Multicrystalline PERC solar cells: Is light-induced degradation challenging the efficiency gain of rear passivation?

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ABSTRACT

The passivated emitter and rear cell (PERC) process has been successfully transferred to mass production, with the market share of multicrystalline (mc) silicon being around 50%. This new technology can, however, lead to severe reliability issues despite the higher initial solar cell efficiencies. In particular, light-induced degradation (LID) of mc-PERC solar cells has been reported to cause efficiency losses of up to 10%$_{rel}$. This highlights the importance of understanding different types of LID and of testing the stability of solar cells under actual operating conditions.

Introduction: PERC technology enters mass production

The passivated emitter and rear cell (PERC) is one cell technology upgrade option that has been the focus of many research and development activities during the last few years. Crystalline silicon solar cells with a passivated rear side have successfully entered mass production and are expected to seize a significant share of the different cell technologies in the near future [1]. Cells of this type yield about 5%$_{rel}$ more power than conventional aluminium back-surface field (Al-BSF) cells [1]; this can be attributed to reduced electrical recombination and improved optical properties.

Solar cell efficiencies of more than 22% using PERC technology on monocrystalline Si material were publicly announced by Trina Solar and SolarWorld in December 2015 and January 2016 respectively. The world record for a multicrystalline cell, with an efficiency exceeding 21%, has also been achieved using the PERC technology and was presented by Trina Solar at the recent SiliconPV conference in Chambéry [2].

The upgrading of a solar cell production line to PERC technology is a rather evolutionary step, since a large part of the existing manufacturing equipment can be used for PERC production as well. Major cell producers – such as SolarWorld, Hanwha Q CELLS, Trina Solar, Jinko Solar and JA Solar among others – have already begun to operate PERC production lines, or have made announcements that they will start to do so, leading to a large number of commercially available PV modules based on PERC technology.

The International Technology Roadmap for Photovoltaic [1] predicts that "PERC cells will gain significant market share over BSF cells", reaching a share of about 35% in 2019. Although the share of multicrystalline silicon solar cells is predicted to decrease, this type of material is expected to dominate the market over monocrystalline silicon solar cells for at least the next five to ten years [1].

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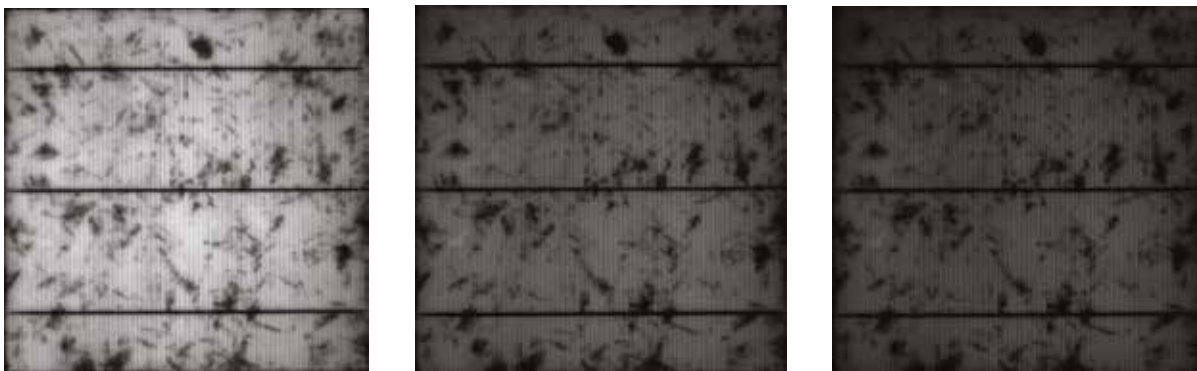

Figure 1. Photoluminescence images (with the same scaling) of an mc-PERC solar cell, initially and after 20 and 30 minutes of a one-sun illumination at an elevated temperature of 95℃.

Degradation of solar cells: PERC technology upgrade brings with it new challenges

While the introduction of the PERC technology leads to a significant increase in cell power, some unexpected challenges concerning cell performance in a normal operational environment have become apparent. Already in 2012 it was reported by Ramspeck et al. [3] that multicrystalline PERC (mc-PERC) solar cells can exhibit significantly stronger power degradations during the first few days of operation than Al-BSF cells produced from the same material.

The phenomenon of illumination leading to the degradation of a solar cell is not a new discovery and has been the topic of investigation for more than 40 years. It was observed that a shift in the Fermi level induced by the increase in excess carrier concentration can cause cell degradation because of the different chemical processes within the solar cell. Since the increase in excess carrier concentration is related to the incident irradiation, this process is generally termed *light-induced degradation (LID)*. However, the same effect is brought about by inducing a current in an unilluminated solar cell, which also causes an increase in excess carrier concentration.

The two best-known mechanisms are the activation of boron–oxygen (B–O) complexes and the dissociation of iron–boron (FeB) pairs. Furthermore, LID has been detected on chromium- and copper-contaminated samples [4–6]. Recently, two additional degradation mechanisms – which differ in their appearance from the well-studied degradation mechanisms – have been described: 1) *mc-PERC LID* [3] (also named *light-and-elevated-temperature-induced degradation LeTID* [7]); and 2) *sponge LID* [8]. The lifetime degradation is reflected by a reduction in the photoluminescence signal, as presented in Fig. 1.

Boron–oxygen complex activation (B–O LID)
The boron–oxygen complex is an extensively studied cause of LID, which in such cases is referred to as *B–O LID*. The efficiency loss depends on the oxygen and boron concentration in the wafer; thus, monocrystalline Czochralski silicon is the worst affected, because of the high oxygen concentration (up to 10^{18} atoms/cm³). Multicrystalline silicon, on the other hand, is much less affected, because lower oxygen concentrations can be achieved. The defect can be avoided altogether by using an alternative dopant, such as gallium, or by using n-type material.

The activation of boron–oxygen complexes occurs within the first few hours of illumination. The activated defects can be transformed into a stable and recombination-inactive state by illuminating the samples at an elevated temperature; this process is called *regeneration* [9–11]. A quantitative model describing the physical and chemical processes during the degradation and regeneration was recently published [12]. Further, it was shown systematically, by comparing light- and electrical-induced degradation, that B–O LID can be traced back to the carrier injection induced by light rather than to other light-induced effects [13]. The first industrial tools, namely regeneration furnaces, are available for performing the regeneration.

Iron–boron pair dissociation (FeB LID)
Another degradation mechanism is related to the iron–boron dissociation, namely *FeB LID*. In the dark, positively charged iron atoms link to the negatively charged boron atoms as a result of Coulomb interaction. These complexes have shallow energy levels and do not reduce the cell efficiency. The shift in the Fermi level under illumination causes a neutralization of the iron ions, which consequently separate from the boron atoms. Interstitial iron causes a much higher charge carrier recombination under solar cell operating conditions. As a consequence, the dissociation of iron–boron pairs results in a severe efficiency loss in cells with a high iron concentration. As in the case of B–O LID, this degradation effect is well understood [14,15].

mc-PERC LID
In 2012 a new LID mechanism – *mc-PERC LID* – was described by Ramspeck et al. [3]. This type of degradation occurs on p-type mc-Si solar cells, though it is more pronounced on PERC cells than on standard Al-BSF cells. The degradation can lead to an efficiency loss of more than 10%$_{rel}$, as seen in Fig. 2; however, in contrast to the other mechanisms described above, it occurs only at elevated temperatures, in particular above 50°C. Hanwha Q CELLS has therefore suggested a new name for this – *light-and-elevated-temperature-induced degradation (LeTID)* [7].

mc-PERC LID differs from B–O LID and FeB LID by the higher temperature that is necessary for inducing the degradation and the much longer timescales over which the degradation occurs. Compared with B–O LID and FeB LID, a complete degradation of mc-PERC cells is observed only after several hundred hours, even at elevated temperatures of between 50 and 95°C [7]. Furthermore, it has been shown that this degradation demonstrates no correlation with the concentration
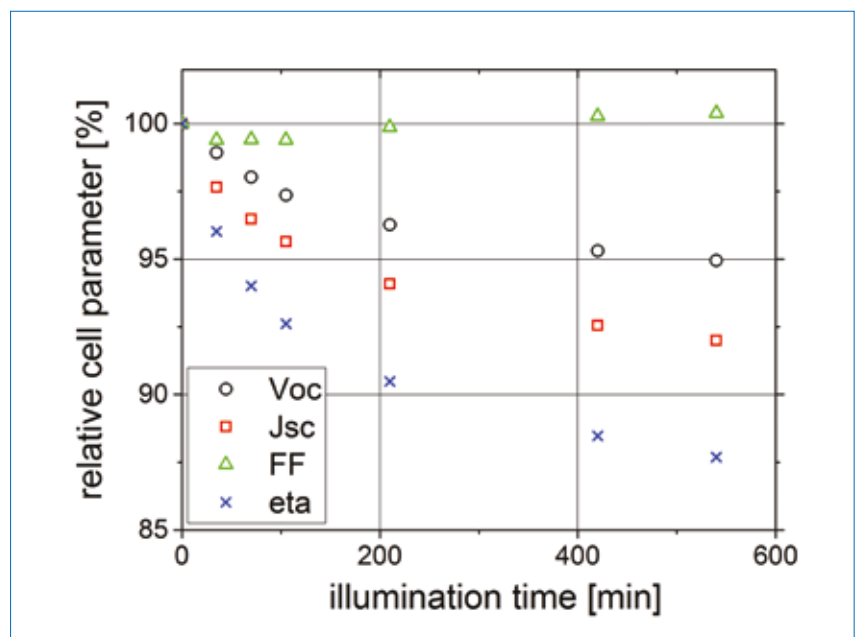

Figure 2. Typical degradation of mc-PERC solar cell parameters under a one-sun illumination and a temperature of 75°C.

of oxygen [7], and that Ga-doped Si degrades in a similar manner [3].

Following a complete mc-PERC LID cycle, the efficiency increases again, an effect referred to as *regeneration* [7]. This is similar to what is known in the case of B–O LID, since the regeneration occurs by carrier injection at elevated temperatures and thus at the same operating conditions as for mc-PERC LID [7]. Similarly to the degradation, the timescale for the regeneration is much longer than that of B–O regeneration, which makes an industrial implementation that matches the process times more challenging. A better understanding of the physical processes involved would support such an industrial implementation. What causes this mc-PERC LID and the corresponding regeneration, however, is still an open question.

Sponge LID

Sponge LID is a new form of light-induced degradation recently published by Hanwha Q CELLS [8]. This form of degradation cannot be explained by the mechanisms described above. It occurs on high-performance multi material – a new wafer type with small grains, but only a few dislocations, which yields an efficiency gain of about 2.5%$_{rel}$ [8]. It has been shown that only the lower part (i.e. up to 20–30%) of the ingot is affected by sponge LID, inducing an efficiency loss of up to 10%$_{rel}$. Hanwha Q CELLS has reported the development of an adapted cell process which leads to solar cells that are stable with regard to sponge LID [8]. Nevertheless, an understanding

of the physics of the degradation has not yet been acquired, and the degradation process is still under investigation.

LID testing and standards

Since light-induced degradation phenomena affect the efficiency of PV modules during their entire lifetime, the quantification of LID is an important task for yield simulations and of great significance for the cost-effectiveness of PV systems. The initial degradation of solar panels is generally tested during certification in accordance with the IEC 61215 standard [16,17]. To pass qualification, PV modules must demonstrate less than 5% degradation after each test, and, for a full sequence, less than 8%. However, a degradation of 5% would already have a drastic impact on the levelized cost of electricity (LCOE).

Elaborate standards at the module level, with regard to preconditioning and testing conditions, are therefore required in order to generate reliable and comparable values for the quality evaluation of PERC solar modules. The various types of LID effect in high-efficiency solar cells, together with their different material- and solar cell process-induced origins, require well-defined test recipes for temperature, irradiation and electrical operating conditions. An implementation of test set-ups, procedures and standards already at the cell level opens up the possibility of quantitatively evaluating LID sensitivity at its origin – the solar cell. This provides quick access to LID quality control at an early stage of the production chain.

In the literature a number of test set-ups based on sunlight, halogen or Xe lamps are described [16]. Fig. 3 presents Fraunhofer CSP's dedicated test set-up, which allows a comprehensive and quantitative LID reliability test to be performed already at the mini-module or solar cell level. The LED-based solar cell LID tester can be used to transfer the IEC standard module test conditions to solar cell testing [17]; it comprises an LED-based illumination source, a solar cell temperature control unit, and a chuck for electrical measurement and conditioning purposes [18].

The individual definitions of temperature, illumination and cell voltage for the degradation and measurement sequences address the specific LID phenomena described earlier, ranging from B–O LID and FeB LID to mc-PERC LID and sponge LID. The implementation of LEDs with specific wavelengths can increase the sensitivity of the test significantly. The basic measurement principle corresponds to a rapid quantum efficiency test as implemented on LED solar simulators [19]. Compared with a standard quantum efficiency test, only a few wavelengths are used, which reduces the measurement time to less than half a second. Furthermore, the heat impact on the cell is reduced by using light in a well-defined wavelength range, making the temperature control more reliable. Additionally, a test set-up using electrical carrier injection and temperature control for the evaluation of accelerated degradation and regeneration processes was developed, allowing an investigation
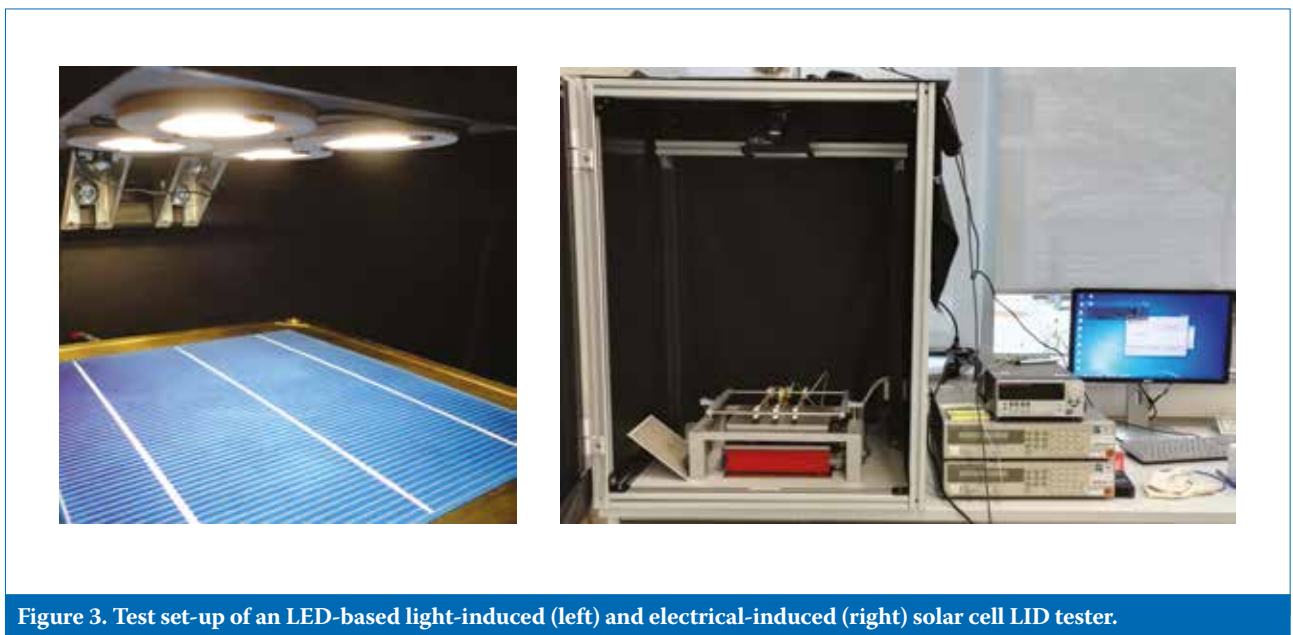

Figure 3. Test set-up of an LED-based light-induced (left) and electrical-induced (right) solar cell LID tester.

and optimization of the corresponding process parameters.

A deep understanding of LID phenomena and the underlying root causes will help to make LID testing of solar cells more comparable to module LID testing. LID metrology tools will help to track down the root causes of material-induced LID along the value chain. Using LED technologies, the monitoring of the affected parts of the solar cell (front or back), as well as crucial processing steps for LID stabilization, can be easily carried out. LID tests at the solar cell level are important for guaranteeing solar cell quality at an early stage of production, as well as for incoming quality control in module production.

Dealing with the root cause of mc-PERC LID

It is necessary to gain a deep understanding of the underlying degradation mechanisms in order to guarantee stable performance of multicrystalline solar cells in a PV module. The physical mechanism causing mc-PERC LID due to light and elevated temperature is not yet completely understood and is currently under investigation. The publicly funded SolarLIFE project [20] is a framework within which some of the major German research institutes work on this task alongside industry partners. The aim of the project is to study the causes of solar cell degradation on medium-to-long timescales; material bulk effects as well as instabilities of the interfaces are also investigated.

Some important results relating to mc-PERC-LID have already been published and are briefly summarized below.

Influence of external parameters on degradation

The mc-PERC LID phenomenon is influenced by temperature, excess carrier concentration, and degradation time. Ramspeck et al. [3] showed that a temperature above 50°C is required in order to observe the entire degradation in under 400 hours, and that the degradation is significantly accelerated when moving up to higher temperatures. The excess carrier concentration is determined by the illumination and operating point of the solar cell (e.g. short circuit, maximal power point or open circuit). A change in the operating mode when switching from open circuit to short circuit can slow down the degradation by a factor of ten, as shown by Kersten et al. [7]. This slower degradation is due to a lower carrier injection in the short-circuit mode.

Without changing the operating conditions (i.e. the carrier injection and temperature), the regeneration process of the mc-PERC LID defects sets in following the degradation [7], in a similar way to that observed for the boron–oxygen complex. The recombination-inactive complexes formed during regeneration are stable, and no further degradation is detected [7].

> "The solar cell process itself, particularly the firing step and the passivation process, also has a significant effect on the degradation."

Impact of cell-specific features on degradation

Even if solar cells are subject to the same external influences, the degradation might appear very different; the reason for this can be the material, the cell process or the pretreatment of the solar cell. Until now, mc-PERC LID has been detected only on multicrystalline samples [3,21,22], which indicates that the silicon material with its specific contaminations has an influence on the degradation. Kersten et al. [7] also detected differences in the degradation after 24 hours of illumination when cells from different regions of the ingot were investigated.

The solar cell process itself, particularly the firing step and the passivation process, also has a significant effect on the degradation. It can be assumed that the hydrogen content within the bulk silicon material induced by the SiN passivation layers plays a role in both degradation and regeneration. Bredemeier et al. [23] showed that a SiN passivated silicon wafer (lifetime sample) fired at lower temperatures exhibits less pronounced lifetime degradation, a behaviour which has also been detected in solar cells [24].

Localization and root-cause analysis of the defect

For a physical understanding of the mc-PERC LID defect, it is necessary to analyse the solar cell in greater detail and investigate the differences in affected and unaffected regions of mc-PERC LID. This can be done using microstructural analysis, which requires the localization of the defects within the wafer or solar cell.

The localization of the degradation source was performed with a focus on both lateral and horizontal inhomogeneities. It was shown that the main component of mc-PERC LID is a reduction in bulk carrier lifetime, indicating the formation of a defect inside the silicon wafer material during degradation. In contrast, the front and rear sides appear to remain stable under degradation conditions [25]; this is reflected in a loss analysis (see
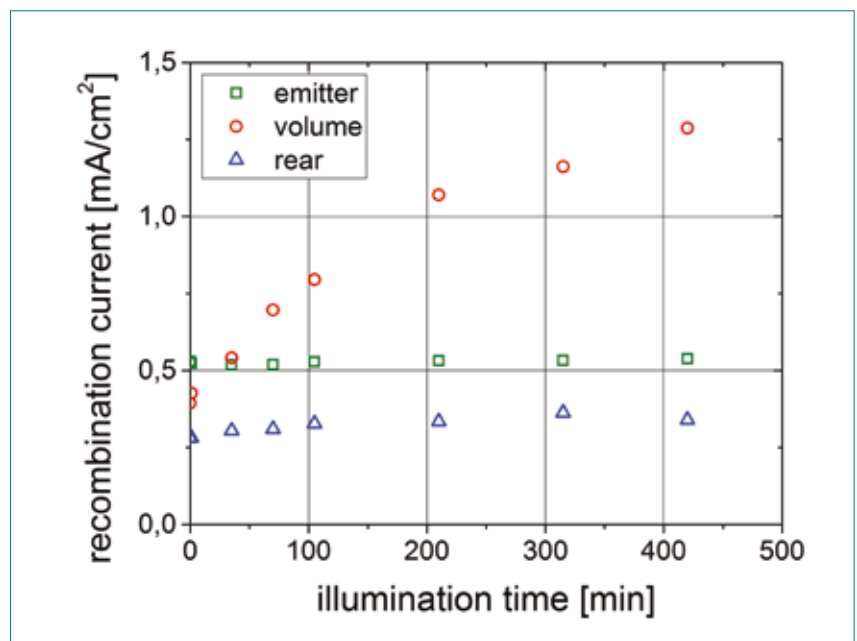

Figure 4. Solar cell loss analysis, showing the impact of mc-PERC LID on recombination currents caused by emitter, cell volume and rear-surface recombination.

Fig. 4) based on quantum efficiency measurements.

Concurrent investigations of lifetime samples and solar cells on a micrometre scale were carried out at Fraunhofer CSP. It was found that the degradation occurs fairly homogeneously over the entire cell area, as seen earlier in Fig. 1. The appearance of localized shunts could be excluded as a source of the degradation. In a cell, variations in degradation are related to structural differences, as grain boundaries and rear contacts show less-pronounced degradation [22,25,26], whereas inside the grains, the degradation does not differ significantly. Differences in the degradation of solar cells on macroscopic lengths scales can be attributed to variations in the cell process, such as temperature variations between the outer and inner regions of a cell [24]. On wafers prepared as lifetime samples, lateral differences in the degradation between individual grains have been detected [22].

Defect model

On the basis of these results, the first defect models have been developed for mc-PERC LID [23,26]: the experimental results show a pronounced mc-PERC LID, which appears homogeneously in intra-grain regions and twin boundaries. The major contribution to the degradation is a change in the bulk material, whereas the surfaces are fairly stable. Compared with the intra-grain regions, a reduction in mc-PERC LID is found at undecorated grain boundaries, independently of the grain boundary type and orientation. Decorated grain boundaries and defect clusters are dominated by other recombination mechanisms and are thus below the detection limit for mc-PERC LID. These results point towards a defect model in which the mc-PERC LID defect is related to an atomic point defect dissolved in the undisturbed crystal structure.

At undecorated grain boundaries, the chemical process leading to the recombination-active defects is inhibited by the large number of structural defects [26]. Bredemeier et al. proposed that the high-temperature firing step dissolves metal precipitates into mobile metal atoms, which are captured by another homogeneously distributed impurity. The complex thus formed, which is relatively recombination inactive, separates under illumination at elevated temperatures, leading to a recombination-active isolated metal defect. A subsequent diffusion of the metal atoms to the surface and to other crystallographic defects has been proposed as the physical mechanism leading to regeneration [23]. A complete and detailed physical understanding has not yet been established, however, and further investigation is necessary.

Implications for PV module operation

The sensitivity of mc-PERC LID has been tested in laboratories under elevated temperatures above 50°C. The degradation is still relevant in the case of module operation, since solar cells inside a PV module can easily reach temperatures of around 50°C and higher. For example, in central Germany the cells inside a module operate at temperatures above 50°C on average, for about 70 hours each year; the temperature peaks at about 62°C. Even higher cell temperatures occur when modules are operated in hot climates, such as desert regions. Thus, losses detected at the cell level can be directly translated into expected yield losses during module operation.

Module degradation in the field, however, takes longer than in accelerated laboratory testing, since the temperatures are typically lower. Kersten et al. [7] predicted that the degradation is complete after 10 years for a rooftop installation in Germany. Regeneration will not become established until after 20 years of module operation under the same conditions. Thus, the regeneration does not proceed fast enough to have a positive impact on the total power output under typical module operating conditions, and the modules remain in the degraded state for many years. Different technological solutions to prevent mc-PERC LID therefore need to be established in order to guarantee a high-efficiency module based on mc-PERC solar cells.

Adapted PERC process

There are different strategies under discussion for avoiding mc-PERC LID at the cell level. First, the solar cell process itself can be adapted to yield LID-insensitive cells. Several solar cell producers and suppliers of production equipment have announced that they are able to produce mc-PERC solar cells resistant to PERC LID [7,25]. While the process details have not been disclosed, the results presented above indicate that the firing step or the SiN layer deposition may play an important role.

Second, additional stabilization processes which lead to stable regenerated cells could be employed. Here, a strongly accelerated degradation and regeneration cycle would have to be performed after cell production in order to transform the cells into a recombination-inactive and stable state before their application in the field. This can be done either by strong illumination or by inducing large currents at high temperatures.

Finally, research activities are focusing on the identification of the contaminations that are relevant to mc-PERC LID. This might eventually lead to an optimized crystallization process which avoids LID issues at the cell level. At Fraunhofer CSP, researchers are working on each of these approaches to prevent LID, by developing a better understanding of the processes involved and by optimizing the relevant solar cell process steps as well as subsequent stabilization processes. Either approach has to be accompanied by a dedicated quality-control process which quantitatively assesses mc-PERC LID.

> **"Dedicated tests regarding mc-PERC LID at the solar cell level are essential for reliable quality control."**

Conclusions

LID is not just a concern with monocrystalline silicon solar cells: this type of degradation has once more entered the spotlight with the introduction of mc-PERC solar cells into mass production. The particular LID mechanism that mainly affects mc-PERC cells can lead to severe power losses of more than 10%$_{rel}$, and is strongly accelerated by the elevated temperatures which can occur under typical module operating conditions.

Some solar cell producers have already addressed the degradation issue, announcing that the solar cell production process can be adapted in such a way that mc-PERC LID is avoided. However, small changes to the solar cell process, such as modified process temperatures or different wafer materials, can lead to substantial performance losses in the PV module as a result of mc-PERC LID. Since the physical and chemical root cause of the cell degradation is not yet fully understood, dedicated tests regarding mc-PERC LID at the solar cell level are essential for reliable quality control.

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