

LIGHT INDUCED DEGRADATION OF SOLAR CELLS MADE FROM HIGH PERFORMANCE MULTI WAFERS

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ABSTRACT — High performance multi wafers are a new wafer class introduced some years ago. These wafers are characterized by creating rather small grains at the start of crystallization leading to a reduced density of structural defects and an increase of up to 0.5 % in solar cell efficiency. During the evaluation of high performance multi wafers, we observed for some wafer types very high light-induced degradation of up to 10 % relative in cell efficiency. More detailed investigations revealed that the affected wafers stem from the “bottom” part of the ingots with small grain size and the degraded cells show a “sponge-like” structure in electroluminescence images. The investigation of regeneration characteristic revealed that this degradation is not caused by formation of boron oxygen complexes or splitting of iron boron pairs. Although we could reduce this degradation mechanism by adapting the solar cell manufacturing process, avoiding this effect on wafer / crystallization level will be needed for future cell efficiency improvements.

Keywords: High Performance Multi-Crystalline Wafers, Light Induced Degradation,

1 INTRODUCTION

Approximately two years ago a new wafer type (high performance multi - HPM) was introduced into the solar market [1]. Nowadays almost all wafer suppliers offer HPM products. HPM wafers are produced in an adapted crystallization process, where the formation of small grains at the start of crystallization is induced due to a special seeding layer in the bottom of the ingot [2]. This process can be considered as the “opposite” to the mono-like-multi process, where it was attempted to grow very large grains, but strong problems appeared due to uncontrolled growth of defect rich areas in the ingot [3]. In the case of HPM, the large number of grain boundaries stops defect rich regions to grow in an uncontrolled manner and the overall defect density is reduced strongly leading to an efficiency increase of up to 0.5 % absolute. During the evaluation phase of different HPM qualities from different suppliers we observed in some cases a very high light-induced degradation (LID) of up to 10 % relative in cell efficiency. Not all HPM wafers were affected. Some suppliers could also reach high efficiencies while having no increased LID. In the following we will describe our measurement results and how we could solve this issue preliminary by using an adapted solar cell manufacturing process. However, this process adaption imposes certain limitations to the overall cell process that it will be necessary for future cell efficiency improvement to solve this problem on wafer or crystallization level.

2 SPONGE LID

2.1 Observation on cell level & distribution across ingot height

For the investigation we used standard industrial multicrystalline solar cells processed from HPM wafers. After measurement at the cell tester, the solar cells were illuminated for 24 hours at 25 °C and 1000 W/m². Fig. 1 shows the relative degradation of solar cells from same average cell efficiency class. The measured values differ strongly from approximately 9 % to values of < 1 %, like observed usually in the production of multicrystalline solar cells.

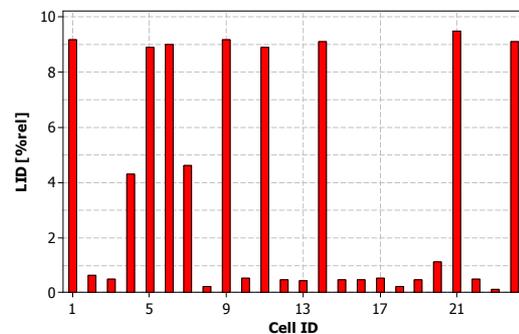


Figure 1:Light-induced degradation of 24 solar cells from one average cell efficiency class. Approximately 50 % of all solar cells show very high degradation values of up to 10 %.

These solar cells were investigated by electroluminescence (EL) or photoluminescence (PL) using a BTI PL/EL inspection system. The EL images are shown in Fig. 2. The cell with approximately 1 % LID (Fig. 2a) looks like a typical multicrystalline solar cell with only a few grains of high defect density. In contrast, the cell with very high LID of approximately 9 % (Fig. 2b) has a different appearance with a high proportion of areas exhibiting low EL intensity around the grain boundaries. Because this structure looks similar to a sponge, we named this new LID effect “sponge LID”. Fig. 3 shows an investigation of the LID for solar cells from different positions of an HPM ingot sorted by height. Obviously, the cells exhibiting sponge LID stem always from the lower third of the ingot.

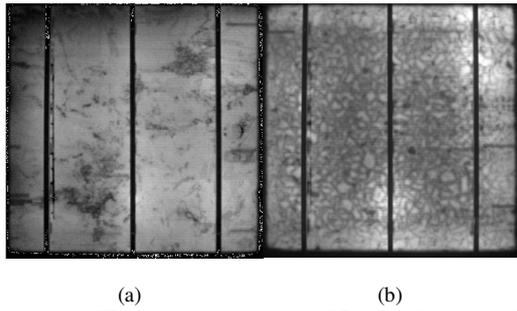


Figure 2: EL after degradation (25 °C / 24 h / 1000 W/m²) of two solar cells from Fig with (a) LID < 1 % and (b) LID ~ 9 % (“sponge LID”).

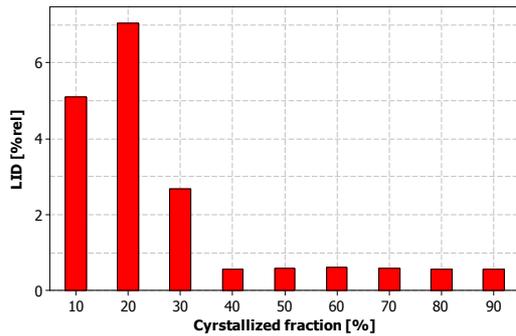


Figure 3: Distribution of LID (25 °C / 24 h / 1000 W/m²) dependent on crystallized fraction, respectively height of a HPM ingot. 0 % denotes the very bottom and 100 % the very top of the ingot.

2.2 Degradation during EL measurements

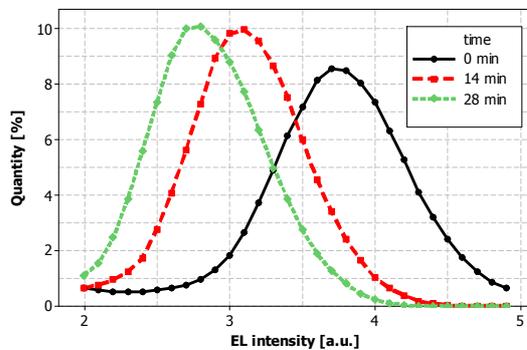


Figure 4: Histogram of EL intensity for degradation after time intervals of 0, 14 and 28 min. The degradation was triggered within the EL system by application of 9 A to the solar cell in forward direction.

We degraded solar cells exhibiting sponge-like LID by applying a current flow to the solar cell in the EL equipment. Fig. 4 shows the histogram of the EL intensity after application of 9 A in forward directions for successive time periods. We used the EL signal in arbitrary units without transforming it into carrier lifetimes. The EL signal is proportional to EL intensity and can be transferred into carrier lifetime [4]. It can be clearly seen that the whole distribution shifts strongly to lower values with increasing time. In addition to that, even the areas with high EL intensity i.e. high lifetime before degradation are degrading. The occurrence of degradation by current application clearly proves that the new sponge LID effect can be caused by carrier injection

in general and not only by illumination.

3 REDUCTION OF SPONGE LID BY ADAPTED CELL PROCESS

We developed a new cell process B, which reduces sponge LID for solar cells dramatically compared to the standard process A.

In Fig. 5 experimental data of sister and height sorted sponge LID sensitive material from the lower half of an ingot are presented. These wafers were grouped into 2 batches. One batch was processed with the standard process A while the other was processed with new process B. Remarkably, the degradation of ~6 % for process A could be reduced with the process B down to < 1 % over the complete ingot height.

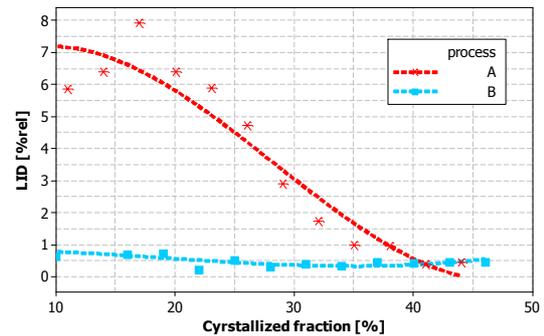


Figure 5: Relative LID (25 °C / 24 h / 1000 W/m²) dependent on ingot height for the standard cell process A and the new developed cell process B.

In Fig. 6 PL pictures of two sister cells after LID (25 °C / 24 h / 1000 W/m²) are presented. The 1st cell (Fig. 6a) is processed with the standard process A. The typically sponge LID dark grain boundaries are clearly visible and the cell efficiency is reduced by 8 % relative. The 2nd cell (Fig. 6b) is processed with the new developed process B. In contrast to Fig. 6a no dark grain boundaries in Fig. 6b are visible. This comparison shows, that the sponge-like structure in PL/EL images is indeed directly related to sponge LID.

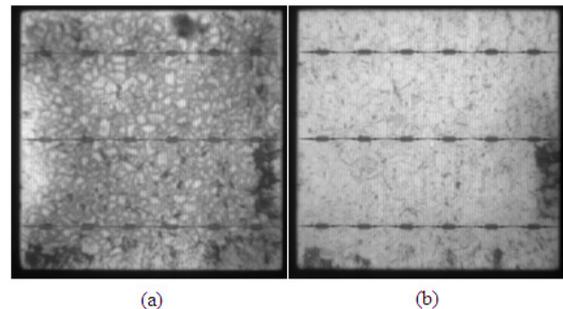


Figure 6: PL picture of sister wafers after degradation under illumination (25 °C / 24 h / 1000 W/m²). (a) Solar cell processed with the standard process A and (b) processed with the new developed process B.

4 DETERMINATION OF TIME CONSTANT

The time constant of defect formation is determined on cell level. Two sister bottom wafers (resistivity ~ 2 Ohm cm) were processed with cell process A (cell A) and B (cell B). The cells were degraded under a constant

illumination of 1000 W/m² at 25 °C. The electrical parameters were measured every 5 seconds for a time period longer than 24 hours.

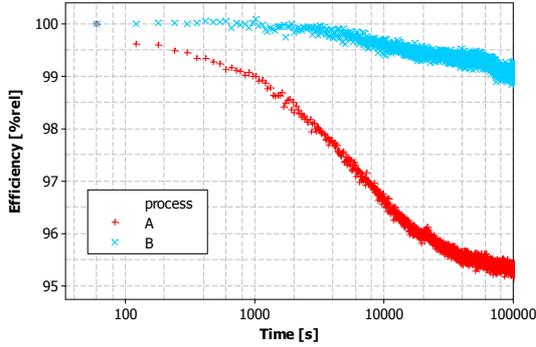


Figure 7: Measured relative efficiency (25 °C / 1000 W/m²) dependent on illumination time for the standard process A (cell A) and the newly developed process B (cell B).

In Fig. 7 the relative efficiencies dependent on illumination time are presented for cell A and B. For cell B the degradation is below 1 % relative even after long illumination time. In contrast cell A shows a much higher degradation for long and short times compared to cell B which is related to the sponge LID.

In Fig. 8 the relative Voc (Fig. 8a) and Isc (Fig. 8b) degradation versus illumination time are presented for both processes. In both cases the degradation is caused by a reduction of Voc and Isc in a ratio of roughly 1/3 to 2/3 respectively.

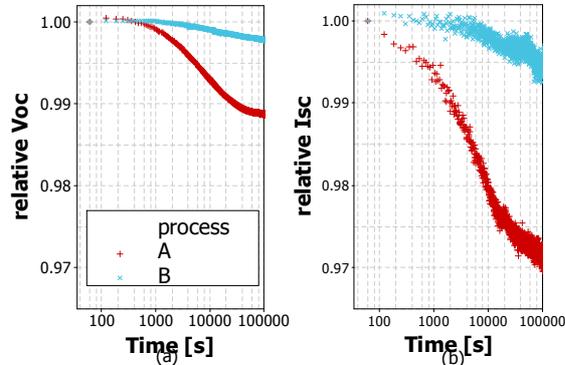


Figure 8: Measured relative Voc (a) and relative Isc (b) (25 °C / 1000 W/m²) dependent on illumination time for the standard process A (cell A) and the newly developed process B (cell B).

In order to determine the time constants of the LID, we used a model described by Bothe *et al.* in [5]. According to this model, the defect concentration $N(t)$ can be calculated by equation (1) from the measured Voc on cell level with the elementary charge q and Boltzmann constant k_B .

$$N(t) = \exp\left(-\frac{q V_{oc}(t)}{k_B T}\right) - \exp\left(-\frac{q V_{oc}(t=0)}{k_B T}\right) \quad (1)$$

The resulting graph can be fitted using equation (2) to determine the time constant of defect formation τ_{gen} .

$$N(t)_{fit} = 1 - \exp\left(-\frac{t}{\tau_{gen}}\right) \quad (2)$$

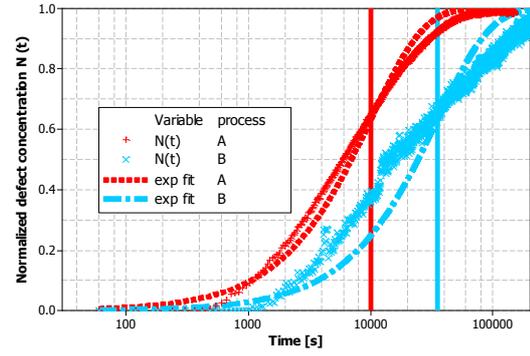


Figure 9: Normalized defect concentration $N(t)$ dependent on illumination time (25 °C / 1000 W/m²) for process A (cell A) and B (cell B). The dashed lines are the exponential fit functions according equation (2). The solid lines symbolize τ_{gen} for cell A (red) and cell B (blue).

In Fig. 9 the normalized defect concentration and the fit according to equation (2) are shown for cell A and B. Apparently, the agreement of the measured data and the fit is not very good, which is understandable, because probably more than one degradation mechanism is involved. Neglecting these deviations, we use this simple model to estimate the time constant by this fit for both cells. The results are given in Tab. 1.

The time constant τ_{gen} can be transformed into defect generation rate (R_{gen}) using equation (3).

$$R_{gen} \equiv 1/\tau_{gen} \quad (3)$$

Cell	τ_{gen} [s]	R_{gen} [1/s]
A	$\sim 1.0 \times 10^4$	$\sim 1.0 \times 10^{-4}$
B	$\sim 3.6 \times 10^4$	$\sim 2.9 \times 10^{-5}$

Table 1: Time constant τ_{gen} and defect generation rate R_{gen} for cell A and cell B extracted from the simple exponential model according equation (2) and (3).

5 COMPARISON WITH OTHER DEGRADATION EFFECTS

The distribution of LID versus the brick height (Fig. 3) can be seen as a first indication that sponge LID is not caused by the known degradation mechanisms due to formation of boron oxygen (BO) complexes or splitting of iron boron (FeB) pairs. The boron and oxygen concentration in a multicrystalline ingot change only slightly in the lower part of the ingot, so that a distribution with a sharp decrease of LID at ~30 % of ingot height cannot be explained by BO degradation.

Degradation due to FeB pairs is also unlikely, because the parts of the ingot with a high iron concentration are cut off before wafering of the bricks (based on carrier lifetime measurements).

If we compare the defect generation time constant from Tab. 1 of cell A to the time constant of the splitting of FeB pairs, which is in the order of < 100 s for 1 sun illumination [6], it is immediately clear that this degradation effect can be excluded as explanation of the observed sponge LID.

To compare with the formation of BO complexes, we

use the calculated generation rate and a graph taken from [5], which shows the defect generation rate versus doping density (Fig. 10). The measured data points (doping density $\sim 7 \times 10^{15} \text{ cm}^{-3}$) are shown for cell A (red star) and B (blue triangle). The R_{gen} for cell B is comparable to the slow BO process, so that the degradation of this cell is probably mainly caused by BO degradation. The R_{gen} for cell A is approximately one order of magnitude higher which is another evidence that sponge LID is not caused by formation of BO complexes.

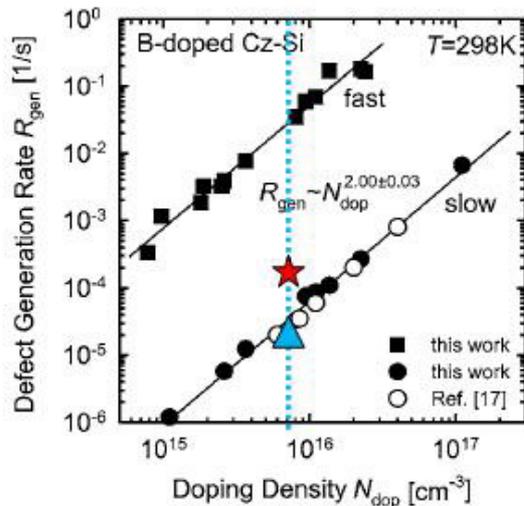


Figure 10: Defect generation rate dependent on doping density taken from [5]. Squares, filled and unfilled circles are data points from [5] for the slow and fast process during formation of BO complexes. Blue triangle is the R_{gen} for cell B and the red star is the R_{gen} for cell A from Tab. 1 from this study.

In order to verify this further, we tested the regeneration of the solar cell efficiency by storage in the dark [7] and heating to 200 °C for 30 min [8]. In contrast to degradation due to splitting of FeB pairs, no regeneration of the efficiency was observed after storage in the dark. Heating at 200 °C regenerated the solar cell only partly ($\sim 2/3$ of degradation remained), which is in contrast to the full recovery reports for BO degradation after this treatment.

In summary, it can be concluded, that all results so far indicate that sponge LID is a new degradation effect not related to either FeB splitting nor BO complex formation. A detailed comparison with other degradation mechanisms like Cu-related degradation [9] has not been carried out so far.

5 SUMMARY

A new degradation phenomenon, that we named “sponge LID”, was observed for some types of HPM wafers. Very high solar cell efficiency degradation of up to 10 % was observed depending on material supplier and ingot position. Solar cells affected by sponge LID reveal a sponge-like structure in PL pictures after degradation. The degradation affects the complete solar cell and can be induced by standard LID (25 °C / 24 h / 1000 W/m²) conditions or by carrier injection (e.g. an EL system).

The new degradation mechanism cannot be explained by the well-known BO degradation or splitting of FeB pairs, because the defect formation time constants, the

distribution in an ingot and the regeneration behaviour differ from what is known for BO or FeB.

We developed successfully a process to reduce sponge LID dramatically. However, the adaption of our new process leads to reduced degrees of freedom in cell processing which strongly requests for an elimination of sponge LID already on wafer level. Nevertheless, more detailed studies are necessary to understand the new effect more clearly and prevent the effect from material site permanently.

ACKNOWLEDGEMENT

This work was partly supported within the Spitzencluster-Solarvalley project by the German Federal Ministry of Research and Technology (BMBF) under contract 03SF0452 (xμ-Clip).

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