

REVIEW OF INDUCED DEGRADATION PHENOMENA AFFECTING PV MODULES

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ABSTRACT: Degradation phenomena of solar modules occurring under operating conditions in the field may cause severe power losses for a PV system. To avoid or at least minimize the negative effects correlated with these phenomena, a good understanding of the nature and origin of the degradation is crucial. In this contribution the state of knowledge of four different important degradation phenomena is reviewed, and mitigation strategies are discussed.

The underlying defects of these induced degradation phenomena form at operating conditions of the solar cell under injection, (elevated) temperature and realistic ambient conditions. Under these conditions, the quasi-Fermi level in p-type based Si wafers changes under injection and may cause defects to change their charge state. This has implications for some of the degradation phenomena, since charge states of species determine the underlying reaction rates and degradation/regeneration kinetics in general.

BO-related light induced degradation seems to be well understood and mitigation strategies are available, although the exact microscopic picture of the defect itself is still unclear. Potential induced degradation of the shunt type is only occurring under specific polarity and high voltage drop in the string of interconnected modules. The formation mechanism seems to be clear and mitigation strategies exist as well. In contrary, for light and elevated temperature induced degradation the underlying defect is still not known, but a lot of empirical findings are available, pointing strongly towards the involvement of H being present in the crystalline Si bulk. Mitigation strategies exist, but seem to cause extra steps/costs in solar cell production. Degradation of surface passivation quality was recently observed for dielectric layer systems being used in new cell architectures allowing high efficiencies. Again, the exact nature of the underlying defect(s) is still unclear, but H may play a role in here, too.

Keywords: c-Si, Degradation, LID, Module

1 INTRODUCTION

Power degradation phenomena in solar cells/modules have been reported for a very long time. They can be separated into phenomena having their origin in the solar cell or in the solar module. As many of them occur only after completion of the cell/module under working conditions of the solar module under illumination and operating temperature over time, they can strongly affect power output and therefore cause warranty issues, as usually which a certain power is guaranteed over 25 or even 30 years of operation.

On cell level, classical examples for cell-based degradation are the Staebler-Wronski degradation in amorphous silicon [1] or light-induced degradation (LID) caused by BO-related defects in crystalline silicon (c-Si) [2] which have been first reported already in the 1970s. Another well-known degradation phenomenon is degradation via FeB-pairing or splitting, respectively [3]. More recently, also Cu was found to form a defect under working conditions of the solar cell in the Si bulk [4]. In 2012, a “new” defect was discovered, which was mainly observed under illumination and elevated temperature $>50^{\circ}\text{C}$ [5]. It was therefore named LeTID (light and elevated temperature induced degradation) [6]. Recently, it was reported that the surface passivation of the solar cell might be prone to degradation phenomena, too (e.g., [7]).

On module level, there exists a multitude of degradation phenomena, too. Examples apart from obvious malfunctions like cracks are delamination issues, hot spots, so-called snail trails and PID (potential induced degradation) [8]. See also [9] for a good overview on PID.

One of the reasons why some of the cell-based degradation phenomena have not been discovered earlier is based on the current shift of solar cell design from a full area Al BSF (back surface field) architecture towards the PERC (passivated emitter and rear cell) solar cell. While in the Al BSF cell the effective charge carrier lifetime τ_{eff}

is mainly determined by the limited surface passivation quality of the Al BSF, the PERC design allows to make use of the high quality of the Si bulk by providing a better surface passivation. This enables higher efficiencies on the one hand, but makes the cell more prone to degradation effects on the other hand, as a degradation effect reducing either bulk lifetime or surface passivation quality has a higher impact on power output and can now be detected more easily on cell level.

In this presentation, a review of some of the mentioned degradation phenomena and possible mitigation strategies will be given. The focus of the review is on c-Si technology and covers BO-LID, PID (shunt-type), LeTID and degradation of surface passivation.

2 EFFECT OF INJECTION ON CHARGE STATE OF DEFECTS

To better understand defect reaction kinetics of some of the discussed degradation phenomena, it is helpful to discuss the consequences of injection conditions on the charge state of defects being present in the bulk of the Si wafer.

Under illumination, the generation of excess charge carriers (electrons and holes) causes a splitting of the Fermi level E_F as defined in thermal equilibrium into two quasi-Fermi levels (one for electrons E_{Fn} and one for holes E_{Fp}). In p-type c-Si with E_F close to the valence band edge E_v , this causes E_{Fn} to move upwards within the band gap towards the conduction band edge E_c . Depending on the position of a defect level in the c-Si band gap, this might affect the charge state of the defect.

One prominent example is the charge state of isolated H in c-Si. H in c-Si can act as a donor or acceptor, showing two defect levels in the band gap [10]. While the formation energy favors the positive charge state H^+ for the Fermi level close to E_v and around mid-gap, the negative charge

state H⁻ is favored for E_F lying close to E_C [11]. Interestingly, the neutral charge state H₀ is never the favored one, but its occupation at room temperature shows a relative maximum for E_F positioned slightly above mid-gap [12].

Assuming a positively charged defect, it becomes clear that in thermal equilibrium H in p-type Si might never have the chance to bind to the defect due to Coulomb repulsion. On the other hand, injection of charge carriers can change the charge state of H⁺ and therefore allow for a binding of H to the positively charged defect. But the situation might be more complicated as the defect itself might also change its charge state under injection conditions.

3 DEGRADATION PHENOMENA

3.1 BO-LID

BO-LID in c-Si is mainly observed in B-doped Czochralski(Cz)-grown wafers due to their high O concentrations originating from the quartz crucible. The degradation can be described with a so-called annealed state A (not recombination active) and a degraded state B (recombination active) which can be reached by injection at room temperature. An anneal at higher temperature around 200°C in the dark allows for the reverse reaction and state A is populated again. In 2006 it was discovered that the defect can be changed under injection at higher temperatures into a third state C, which shows no recombination activity and is stable under standard degradation conditions (injection at moderate temperature) [13]. This B→C reaction (also termed regeneration) seems to be only possible with the presence of H in c-Si [14,15].

As BO-LID has a severe impact on the efficiency potential after installation of c-Si modules made of B-doped wafers, a lot of research effort went into strategies to avoid or minimize the negative effects of BO-LID. One mitigation strategy is to treat the fully processed solar cell in an extra step after the co-firing to bring ideally all of the BO-related defects into state C. Doing this in an industrial production environment in a cost-effective way means to find solutions that can be applied fast with reliable results. Therefore, it is desirable to be able to manipulate the degradation and regeneration rate to speed up the population of state C.

It could be shown that degradation can be sped up not only by increasing temperature, but also by strong injection conditions [16]. For manipulating the regeneration rate, a multitude of findings are reported in literature. While increase of injection and temperature also speed up regeneration rate [13,17], it can also be manipulated by changes in the dielectric surface passivation layer system and the firing conditions. The introduction of an AlO_x layer between c-Si and SiN_x:H layer slows down the regeneration rate. The regeneration rate is getting slower with thicker AlO_x interlayer, pointing towards AlO_x being a barrier of H diffusing from the SiN_x:H into the c-Si bulk during the firing step [18]. A high peak firing temperature causes a faster regeneration rate and a high belt speed during firing also helps to speed up regeneration [19]. All these results can be explained by the regeneration rate being influenced by the amount of H present in the c-Si bulk during the regeneration process, with high concentration of H being beneficial for a fast regeneration process. As a side note, it has to be mentioned

that the H has to be present in a suitable form, as low temperature annealing steps after the firing step can affect the regeneration rate, too [20]. This could be explained by the low temperature anneal changing the form H is present/bound in c-Si [21].

The most obvious technical solution to apply the regeneration procedure is to illuminate the cell after firing at elevated temperature. Depending on the technical solution typical temperatures are around 250°C at 10-20 suns illumination, with treatment times <1 min (e.g. [22]).

Another method is to apply a bias to the solar cell at elevated temperature. This can be elegantly realized by stacking the solar cells after firing and applying a bias to the stack in an environment providing the envisaged temperature for the stack [23]. As the cells are stacked, treatment time can be increased without negatively influencing throughput, and treatment temperatures are in the range of 180°C [24]. This seems to be currently the most cost-effective method to regenerate B-doped solar cells and is widely used in industry.

A third mitigation strategy is to avoid B as a dopant completely by using Ga. For a long time, this has been ruled out as the segregation coefficient of Ga in Si is much smaller than for B, causing an inhomogeneous distribution within the grown ingot. But continuous feeding during Cz crystal growth allowed for the use of Ga and industry has started shifting from B- to Ga-doped material much faster than anticipated in the ITRPV roadmap of 2020 [25,26].

In summary, the problem of BO-LID seems to be solved/solvable on an industrial scale, although the microscopic picture of the defect is not yet fully clear. See also [27] for the current understanding of influencing factors of BO-LID regeneration.

3.2 PID (Shunt Type)

Another frequently observed type of degradation affecting only modules, but not isolated solar cells, is potential induced degradation of the shunt type. Here a reduction in parallel resistance R_p of the module under working conditions (illumination/injection, elevated temperature, realistic ambient conditions) is observed in the field, reducing power output over time. This degradation phenomenon resulted in severe losses of power output of many PV systems worldwide and was therefore heavily researched. It could be shown that this degradation is triggered by a high potential difference between the glass and the embedded cells, with humidity and temperature playing important roles, too.

A closer look revealed that degradation strength depends strongly on polarity of the potential difference, with PID becoming stronger when the cell is on high negative potential compared to the grounded frame/glass [8]. Degradation strength also depends on the position of the cell in the string or module, with cells closer to the grounded frame having a higher probability to be affected by PID [28]. Humidity, soiling and temperature are other parameters that have been found to trigger the strength of PID.

An important finding was the detection of Na decorating stacking faults penetrating the space charge region at locations showing a locally reduced R_p in a solar cell affected by PID [29]. With this finding, a model explaining the mechanism behind PID of the shunt type could be proposed. It is based on drift of Na ions from the glass through the encapsulant and the dielectric layers on top of the cell into the emitter. Here the Na decorated extended defects, reducing R_p and causing a local shunt.

The drift is triggered by the high potential difference between the frame (grounded) and the cell lying on high negative potential. This also explains why the opposite polarity (cell on a positive potential compared to the grounded frame) does not provoke PID in standard monofacial cells, due to the positively charged Na^+ ions.

Within this model, the conductivity of the surface of the glass plays an important role, as it determines how far the high potential difference between frame and cell reaches out into the center region of the module. The conductivity can be strongly influenced by humidity, soiling and temperature, and modules in hotter and more humid climate zones show indeed a much higher probability of being affected by PID indeed due to the higher average conductivity of the surface of the glass [28].

Mitigation strategies can be separated into the different regions where action has to be taken. On cell level one possibility is to avoid the high voltage drop over the dielectric layer ($\text{SiN}_x\text{:H}$ -based anti-reflective coating (ARC) on the front). An increase in conductivity of the layer can, e.g., be reached by using a more Si-rich $\text{SiN}_x\text{:H}$ layer, showing a higher refractive index. As the ARC/optical conditions might be negatively influenced by that change, frequently multi-layer dielectric layer stacks are in use nowadays. Another measure is the use of a thin SiO_x layer on top of the emitter, although the exact mechanism of how this reduces PID seems to be not clear yet [8].

Mitigation strategies on module level follow the idea to avoid the drift of Na^+ towards the cell. Therefore, an adaption of the encapsulation material showing a higher electrical resistivity or the avoidance of Na in the glass show the wanted effect, although the use of Na-free or Na-lean glass might not be the most economical solution.

Measures can also be taken on system level. The most obvious strategy would be to completely avoid a negative bias between grounded frame and cell. Depending on the inverter used, this might be an option or not. Module level inverters and/or power optimizers might be an option, too. If no other measures to avoid PID from developing can be taken, the last option is to use an opposite biasing of the string to drive the Na out of the cell (e.g. at night). It could be shown that up to a certain level of decoration of the extended defects this is working.

In summary, PID of the shunt type is a quite well understood phenomenon, although some open questions remain. But mitigation strategies exist to avoid its negative impact for future installation of PV systems. See [8] for a very good overview.

3.3 LeTID

In 2012 a degradation mechanism was first described in multicrystalline (mc) p-type material that causes a reduction of bulk lifetime in c-Si under illumination at elevated temperature [5]. As it was not scaling with the B and O concentration and only detectable at elevated temperatures, its origin is different from BO-LID and it was named LeTID [6]. As for BO-LID, also for LeTID the prerequisite is not the presence of photons, but the presence of excess charge carriers, therefore both abbreviations are misleading as the degradation can also be triggered by biasing the solar cell. Similar to BO-LID, a degradation and regeneration phase can be observed, but degradation on realistic timescales is only visible at temperatures $\geq 50^\circ\text{C}$. LeTID kinetics can be increased by higher treatment temperature and higher carrier

concentration [6], indicating that both reaction rates show a strong injection dependency. LeTID can also be observed under realistic outdoor conditions on module level [30], with the extent and kinetics strongly dependent on the geographic location, mainly due to varying solar cell temperature.

Many studies have been carried out to find the root cause of LeTID, as the phenomenon can strongly affect module power output, especially for the PERC design [5]. It could be shown that the degradation affects all areas of the solar cell, independently on the initial material quality, provided that firing temperature is high enough [31]. Higher firing temperatures lead to more severe LeTID, while samples fired at temperatures $\leq 650^\circ\text{C}$ do not show LeTID [32]. Regeneration sets in earlier in areas of initially high τ_{eff} , indicating that regeneration kinetics depend on injection conditions [33]. Thinner samples show less degradation, pointing towards a mobile species involved in the LeTID phenomenon, interpreted in [34] as a possible involvement of a mobile species diffusing towards the surface in the course of the degradation/regeneration cycle. Firing with H-lean dielectric layers or the use of interlayers between H-rich $\text{SiN}_x\text{:H}$ and c-Si leads to less LeTID defects [35]. Thicker AlO_x interlayers cause less LeTID most probably as they act as a barrier layer for H diffusing from the $\text{SiN}_x\text{:H}$ through the interlayer into the c-Si bulk [36]. Slow cool-down ramps after firing are also beneficial for a less LeTID [37].

The findings listed above all point towards H being involved in the LeTID phenomenon. But contrary to BO-LID, where H in high concentrations (in a suitable form) is desired for fast regeneration kinetics and therefore cost-effective treatment of BO-LID when going through the degradation/regeneration process within short treatment times, H seems to be a prerequisite for LeTID to occur. The microscopic picture of the defect is still unclear, but some models have been proposed. One of it is the ‘‘H in buckets’’ model which is based on the BO-LID 3-state model, but contains an additional reservoir state [38]. It is based on H diffusing in c-Si being released from dopant-H pairs under LeTID conditions and being recaptured in more stable bonds during the regeneration phase [38]. Most models assume that an additional species is involved, but its nature is not clear yet.

LeTID was also observed in p-type Cz [39,40] and also p-type Floatzone material [41], but with different kinetics than in mc-Si using similar illumination and temperature conditions. As it is partly triggered by the same conditions necessary for BO-LID (carrier injection) and the kinetics are similar in monocrystalline material, usually an overlay of BO-LID and LeTID is observed in B-doped Cz material. One possibility to differentiate between both phenomena are the different ratios of capture cross sections for electron and holes for both phenomena. Using this, it could be shown that at high firing temperature LeTID is the dominating phenomenon, while BO-LID dominates for lower firing temperature [42].

Mitigation strategies are based on controlling the H content in the c-Si bulk, e.g. via adapting firing temperature and ramps or the composition of the dielectric surface passivation layer stack. Going towards thinner wafers is currently not an option for industry due to yield issues. Annealing steps can influence the LeTID kinetics [43] and apparently can influence the defect precursors and/or the reservoir and might be interesting to speed up the LeTID degradation/regeneration cycle.

In summary, LeTID is a phenomenon that remains a little bit mysterious, as not much is known yet about the composition of the defect. But it is known empirically how the kinetics can be influenced by external parameters (temperature, injection, processing steps). LeTID is also occurring in Ga-doped material, and with the change towards Ga doping it remains to be seen how LeTID can be treated in the future.

3.4 Degradation of Surface Passivation

Decrease in surface passivation quality over time is affecting solar cell power output as it reduces the effective lifetime of charge carriers. Various degradation phenomena have been studied, some of them could be tracked down to ultraviolet (UV) radiation cracking Si-H bonds.

Recently, it could be shown that PERC solar cells with SiO_x/SiN_x:H surface passivation stack suffer from loss of surface passivation quality after a treatment at 1 sun and 150°C [7]. A similar loss in surface passivation quality could also be seen in lifetime samples with different passivation stacks and different doping (p- and n-type) [44]. Here the degradation occurred already at 1 sun and 80°C, therefore this effect could really harm solar cell performance in realistic outdoor conditions. It could be tracked down to a loss in chemical surface passivation quality.

The root cause for this type of degradation is not yet clear, but it was speculated that H diffusing towards the c-Si surface might be responsible for the observed degradation. For longer treatment times and/or higher treatment temperatures, again a regeneration phase can be observed after the degradation of surface passivation, indicating that the loss in surface passivation is only temporarily [44,45].

Most probably, loss in surface passivation quality under outdoor performance conditions (illumination, elevated temperature) will have an effect on a variety of solar cell architectures. But not too much published results can be found in that direction of research, although many new cell concepts are currently in development. Nevertheless, intense long-term stability testing under injection and elevated temperature should be done for all of these new concepts to clarify the underlying mechanisms and to avoid surprises.

4 SUMMARY

In this contribution, the state of knowledge for some prominent examples of degradation phenomena has been presented. The shown examples all have in common that they are triggered by typical operation conditions of solar modules (illumination, elevated temperature, realistic ambient conditions).

To understand some of the observed findings, the understanding of the underlying defect reactions is very helpful. The charge state of the species interacting during the degradation/regeneration reactions may change during injection, as it may depend on the position of E_{Fn} in the band gap. As H seems to be involved in some of the described phenomena, especially its change of charge state under operation conditions of the solar cell is key for understanding the underlying mechanisms.

BO-LID seems to be understood up to the degree that satisfying mitigation strategies exist (regeneration procedure on fired solar cells or use of Ga doping).

For PID of the shunt type an accepted model exists, based on drift of Na ions from the glass into extended defects in the space charge region. Here also mitigation strategies are available (on cell, module, and system level), although some of them might increase fabrication costs significantly.

The microscopic picture of the defect causing LeTID is unknown yet. It is only known that H triggers its occurrence. Therefore, mitigation strategies mainly deal with the H management and/or thermal treatments to go through the regeneration process. Most strategies cause extra costs. Therefore, a more detailed understanding would be very helpful to try to better control its occurrence.

Degradation of surface passivation due to injection at elevated temperature was observed during LeTID tests. Not much is known yet about its origin, but H seems to play an important role here, too. More research effort is needed to clarify its possible impact, especially for new cell architectures.

With solar cell efficiencies increasing due to improved c-Si wafer quality and new solar cell architectures with less losses at surfaces, contacts and highly doped regions, degradation effects gain more and more importance. Or in short: with higher efficiencies, there is more to lose.

5 ACKNOWLEDGEMENTS

Part of this work was funded by the German BMWi (0324204B, 03EE1051C, 03EE1052A). The content is the responsibility of the author.

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