Light beam induced current of light-induced degradation in high-performance multicrystalline Al-BSF cells

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Abstract

Multicrystalline silicon solar cells are plagued by different types of light-induced degradation (LID), including Sponge-LID. Sponge-LID decreases the Al-BSF cell efficiency by up to 10 \%rel. and is only partially recoverable at 200°C. This contribution shows that Sponge-LID occurs at and near most grain boundaries, but only in the centre of the affected cell. Furthermore, Sponge-LID is not the only type of LID in the silicon bulk. High-resolution Light Beam Induced Current mapping reveals local internal quantum efficiency losses of up to 8 \%rel. at dislocation clusters and small angle grain boundaries, which recover (nearly) fully at 200°C. Nevertheless, this dislocation-related LID appears to reduce the Al-BSF efficiency by less than 1 \%rel.

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1. Introduction

In addition to boron-oxygen LID (BO-LID), industrial high-performance multicrystalline (hpmc) silicon solar cells can suffer from light- and elevated temperature-induced degradation (LeTID) \cite{1,2} or Sponge-LID \cite{3,4}. LeTID forms in Al-BSF and PERC cells as homogenous grain degradation \cite{5,6}, which worsens with increasing...
temperature and/or injection level [1,2]. Sponge-LID is a non-uniform type of bulk LID [4] in Al-BSF cells from the lowest third of the ingot, which appear strongest (up to 10 %rel.) near the grain boundaries [3,4]. Increasing the intensity or temperature makes Sponge-LID form faster, but no increase is observed in the defect density [4]. The 200°C anneal that reverses BO-LID has been shown to recover only some two thirds of Sponge-LID [3]. The involvement of interstitial iron has been excluded, as Sponge-LID occurs over days of illumination and does not change after dark storage [3].

Previously, Sponge-LID has been characterized with fast but low-resolution photo- (PL) or electroluminescence (EL) [3], and medium-resolution Light Beam Induced Current (LBIC) [4]. Nevertheless, the non-uniform distribution of Sponge-LID requires analysis at higher spatial resolutions, in order to identify the responsible defect. As the short-circuit current ($I_{SC}$) is very sensitive to Sponge-LID [4], this contribution presents internal quantum efficiency (IQE) maps measured down to 12.5-µm spatial resolution. After illumination and 200°C recovery annealing, we conclude that Sponge-LID is not the only non-uniform LID effect in the hpmc-Si Al-BSF cells.

2. Experimental details

Boron-doped wafers from the bottom (~5 cm height) and the middle (~10 cm height) of two hpmc-Si ingots were processed into two different types of Al-BSF cells at Hanhwa Q Cells GmbH. The bottom cell subjected to process A was expected to suffer from Sponge-LID, while process B had been shown to eliminate the effect [3]. The IQE was mapped with LBIC at spatial resolutions of 12.5, 50, and 250 µm. The spatial resolution refers to the step size and the matching beam width. At the incident wavelength of 826 nm, the IQE is dominated by the bulk minority carrier recombination lifetime but also affected by back-surface recombination. The laser power was kept at 1.7 µW to induce low injection ($10^{12}-10^{13}$ cm$^{-3}$) [7]. The cells were illuminated by a 1-sun halogen lamp for up to 110.5 h at 40±5°C, and dark annealed at 210±10°C for 2 min. Before each LBIC measurement, the cells were stored overnight in the dark to allow the formation of FeB. At each step, the I-V response was measured independently at standard testing conditions.

Next, the cells were laser cut into samples of 25 mm x 25 mm, and subjected to grinding and polishing. The samples were then Secco etched for 1 min, after which the surface grain structure was imaged automatically by an optical OLYMPUS microscope at 20x magnification. After manual removal of scratches, surface contamination spots, and grain boundaries from the images, ImageJ was used to extract properties of the etch pits. Finally, the etch pit density map was calculated averaging over a radius equal to the assumed average diffusion length of 645 µm, using a modified Bessel function as weighting function [8].

3. Results and discussion

3.1. Sponge-LID

Figures 1a and b show the IQE maps before and after 99h 33 min of illumination of the bottom Al-BSF cell from process A, which is expected to suffer from Sponge-LID, while process B had been shown to eliminate the effect [3]. Figure 1d depicts an average IQE decrease of 3.4 %rel., with local IQE losses of up to 15 %rel. I-V measurements after dark storage (Degraded) in Fig. 2a confirm an $J_{SC}$ loss of 2.1 %rel. and an open-circuit voltage ($V_{OC}$) decrease of 0.6 %rel., respectively. After dark annealing, Fig. 1c shows partial IQE recovery next to the grain boundaries, but interestingly Fig. 1e reveals that particular areas of the cell recover fully.

In order to better characterize Sponge-LID and determine why certain areas recover fully, the IQE changes in region 1 are displayed at high resolution in Figs. 3a-c. Figure 3d depicts the grain structure of region 2 on top of map 3a, and Fig. 3f shows the grain structure on top of the calculated etch pit density map. Together the images reveal that the fully recoverable area A1 contains grains with high dislocation densities and several small-angle grain boundaries (SAGBs), formed by dislocations. Inside A1, the highest IQE losses of up to 8 %rel. occur at some of the dislocation clusters and SAGBs in Fig. 3d and f. Full recovery at 200°C is usually associated with boron-oxygen LID. However, the homogenous distribution of boron and impurity oxygen cannot explain the non-uniform LID observed at dislocation clusters and SAGBs. Since this recoverable non-uniform LID has also been measured with
LBIC in other mc Al-BSF cells [9], we refer to it as dislocation-related LID.

Fig. 1. IQE maps of the bottom A cell (at 250 µm resolution) (a) before illumination; (b) after 99 h 33 min of illumination; and (c) after dark annealing. Relative IQE changes comparing maps (d) after and before illumination; (e) after annealing and illumination; and (f) after annealing and before illumination.

Fig. 2. Relative change of the (a) short-circuit current density $J_{SC}$; and (b) the open-circuit voltage $V_{OC}$ measured immediately after 1 h, 1 day, and > 99 h of illumination (illum.), and measured later after dark storage (degraded), followed by annealing and dark storage (annealed).
Fig. 3. Relative IQE changes in region 1 comparing 12.5-µm maps (a)-(c) before illumination, after 99h 33 min of illumination, and after annealing. The grain structure of region 2 is shown on top of (d) the “Degraded/Initial” map; and (f) the etch pit density map. IQE linescans (f) L1; and (g) L2 show Sponge-LID at and around the centre of different grain boundaries (GB) in region 1.

Since the local Sponge-LID detected near most grain boundaries recovers only by about one third in Fig. 1f and
3c, the bottom cell from process A appears to suffer from two types of LID: 1) Sponge-LID around most grain boundaries, and 2) dislocation-related LID at some dislocation clusters and SAGBs. The quotient maps “Degraded/Initial” in Figs. 1d and 3a make it difficult to distinguish between these two LID types, since both cause severe non-uniform IQE losses. Nevertheless, the quotient maps “Annealed/Degraded” in Figs. 1e and 3b reveal the cell areas with dislocation-related LID, without the need for dislocation density analysis. Correspondingly, the quotient maps “Annealed/Initial” in Figs. 1f and 3c show the areas still affected by Sponge-LID, after partial recovery annealing.

Figure 1f suggests that Sponge-LID forms only in the centre of the cell, which cannot be explained by non-uniform illumination or temperature conditions during degradation [4]. Mid-resolution maps in Fig. 4 show that Sponge-LID weakens towards the edge of the solar cell, disappearing completely in the edge grains. Dislocation-related LID is still detected at the cell edge, confirming that it is a second type of LID in the bottom cell A. Figures 4a-c show the strongest LID (up to 15 %rel.) in a narrow vertical stripe in the lower right corner. By examining the back contacts, we note that the degraded stripe forms in the narrow area, where Al is pasted on top of an Ag back-contact pad. Such strongly degraded stripes are observed at every Al-Ag contact in the centre of the cell. Nevertheless, no stripe is seen in Figs. 4d-f near the cell edge, where Sponge-LID has become weaker. There is no clear reason for why the Al-Ag contact would impact bulk LID, which means that it could be a measurement artefact. However, its disappearance towards the cell edge suggests a connection to Sponge-LID.

![Fig. 4. Relative IQE changes in 50-µm maps of (a)-(c) region 3 in the centre of bottom cell A; and (d)-(f) region 4 at the left cell edge. The regions are marked in Fig. 1a. Region 3 also contains regions 1 and 2 from Fig. 3.](image-url)

Now that recovery annealing has been applied to distinguish the areas with Sponge-LID from those with...
dislocation-related LID, the properties of Sponge-LID can be studied in more detail. Figures 3e and g displays two IQE linescans over different Sponge-LID areas, the position of which are indicated in Figs. 3b and c. The linescans show that the centres of all three grain boundaries degrade by up to 4 %rel. and recover by up to 2 %rel. Sponge-LID increases when moving away from the grain boundary and is at its strongest (up to 10%rel) at a distance of 0.5-2 mm from the BG centre, regardless of the type of grain boundary. Sponge-LID then decreases towards the middle of the grain and disappears completely inside some of the larger grains. Sponge-LID is not constant along the grain boundaries nor symmetrical around the GBs. Although neither the grain boundary analysis in Fig. 3d or the etch pit map in Fig. 3f offer an explanation for the irregular Sponge-LID, Fig. 3d shows that the areas free of Sponge-LID often consist of several small twinned grains, as in the case of area A2. However, areas A3 and A4 display that Sponge-LID can also spread over $\Sigma^3$ grain boundaries and into twinned grains.

3.2. Sponge-LID prevention

Sponge-LID reportedly disappears when moving upwards in the mc-Si ingot [3], but some lower level $I_{SC}$ and $V_{OC}$ loss is still detected in the middle cell A in Figure 2. The IQE quotient maps in Fig. 5a-c show that the average IQE loss of 1.3 %rel. is caused by non-uniform areas of local IQE degradation of up to 8 %rel., which recover fully. The high-resolution maps in Fig. 5d-f indicate that the strongest degradation is formed at small-angle grain boundaries that

![Image of IQE changes](https://example.com/image.png)

Fig. 5. Relative IQE changes in (a)-(c) the middle cell from process A at 250-µm resolution; and (d)-(f) region 5 at 12.5-µm resolution. The cell was illuminated for 99 h 33 min.

are initially nearly free of recombination. Therefore, even though the middle cell A is free of Sponge-LID, it appears
to suffer from dislocation-related LID. The LID areas are larger than in the bottom cell A, as the number of dislocations and SAGBs is expected to increase towards the middle of the ingot, even in hpmc-Si [10].

Sponge-LID can be prevented in the bottom cells by modifying the Al-BSF process [3]. Process B leads to a significantly lower $j$ decrease of 0.7 %rel. and $V_{OC}$ degradation of 0.3 %rel., respectively, compared with the bottom cell A. Figure 6 presents the quotient maps of the bottom cell B, which link the average IQE loss of 1.0 %rel. to dislocation-related LID. Local IQE losses of up to 8 %rel. are again measured at SAGBs, indicating that while process B prevents Sponge-LID formation, it has little effect on dislocation-related LID. When moving upwards in ingot B, the areas with dislocation-related LID become larger (not shown) similar to ingot A, explaining the increased $J_{SC}$ loss in the middle cell B in Fig. 2a. In all three cells that are free of Sponge-LID, no LID stripe is seen under the Al-Ag contact, supporting the conclusion that the strongly degraded stripe is linked to Sponge-LID.

Unlike previous electroluminescence (EL) and photoluminescence (PL) studies [3,4], LBIC mapping shows no homogenous LID in the cells without Sponge-LID. Correspondingly, the dislocation-related LID is barely detectable with EL or PL. These discrepancies are most likely caused by the large difference in the injection level, but they incite the need for further characterization, in order to confirm whether dislocation-related LID dominates LID in mc Al-BSF cells (without Sponge-LID).

![Fig. 6. Relative IQE changes in (a)-(c) the bottom cell from process B at 250-µm resolution; and (d)-(f) region 5 at 12.5-µm resolution. The cell was illuminated for 99 h 33 min.](image-url)
4. Conclusions

High-resolution LBIC mapping reveals two types of LID in the mc Al-BSF cell from the bottom of ingot A: Sponge-LID and dislocation-related LID. Annealing at 200°C separates the two effects, revealing that Sponge-LID only forms in the centre of the cell as 0-4 %rel. IQE loss at most grain boundaries and as strong (≤10 %rel.) asymmetrical IQE loss next to them. Areas resistant to Sponge-LID often contain clustered twin grains. Dislocation-related LID is observed as local IQE degradation of up to 8 %rel. at dislocation clusters and small-angle grain boundaries over the whole cell. Even though the modified Al-BSF process B removes Sponge-LID, dislocation-related LID remains both in the bottom and the middle of the ingot. Nevertheless, dislocation-related LID appears to be responsible for less than a 1 %rel. decrease in the cell efficiency, which explains the lack of previous high-resolution characterization of LID in mc Al-BSF cells.

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References