Keep a LID on it

PERC LID: Monocrystalline solar cells have always sported higher cell efficiencies, yet higher production costs and specific loss mechanisms limited the broader adoption of this production technology. As the industry moves to PERC structures and new cure technologies are being adopted, the relative appeal of monocrystalline cells is rising once again.

Twelve months ago, centrotherm introduced a new production tool to the market named "C. Regeneration." It is a modified belt furnace with the ability to condition monocrystalline solar cells in such a way that a degradation mechanism specific to these cell types – dubbed "light induced degradation" (LID) – can be significantly reduced.

In recent weeks, equipment vendors Applied Materials and Despatch have both made announcements that they are either developing production tools that address this degradation problem or – in the case of Despatch – have them ready for market introduction.

Interestingly the fundamental scientific discoveries that form the basis for these new production tools were made 10 years ago. However, a great many different ingredients had to come together, and certain improvements had to be made before a scientific discovery eventually saw its adoption in production lines.

10 years in the making

In 2005 Axel Herguth was working as a student assistant in the PV research group of Professor Giso Hahn at the University of Konstanz, Germany. He was studying the dynamics of degradation mechanisms of industrial monocrystalline solar cells. At that time it was well established through the work of several research groups like the teams of Stefan Rein and Stefan Glunz at the Fraunhofer ISE, the research of Karsten Bothe and Jan Schmidt at ISFH, and the group of Prof. Saitoh in Japan that the observed LID on standard BSF monocrystalline solar cells was related to the boron-oxygen complex in the crystal.

From different experiments it was possible to conclude that the defect concentration scaled linearly with the boron concentration (B) and roughly quadratically with the interstitial oxygen concentration (Oi). The formation of the actual BO-defect could be induced by illuminating the cells, thus the effect was named light-induced degradation (LID). Actually, any carrier injection into the cells would induce the BO-defect, but the term LID had already stuck.

It was also known that after the formation of the defects, heating the cell in the dark at temperatures of around 200°C for a few minutes could anneal the recombination active BO-related defects, and the cell would exhibit a higher charge carrier lifetime once more. But under normal operating conditions the BO-related defects formed again, so the state reached under these annealing conditions did not lead to a stable high lifetime state.

When the cells were exposed to even higher temperatures under illumination, Axel Herguth made an unexpected discovery: Instead of an accelerated degradation he observed an increase in cell efficiency. At first he did not trust his results since they were not explicable under the assumption of only two states of the boron-oxygen complex. Yet when the effect could be reproduced, the team around Professor Giso Hahn intensified their research and came up with the conclusion that under the presence of heat and excess carriers the boron-oxygen complex could be transferred to a third state that was no longer recombination active.

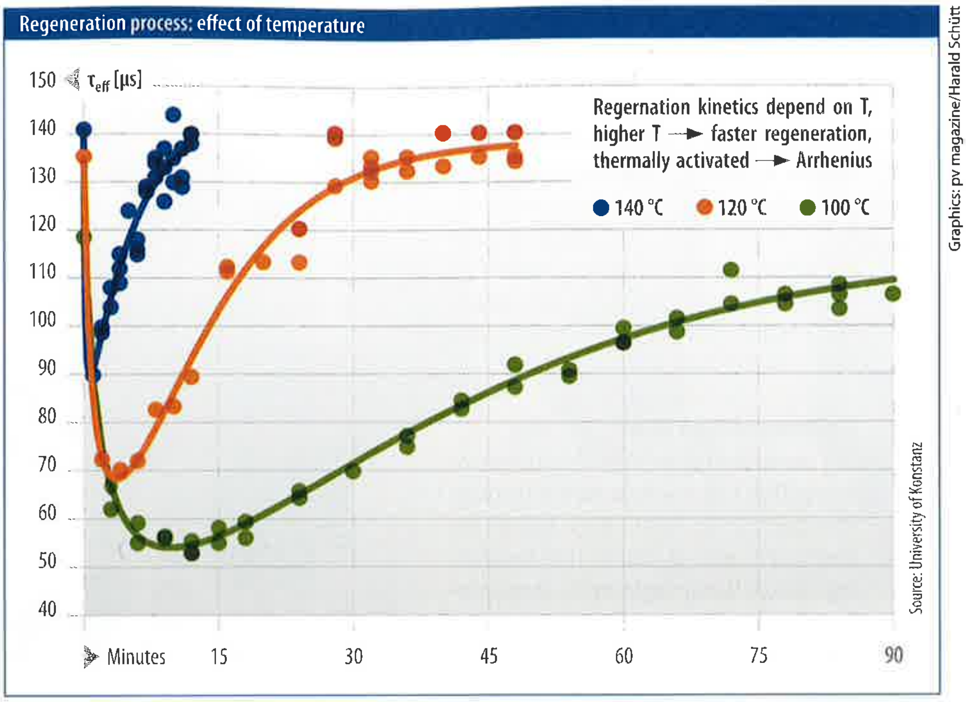
What was even more striking was the fact that when temperature and carrier injection were applied in a specific way, the improved efficiency remained stable even under normal operating conditions

Photo: Centrotherm

Centrotherm's C. Regeneration tool is a modified belt furnace with the ability to condition monocrystalline cells in order to reduce instances of LID – light-induced degradation.

(i.e. without any additional heat having to be applied). This was exciting because until then the efficiency of monocrystalline solar cells typically degraded over time by around 0.5-1.0%abs, compared to the initial state directly after manufacturing due to the recombination active BO-related defects. Up until then the main workaround in the industry to reduce the BO-related efficiency limits of the solar cells was to use lower doped material. While this approach reduced the impact of the detrimental BO-defect at the same time, it also limited the overall cell efficiency.

Therefore, the initial scientific results published back in 2006 spurred quite some interest in the industry, and a number of cell manufacturers looked into the regeneration approach proposed by the researchers of the University of Konstanz.



Accelerating regeneration

The University teamed up with several solar cell manufacturers and performed a series of fundamental tests in order to better understand the exact dependencies of the regeneration effect on the different external parameters. It turned out that, based on the technologies applied at that time, the process times required to achieve the desired recombination inactive BO-state were in the order of several minutes.

Under these conditions the process did not appear economically viable for mass production. Consequently, the cell manufacturers shifted their research focus to other areas where they saw a higher potential to improve the cost efficiency of their cells. Yet the team of Professor Giso Hahn was unwilling to give up. Instead, they applied for a scientific research grant to develop a better understanding of the regeneration kinetics and identify ways of how to further improve the regeneration dynamics.

In the course of this detailed study, Svenja Wilking, another young researcher in the group of Giso Hahn, was able to identify the relevance of hydrogen and of the firing step parameters for the regeneration process. As can be seen in Graph 1 (above right), higher process temperatures accelerate the regeneration process. Yet increasing just the peak firing temperature was not sufficient to achieve the desired faster regeneration rates. In order to trap the hydrogen together with the BO-complex in a recombination inactive state, it turned out to be of high relevance to quickly cool down the cells after the recombination inactive state had been formed, and thus avoid the dissociation of hydrogen from the BO-complex once again (see Graph 2 on p. 46).

These experiments, together with a detailed understanding of the different reaction paths and their corresponding reaction constants, ultimately paved the way for a much improved "high speed regeneration process" that can be carried out in just a few seconds and achieves an almost complete regeneration. These findings were published in 2013; based on these improved regeneration process dynamics, centrotherm was the first equipment vendor to realize the inherent potential of these results for the industry, and started a tool development project in order to transfer these advances into mass production. Twelve months later the first regeneration tool was shipped to a customer.

Upgrading to PERC

At the same time, another development led to an increased interest in the industry to reinvestigate ways to minimize the LID. In 2013 an increasing number of cell manufacturers were evaluating the upgrade of their conventional aluminum back surface field (Al-BSF) production lines to passivated emitter and rear contact (PERC) type solar cells in order to benefit from the higher cell efficiencies achievable with this technology.

While in full Al-BSF cells the moderate rear side passivation limits the efficiency potential of the cell, in PERC cells the improved rear side passivation enables higher efficiencies. At the same time, the relative importance of the bulk charge carrier lifetime for the cell efficiency increases, and so a higher boron doping level is desirable. Yet when using higher doped material in PERC structures, the BO-related degradation increases to values of 1.0%abs or more if the cells remain untreated. This dilemma could only be resolved through the application of the regeneration process that inactivated the recombination active BO-states. In summary, in order to take full advantage of the efficiency potential of PERC-type solar cells, it was more important than ever to tackle LID.

Professor Hahn and his team are excited to see that their ongoing research over almost a decade has found an adoption in today's production tools. They expect that a broader adoption of the PERC technology will lead to a renewed interest in other optimization technologies as well.

"Once you have improved the physics on the back side of the cell, the efficiency limiting factors in the bulk and on the front surface of the cell play a more important role," said Hahn. He cites as an example the increased interest in the selective emitter technology among PERC cell manufacturers. "Not only is the relative efficiency gain through the selective emitter more pronounced on PERC cells, but in order to apply the regeneration process one requires a broader processing window for the firing step.

"This is compatible with the selective emitter technology, while the optimizations achieved on the homogenous emitter in the past few years that almost made the selective emitter technology obsolete require tight processing conditions. These tighter conditions don't match that well with the regeneration process."

Photo: University of Konstanz

Professor Giso Hahn, Svenja Wilking and Axel Herguth of the University of Konstanz.

Limiting LID on PERC

The cost advantages achievable for monocrystalline cell manufacturers through the upgrade to PERC have led to the impressive rate at which this technology is now being deployed in mass production. In contrast, the adoption rate among multicrystalline cell manufacturers is much slower.

The root cause for the difference in the adoption rate of PERC technology is another LID effect. Surprisingly for PERC cells the sensitivity to LID is much more pronounced in multicrystalline cells than in monocrystalline cells. Professor Hahn concedes that this discovery came unexpectedly.

Experimental data indicate that this newly observed LID degradation on multicrystalline PERC cells is not related to the same BO-complex as in monocrystalline cells. Yet he is optimistic that a cure can also be found for this degradation phenomenon. Recently a number of cell manufacturers like Hanwha Q Cells, SolarWorld and REC have announced that they were able to optimize their production process in such a way that the detrimental LID on multicrystalline PERC cells can be limited to 1.0-2.0%rel compared to 8.0-12.0%rel in untreated cells.

For obvious reasons the successful manufacturers have not disclosed what modifications exactly they apply to their production process in order to minimize the newly observed LID degradation on multicrystalline PERC cells.

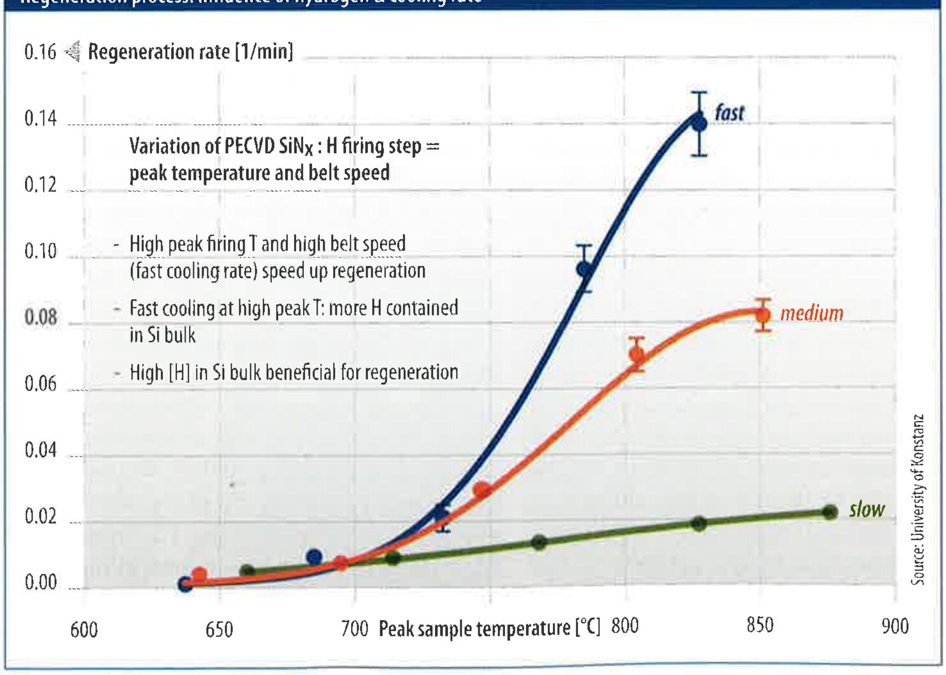
Professor Hahn and his team have recently started a new research project that will closely investigate this newly observed LID degradation phenomenon, as well as other degradation effects. "Only if we have a clear understanding of the underlying physics that are responsible for the different degradation mechanisms can we also be sure that the applied 'cure treatments' will lead to a long-term, stable cell and module efficiency over the lifetime of the module," he said.

Given the high interest among multicrystalline cell manufacturers in addressing the newly observed LID degradation mechanism, Hahn believes that a transfer of research results into production tools would occur significantly faster this time around.

Yet as long as the new degradation mechanism isn't fully understood, Hahn would not be surprised if monocrystalline technology was to gain market share. Even more so as, over the past few months, the price differences between mono and multicrystalline wafers have further diminished. "Ultimately, the ongoing competition between the different cell technologies has benefited the industry and has fostered the enormous progress in production costs achieved over the past decade." And for the next decade he sees a significant potential for further technological advances at the production level that will continue to drive down the cost for solar power. ◆

Götz Fischbeck

Regeneration process: influence of hydrogen & cooling rate



"We guarantee the percentage of LID reduction"

Photo: centrotherm

PERC LID: While it brought one of the first regeneration tools on to the market, Germany's centrotherm has observed a lag before market adoption, until now. Wolfgang Jooss (pictured), centrotherm's Director R&D and Technology photovoltaics, and Thomas Pernau, Product Manager Firing and Regeneration Furnaces, spoke to **pv magazine**.

I believe centrotherm was the first equipment vendor to develop a tool for mass production that addressed the LID observed in Cz-Si solar cells that was introduced as c.REG last year. When did you initiate the development process?

WJ: Besides our close cooperation with customers, we collaborate with established institutes and research facilities. This was a trigger for kicking off the development of a regeneration furnace in mid-2014. Motivated by reports from the University of Konstanz about fast regeneration of solar cells, our R&D and engineering team developed a prototype in order to provide a tool for mass production within a short period of time. Following first in-house tests, we regenerated batches of 100-200 cells from various cell suppliers covering a wide range of wafer material parameters to find the best fast regeneration conditions. The key findings of these tests were transferred into the first mass production regeneration furnace. The first two regeneration furnaces c.REG were already delivered in June 2015 to a Taiwanese customer. Due to the convincing results of customer samplings, the centrotherm c.REG has been adopted very quickly. It is now in mass production at several solar cell manufacturers in Asia and Europe. The stand-alone tool can also be integrated into module production lines.

The first academic publications of the underlying mechanisms for the regeneration treatment date back to 2006. Why the eight year lag before industry adoption?

TP: Initially, regeneration was done at lower temperatures and not at optimized illumination conditions, leading to long regeneration times well beyond several minutes. It took the research community several years to find out that regeneration can be done in a short period of time – within less than one minute. This made it possible to develop industrial inline manufacturing tools with low cost of ownership. In parallel the need for regeneration came up with the evolution of PERC cells, in which LID is more pronounced than in conventional BSF cells.

What improvement of cell efficiency is typically achieved through the regeneration treatment? How strongly are these improvements material-dependent?

TP: We have tested many different wafer materials. For all of these materials, we did not observe an efficiency loss after an optimized regeneration treatment. For some materials we could even measure a higher efficiency. Considering all of the different materials tested by us, the LID could be reduced from 4-10% rel. down to 1% rel. on average. Even the "worst" material had an LID below 2% rel. We guarantee the percentage of LID reduction depending on wafer material of our customers.

After introducing the first generation c.REG tool in 2014, how has market adoption evolved?

WJ: Due to the fact that leading cell manufacturers have turned from standard solar cell towards new cell architectures like PERC, or have added new production capacity of PERC cells, the LID issue has become problematic and an obstacle for further adoption of such cell concepts. We were the first to have solved the LID of mono CZ with our c.REG. PERC cell architectures will become increasingly common and in consequence there will be higher demand for our solution.

What is the typical payback time that manufacturers can expect with a regeneration tool?

TP: The investment for a module manufacturer will pay off after three months. Depending on cell throughput the payback time for a solar cell manufacturer ranges from seven to nine months.

When can we expect the second generation c.REG tool from centrotherm? How will it differ from the current tool?

TP: We have also developed an integrated firing and regeneration furnace with an optional dryer. Three different furnace lengths and regeneration durations optimally match wafer requirements of our customers and deliver floor-space savings. This integrated c.FIRE REG can be used in existing solar cell production lines as it matches the length of our legacy FF-HTO models that have been in place for 10 years. The new c.FIRE REG is already available for our premium customers. A third generation, which can also be used for hydrogenation in multi-crystalline cells, is under development. ◆

Interview by Götz Fischbeck