout the entire value chain. Performing the tests early in the production process allows a timely detection of the LeTID sensitivity and thus reduces financial losses for manufacturers. However, according to the current state of research, the earliest tests are reasonable on solar cells, since the solar cell process significantly influences the LeTID sensitivity. Additionally, stability tests on the finished modules should be carried out to guarantee the long-term stability of the final products, which is decisive for the customer satisfaction. Plant owners are strongly advised to demand detailed information on the LeTID stability before investing in PERC solar modules with mono- or bifacial design. Furthermore, they should keep track of their plant's performance, to observe reliability issues early on.

To generate comparable results throughout the value chain and among different test facilities, it is mandatory to use comparable treatment conditions. However, currently used test conditions differ significantly regarding the treatment conditions, i.e. temperature and injection level, and also the treatment time.

Cell producers' view

Solar cell producers started to become aware about LID in 2014. At this time, no dedicated test equipment was available, and first tests were done on existing, modified *IV*-test equipment. The temperature and injection contribution to the test was unclear. In the meantime, the testing methods and equipment have been optimised to use much better temperature and injection control.

centrotherm approached solar cell producers about light-induced degradation conditions in 2014. At that time, the test was intended to be a LID test to detect BO related defects. The light intensity for this purpose was considered to be sufficient if performed at 0.05-0.1 suns (where 1 sun is equivalent to 1,000W m^{2} illumination with AM1.5 spectrum) at <40°C and for 24-48 hours while the cell is in open circuit condition, i.e. no load attached. Higher intensity and higher temperature were already identified to be able to drive a regeneration effect related to BO-LID [15].

As a first response about degradation parameters in use, only about 15% of the producers confirmed to perform tests. These tests were at 0.5-1 suns and at V$_{oc}$ condition, cell temperature 60-100°C and 60-120 hours duration. This strong BO-LID test was accepted as an additional test by those cell makers taking care about light-induced degradation. The effort for a long test (60-100 hours) and powerful testing equipment (1 sun, >50°C) was accepted because module manufacturers requested tested cells or offered a higher price for guaranteed stable cells.

In 2017, LID came into focus also by Chinese cell manufacturers. They soon realised that the strong BO-LID testing can be compressed to 2.5-5 hours without too much loss in information. The shortened test was considered good enough. By the end of 2019, 62.5% of LID testers used a short test <6 hours. All devices in use did not control the cell temperature exactly. The cell temperature was a result of 1 sun light intensity and fan-cooled glow discharge lamps. The typical cell temperature in non-temperature-controlled testers was around 60°C.

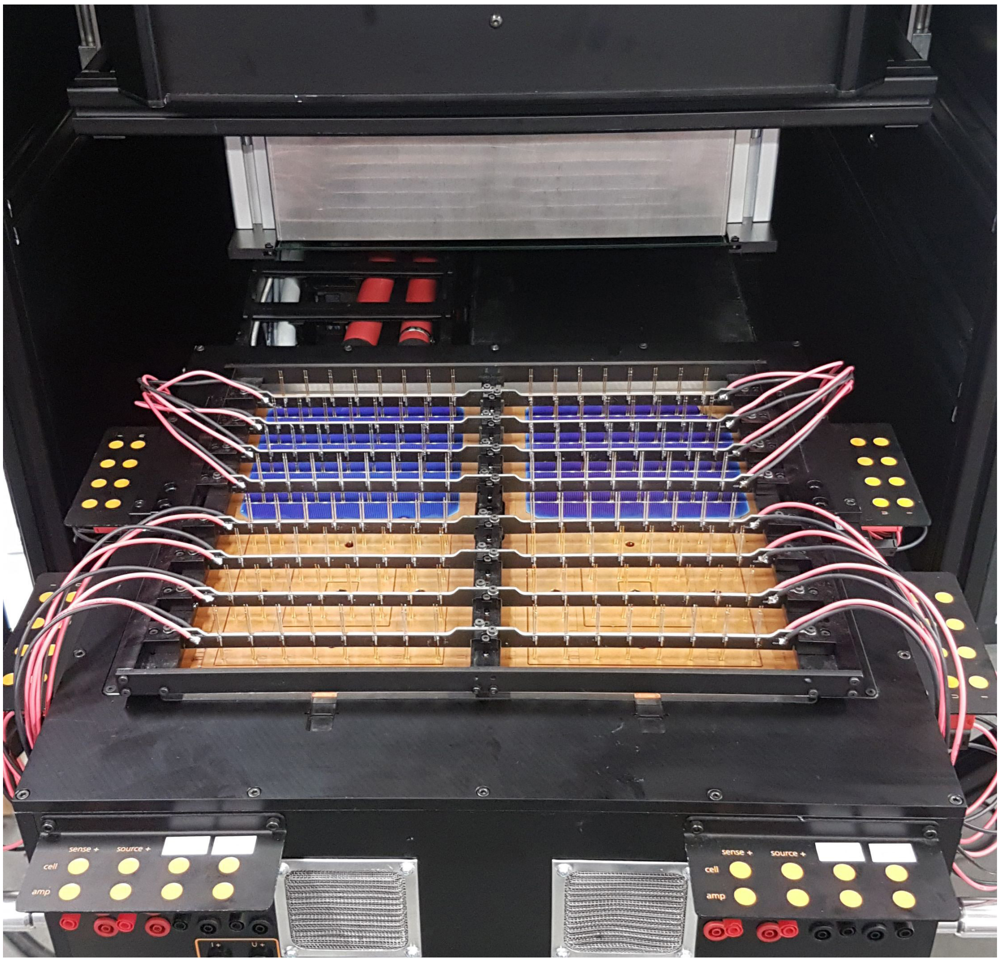

Figure 3. LeTID test set-up designed by WAVELABS in cooperation with Fraunhofer CSP allowing quantitative LID reliability tests

In our continued survey, intentionally temperature-controlled degradation conditions showed up in early 2019, at the same time the additional light-induced degradation measurement was clearly named "LeTID" [2]. The first reporting user introduced a quick test with 4 hours' exposure and a long-term test with 200 hours at the same time. The degradation was driven by current at roughly 33% of the I_{SC}. The temperature was intentionally raised to 105°C to speed up the test. The quick test was found to be usable for selected material that already passed the long-term test. The reported LeTID tests that followed were done at I_{SC}-I_{MPP}, 75-110°C and 60% of the test procedures were intended as a quick test within 8 hours. From these surveys and from basic productivity and cost considerations, it is clear that many solar cell producers would prefer a short LID or LeTID test procedure, since the expectation to have a short test grew bigger.

Individual accelerated testing

For solar cell producers, it might be favourable to shorten the test duration to be able to regularly test a fraction of the produced cells and thus to ensure that the cell process is stable regarding LeTID sensitivity. There are different approaches to accomplish an accelerated LeTID test. A forecast of the total degradation extent based on the losses at the beginning of the degradation might be possible. Also increasing the treatment temperature and the charge carrier injection accelerates the degradation. However, a temperature increase (above 75°C) reduces the total degradation extent and the LeTID kinetics differs significantly depending on the material and the cell process [16]. Thus, for such strongly accelerated testing to be reliable, a good understanding of the solar cells is indispensable. Furthermore, the correlation of the accelerated test results to the treatment conditions, that are implemented in a LeTID standard, should be known. Thus, an in-house quick-test for well specified cells (material and process) where the correlation to the standard LeTID test is well understood could be individually developed. However, a long-term test with a wide range of applicability

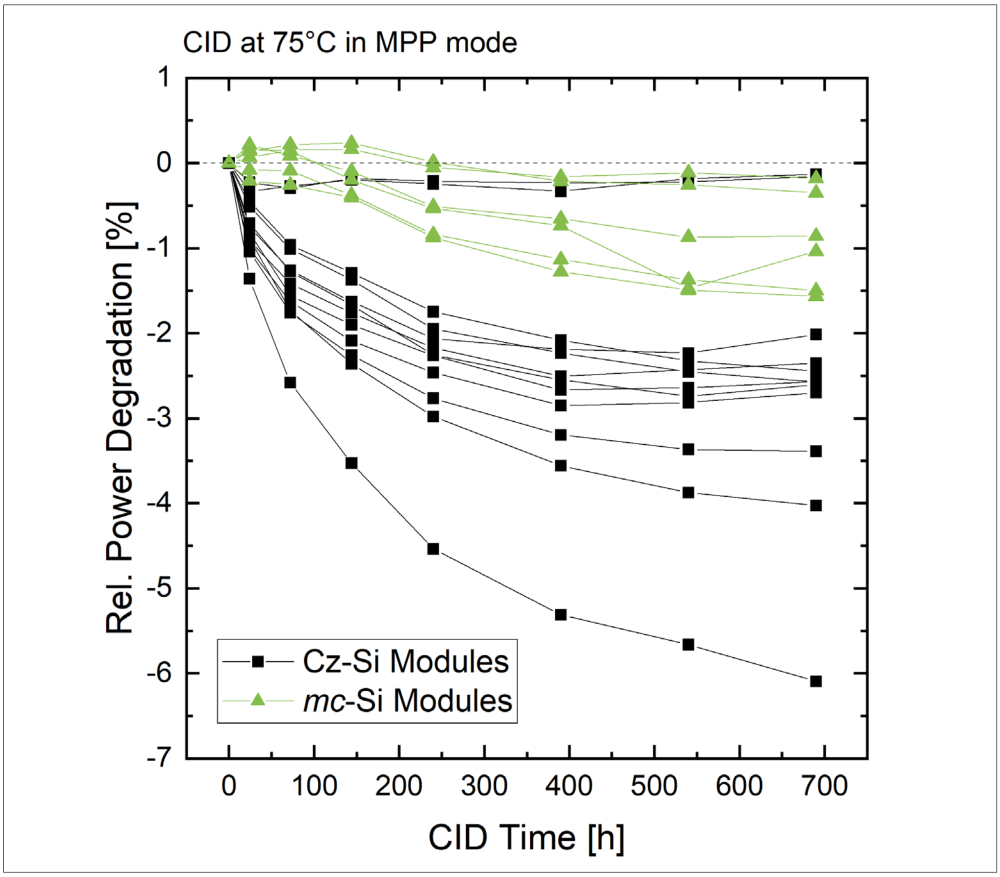

Figure 4. Results of LeTID benchmark showing the power degradation of commercial modules during LeTID test at 75°C and I_{CID} = 1.0A. Figure adapted from [17]

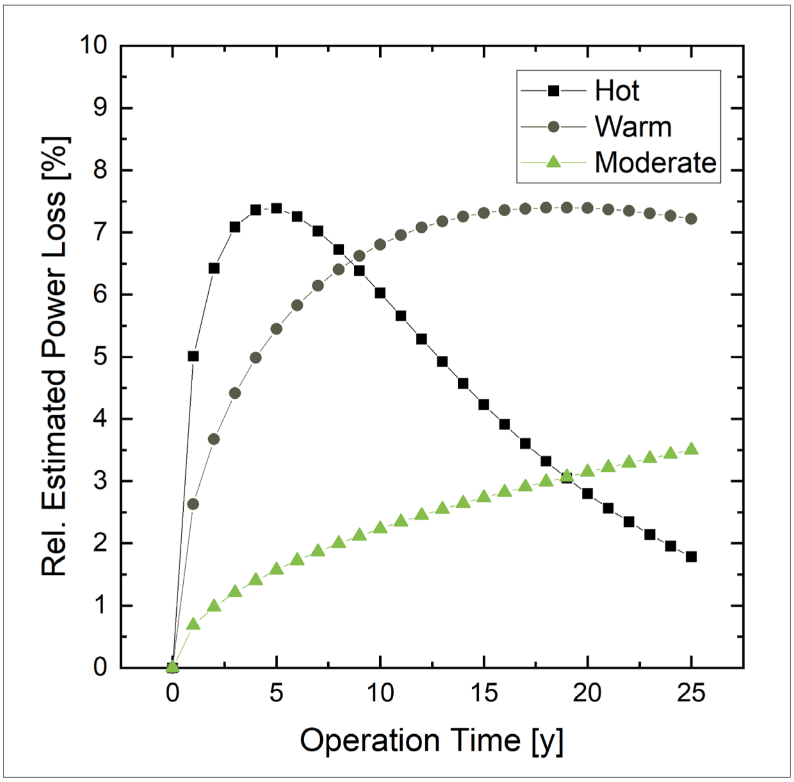

Figure 5. Estimated power loss due to LeTID for different climates for the module with highest LeTID susceptibility in benchmark test. Figure adapted from [20]

is necessary for proper standardisation and comparability of products.

Degradation setups

First test set-ups are commercially available which can be used for standardised testing as well as accelerated testing. WAVELABS in cooperation with Fraunhofer CSP has designed a LeTID test set-up allowing quantitative and user-friendly LID reliability tests (see Figure 3). The set-up allows advanced illumination techniques as well as electrical carrier injection. Both, carrier injection by light or by electrical current lead to the same LeTID effect. The LeTID behaviour of solar cells or PV mini-modules is characterised through *IV*-measurements and also through quantum efficiency measurements, that are extremely sensitive regarding losses due to LeTID.

LeTID on module level

At the EU-PVSEC 2018, the Fraunhofer CSP presented the result of a LeTID-specific benchmark test of commercially available PERC modules (see Figure 4) [17]. To separate the losses due to LeTID from other known LID effects (i.e. BO-LID and FeB-LID), a pretreatment was carried out at 25°C injecting a current of I_{CID} = 9A for one week. Additionally, before each measurement of the cell parameters the modules were stored in the dark at room temperature for at least 12 hours to avoid the effect of FeB. The LeTID test was performed at 75°C inducing the current $I_{CID} = I_{SC} - I_{MPP}$. A high degradation of >6% was found for some of the monocrystalline Si-PERC modules. Additionally, a large variation in power loss of LeTID affected modules of the same type is observed, due to different quantities of strongly affected cells inside the modules. This is a challenge for quality control and shows that at least two modules of each type should be investigated during a standardised test. Similar results were found in other investigations [18, 19]. These results clearly show that not all manufacturers are capable of reducing the degradation permanently to a minimum. If the production processes are not sufficiently under control with respect to the LeTID susceptibility, several cells in a given module can be LeTID sensitive.

LeTID field progression depending on different climate conditions

The benchmark in Figure 4 shows that there is a potential problem for system planners that can affect energy yield calculations and risk assessment. As a consequence of the potentially high power losses, the question arises how high the potential yield losses of PERC modules with LeTID-sensitive cells are in operation.

Based on the experimentally determined degradation values, an estimation was made for different locations. Three sites were selected for this yield loss assessment. The classification was based on the time in which module temperatures above 50°C occur. In a moderate climate only ~1% of the time of the year the module operates above 50°C, in the warm climate it is ~5% and ~15% in the hot climate. The temporary recovery, which is observed at lower temperature [4] and during a cold winter [3], is not considered in this estimation, due to the scarce available data on this topic. Thus, the power loss in moderate climate might be slightly lower than here estimated.

An Arrhenius behaviour was assumed to calculate a time equivalent to the field conditions in the laboratory test. The activation energy was chosen based on cell test data [9]. For each year of operation, the additional average power loss due to LeTID was then estimated (see Figure 5).

As a temperature-activated degradation, LeTID develops faster in hot climates due to increased operating temperatures. Specifically, for the highly LeTID susceptible module with over 6% relative power loss in the LeTID benchmark test, it is estimated that the maximum degradation will be reached in the first five years of operation. It is then likely that the reduction in output can regenerate over the years of planned system operation and thus the average loss in output power is reduced again.

> "As LeTID can have a significant impact on the energy yield and thus the revenue of a PV system, customers as well as manufacturers urgently need a test standard in order to quantify the impact of LeTID and to qualify products"

The effect is even more relevant in warm climate zones, as the reduction in performance develops more slowly and over a longer time period. A long period of 5% and more power losses occur after five years in operations. In moderate climates the power losses increase slowly over the years and are thus difficult to separate

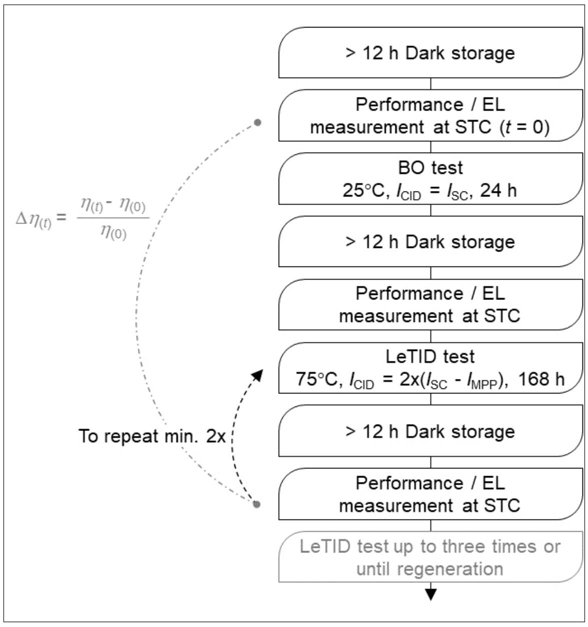

Figure 6. Test sequence of BO and LeTID test

from other reductions in performance.

These calculations show that the operating conditions and thus the LeTID kinetics differ strongly at various locations (i.e. moderate climate, or tropical climate). Furthermore, the module temperature strongly depends on the installation type (i.e. a solar park or roof-integrated photovoltaic system). Thus, testing at actual outdoor conditions is extremely time-consuming and inconvertible to appropriate test conditions. Therefore, currently the suggested LeTID tests are aligned to extreme outdoor conditions to accelerate the degradation and determine the most serious efficiency loss that is to be expected during operation.

Latest standardisation activities and our recommendation on how to test LeTID

As LeTID can have a significant impact on the energy yield and thus the revenue of a PV system, customers as well as manufacturers urgently need a test standard in order to quantify the impact of LeTID and to qualify products. Several standardisation activities are currently ongoing which all more or less employ the same or similar test conditions. IEC (International Electrotechnical Commission) as the most important standardisation body for solar industry is currently working on a LeTID test standard in its working group 2 (modules). A formal draft is expected to be circulated this spring. SEMI has already published a standard for LeTID, which is focused mainly on cells and mini modules [21]. Also, TÜV Rheinland has published an internal standard (2PfG2689/04.19) with similar conditions [22].

The test procedure recommended by the LeTID Norm project consortium as well as the conditions by TÜV Rheinland or IEC assesses LeTID on a module level by application of an electrical current at elevated temperatures rather than by illumination for reasons of practicality and cost. On cell level, illumination and electrical current can equally be used. The proposed test procedure aims at separating LeTID from BO-LID as well as FeB-related degradation phenomena which already occur at room temperature under the presence of light and on much faster time scales.

At least 15 solar cells or two modules (test specimens) are recommended for the proposed test sequence. In addition, five cells or one module from the same batch is used for reference to guard against deviations in STC measurements.

For the module test it is recommended to use a climate chamber with automatic temperature control with means for circulating the air inside and capable of subjecting one or more modules to temperatures from 25°C up to 75°C. During degradation a constant carrier injection is applied. It is recommended to log in situ the voltage of each test cell or test module, taking into account the correction for temperature fluctuations using the temperature coefficient of the sample and the measured treatment temperature. First, the samples are subjected to a BO test at 25°C for 24 h. Thereby the injected current is equal to initially measured I_{SC} (alternatively an equivalent illumination of one sun can be used on cell level). Subsequently, the LeTID test is carried out at 75°C by injecting a current I_{CID} that correlates to the excess carrier density present during field operation at maximum power point conditions (MPP) (on cell level an equivalent illumination can be used alternatively). This current can be calculated from the short circuit current (I_{SC}) and current at MPP (I_{MPP}) by using equation 1:

$$I_{CID} = 2 \times (I_{SC} - I_{MPP}) \qquad (1)$$

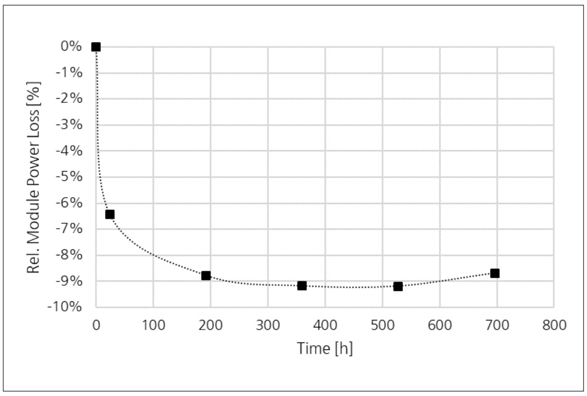

Figure 7. Module power loss due to BO and LeTID

The samples are subjected to one week (t_{CID} = 168 h) of stress at 75°C. During the treatment of the samples, the references are stored in the dark to avoid any degradation. After the treatment the samples are also stored in the dark for >12h in order to associate FeB. The whole test sequence is shown in Figure 6.

As shown in Figure 6 the LeTID sequence is repeated at least three times or until regeneration in terms of a performance increase begins, verified by detecting the minimum while tracking the dark voltage. In Figure 7 the test results of a BO and LeTID-susceptible module during the proposed test procedure are exemplarily shown. During CID in climate chamber the dark voltage of the module is measured. The obtained data are corrected by chamber temperature and averaged in a way that allows reproducible and accurate detection of the power degradation. When the hourly average of temperature-corrected measured voltage exceeds the sum of minimum dark voltage, then the module has entered the regeneration phase and the test is stopped. The error of not exactly meeting the stop time is assumed to be very small, since the regeneration rate under MPP conditions is very low.

The relative module power loss is calculated by using equation 2:

$$\Delta\eta = \frac{\eta_{(t)} - \eta_{(0)}}{\eta_{(0)}} \qquad (2)$$

The BO and LeTID-susceptible module in Figure 7 shows a high degradation of 6.4%$_{rel.}$ due to BO in the first 20 hours and an additional degradation after three weeks LeTID test at 75°C up to 9.2%$_{rel.}$ in total. After 700h cumulated test time in a climate chamber the regeneration of the module power had set in and the test was stopped.

This test run shows that the proposed test sequence can be used to evaluate the influence of stress on a combination of carrier injection and elevated temperature on module performance. The proposed test procedure can demonstrate the sensitivity of the sample to BO and LeTID degradation mechanisms on module level.

Summary

Light and elevated temperature-induced degradation (LeTID) is a critical topic for investors and plant owners, since it can permanently reduce the power outcome of PERC-modules. This degradation effect can be mitigated by optimising the cell process or passivating the LeTID defects. Since both metal contamination and the hydrogen content have a decisive impact on LeTID, process control has to address these two parameters in some way. However, recent benchmark tests have shown that not all module producers have the degradation under control and some commercially available products show a pronounced degradation. Thus, it is necessary that LeTID tests are performed throughout the value chain to reduce the risk of financial losses of producers due to failing modules and the risk of investors.

The LeTID Norm project consortium is working on a better understanding of the defect and a LeTID test standard. To quantify LeTID, the separation to other LID effects is recommended, which can be achieved by a pretreatment at 25°C and dark storage before each measurement. The LeTID test should be carried out at 75°C by injecting the current $I_{CID} = 2 \times (I_{SC} - I_{MPP})$ or illumination with an equivalent light intensity for at least three weeks. ■

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Dr. Max B. Koentopp received his PhD in physics from the Karlsruhe Institute of Technology (KIT) in Germany. After post docs at Columbia University, Princeton University and Rutgers University in the United States he joined Q CELLS in 2009. As director test labs and analytical services at Hanwha Q CELLS GmbH he is globally responsible for module reliability testing and outdoor test fields, cell and module characterisation, and device simulation.

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