PHYSICAL MECHANISMS OF BREAKDOWN IN MULTICRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT: For the construction of solar modules, the reverse characteristic of the employed solar cells is important. Diode breakdown in shaded cells can lead to hot spot development which can destroy the cell encapsulation and thus seriously damage the module. We investigated the breakdown behaviour of multicrystalline silicon solar cells. Three breakdown types are discerned: (i) Early pre-breakdown, (ii) soft breakdown related to recombination-active regions and (iii) hard avalanche breakdown at etched dislocations. We give a summary of their physical properties and their likely origin. Finally, we discuss the dangerousness of each breakdown type for solar modules.
Keywords: Multicrystalline Silicon, Diode breakdown, Impurities

1 INTRODUCTION

In solar cell research, primarily the global *I-V* curves in forward bias are used for the qualification of solar cell parameters like efficiency, shunting behaviour, contacting problems etc. However, the *I-V* characteristic in reverse bias becomes important when the solar cell is operated in a module. The local reverse current – which can occur when one solar cell in a string is shaded and thus reversely biased – leads to heat development. So-called "hot spots", sites with excessive heating, can damage the sensitive cell encapsulation and thus result in the destruction of the module. There are generally two possibilities for hot spot development. Firstly, a local shunt resulting e.g. from imperfect laser edge isolation or from microcracks induced during the module string fabrication can conduct the reverse current. Secondly, diode breakdown at localized spots can occur at lower voltages than are expected from theory (at typical base and emitter resistivities, silicon should show avalanche breakdown in the order of $|V_B| > 50$ V).

Therefore, an understanding of the processes leading to local pre-breakdown in multicrystalline silicon solar cells is necessary. Especially in the light of recent developments, the performance of low quality silicon with respect to its use in solar modules needs to be evaluated. V. Hoffmann et al. [1] reported that industrial solar cells made of silicon feedstock fabricated in the upgraded metallurgical grade (UMG) route showed a cell efficiency comparable to reference solar cells, but their reverse characteristics were inferior. This necessitated an adaption of the module design which results in increased module costs.

In this contribution, we first review that in an industrial multicrystalline silicon solar cell, several different pre-breakdown mechanisms are present. Some of them are process-induced while others are related to the material quality. The breakdown is always localized within micrometer-sized spots, having the potential to develop high local power densities when the reverse current increases. However, the breakdown types behave very differently with increasing reverse bias. Therefore, in this work we evaluate the dangerousness of each breakdown type.

2 EXPERIMENTAL

Spatially resolved data on the pre-breakdown is accessible via several complementary techniques making use of different physical properties of breakdown sites. It has been long known that silicon p-n junctions in avalanche breakdown as well as in internal field emission (tunneling) emit light in the visible range [2, 3] within micrometer-sized spots. This radiation can be detected by a simple silicon CCD camera often used in electro- and photoluminescence (EL/PL) setups, or alternatively by spectrometers working in the visible spectral range. The heat resulting from the current which flows through the pre-breakdown sites can be measured with the help of Dark Lock-in Thermography (DLIT) which is widely used for the imaging of shunts.

While the breakdown light emission yields information about the exact position of the breakdown sites, the DLIT measurements cover the relevant measurand for solar cells in a module – the heat. In addition, via a combination of DLIT images taken at different temperatures, a local temperature coefficient (TC) can be defined giving information about the breakdown mechanism (avalanche or tunneling). For details, refer to [4].

On the microscopic level, we employed an EL-/PL-mapping technique using a confocal optical microscope. The sample can be illuminated by laser or connected to a voltage generator. The luminescence or the breakdown light are coupled into a glass fibre which is then detected in an IR or a UV/VIS spectrometer, respectively, which makes it possible to correlate breakdown with the local recombination activity. Lock-in Electron Beam Induced Current (Lock-in EBIC) and transmission electron microscopy (TEM) investigations were used to analyze the influence of the surface morphology on pre-breakdown. Synchrotron-based micro X-ray fluorescence (µ-XRF) was employed to detect metal precipitates within some ten micrometers below the wafer surface. The µ-XRF measurements were performed at the European Synchrotron Radiation Facility (ESRF) at beamline ID22ni.

3 RESULTS

Figure 1 shows an example of reverse bias-dependent EL measurements on a mc-Si standard industrial solar cell. It was processed of a wafer from high-purity solar grade feedstock. During the solar cell process, a wet chemical acidic surface texturization was used. On this solar cell (as well as on most other solar cells under investigation), we identified at least three different stages of pre-breakdown [5, 6] characterized by the voltage of breakdown onset, the bias-dependent EL and DLIT intensity and their local TC. In the following, the three types are analyzed in more detail.

(a)

(b)

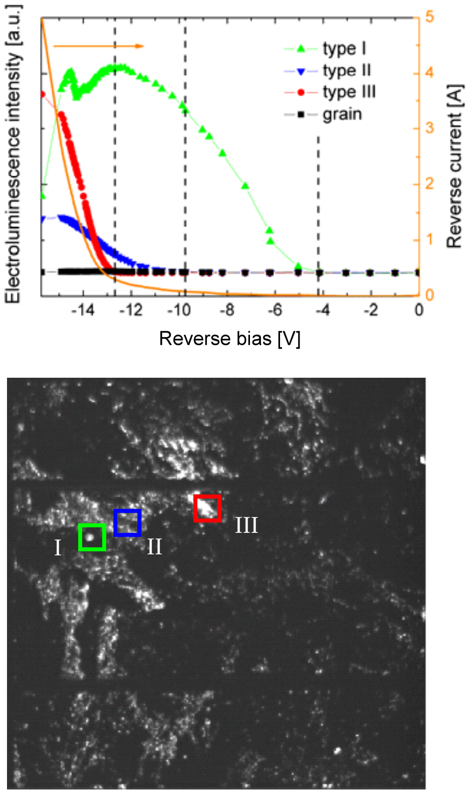

Figure 1: Local reverse-bias EL intensities (a) of selected regions indicated in the reverse bias EL image taken at -14 V of a standard industrial mc-Si solar cell (b). The orange continuous line in graph (a) marks the global IV characteristic of the solar cell.

3.1 Early pre-breakdown (type I)

With increasing reverse bias, the first pre-breakdown spots start to appear at reverse bias voltages as low as -4 to -5 V. Their luminescence grows brighter very quickly while the DLIT intensity remains moderate. The breakdown sites are mainly found at the edge of the solar cell or close to grid fingers of the front contacts. The vicinity to surface structures related to the cell processing indicates in our opinion that this breakdown type is process-induced.

The temperature coefficient varies: breakdown sites located on the wafer surface show a negative TC (avalanche breakdown) while the coefficient of edge breakdown is positive, which may imply that two different breakdown mechanisms are at work [7]. The spectrum emitted in type I breakdown sites is broadly distributed around a central wavelength of approx. 700 nm. Interestingly, it is very similar to the spectral distribution of breakdown sites of type II (see Figure 3), although we found no correlation with the silicon material properties like crystal defects.

Up to now, the reason for this type of pre-breakdown has not been identified.

3.2 Soft pre-breakdown related to recombination active defects (type II)

By comparing areas of recombination-active defects, which appear as dark clusters in forward bias EL images, with the location of pre-breakdown light emitting regions, a strong correlation is found. If one looks a little closer, two kinds of recombination activity-related breakdown can be discerned. One kind emits bright light at increased reverse bias (compare e.g. Figure 1(b), region labelled with II). The other, although found in very dark areas in forward EL images, shows only weak breakdown radiation. Interestingly, we observed that in these regions, the dislocation luminescence intensity is increased [8] while in the bright breakdown areas, only weak dislocation luminescence is measured.

The generally good spatial correlation between recombination activity and type II breakdown light emission suggests that the same material property causes both solar cell properties.

It is widely accepted that crystallographic defects, e.g. dislocations and grain boundaries, are often decorated with impurity atoms like e.g. transition metals [9]. The coincidence of crystallographic defect-induced band distortions and deep band gap levels of impurity atoms accounts for the high recombination activity of dislocations and grain boundaries which can be seen by the dark contrast in EL measurements.

Regarding the pre-breakdown behaviour, early work has already shown that dislocations crossing a simple monocrystalline silicon p-n junction already lead to pre-breakdown [10]. However, the authors did not mention any measurements concerning the recombination activity of these dislocations. The effect of metal impurities in silicon diodes was studied by a number of authors (see e.g. [11, 12]). They suspected that metal precipitates cause soft diode breakdown behaviour.

In order to shed more light on the influence of metals on the breakdown in mc-Si solar cells, we investigated the correlation between recombination activity and the soft pre-breakdown in more detail keeping in mind that this piece of information is of special importance for the use of solar grade silicon with higher impurity concentrations in solar cell production.
Five mc-Si blocks were cast with high purity solar grade feedstock to which different transition metals were added: (i) 40 ppmw Ni, (ii) 40 ppmw Cr, (iii), 200 ppmw Fe, (iv) 40 ppmw Ni + 40 ppmw Cr + 200 ppmw Fe, and (v) a reference block without contamination. It was verified with the help of NAA measurements that the intentionally added impurities were present as expected and that segregation towards the top of the blocks took place. Wafers were taken from different block heights and processed in one run to industrial acidically texture etched solar cells. Their breakdown behaviour was characterized with the help of bias-dependent EL measurements. On each of these solar cells, only a small number of type I breakdown spots were present. The EL measurements were carried out until a reverse current of -2 A in order to avoid solar cell destruction. In this

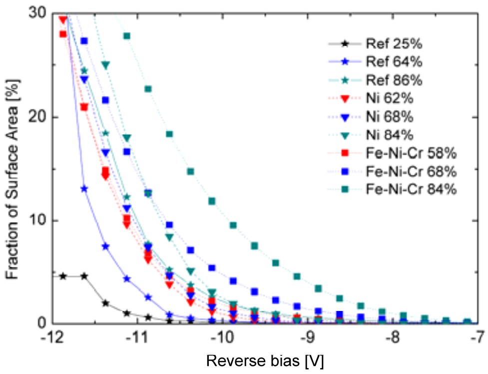

Figure 2: Bias-dependent fraction of the surface area which shows breakdown light emission of a selection of solar cells. The percentage denotes the distance of the solar cell to the bottom of the ingot (0%=bottom, 100%= top of the ingot).

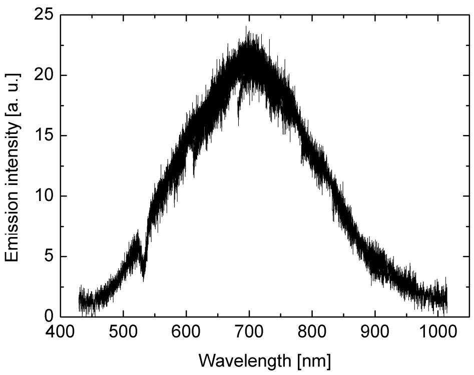

Figure 3: Spectral distribution of the breakdown light emission measured at one site of type II.

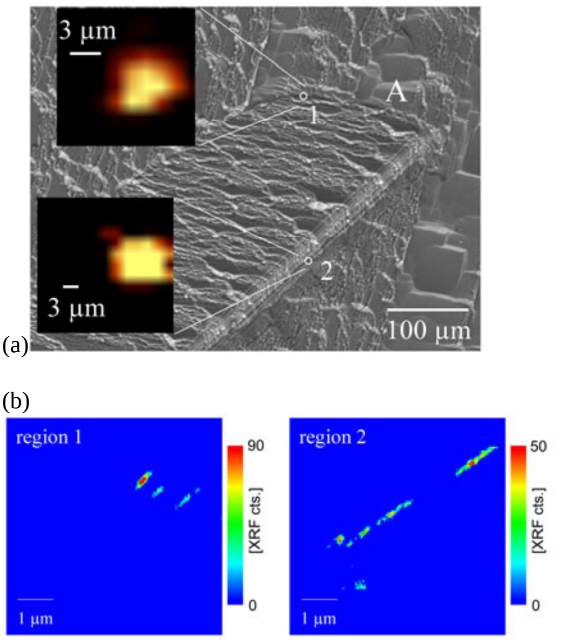

Figure 4: (a) SEM image of the grain at which two type II breakdown sites were found (light emission shown in the insets) and (b) µ-XRF measurements of the Fe Kα-line at the emission regions 1 and 2.

current-voltage range, no breakdown of type III was observed.

For a selection of these solar cells, Figure 2 shows the fraction of the surface area which emits light versus the reverse bias. For more detailed information about this analysis, refer to [6]. A clear correlation between impurity level of the wafer and the voltage at which pre-breakdown sets on is observed. While in the reference solar cells, the soft break down starts around -10 V or higher, light emission of highly contaminated Fe-Ni-Cr solar cells already starts between -8 to -9 V. The same tendencies are found from bottom to top of each ingot which can result from the impurity segregation during crystallization.

This clearly indicates, that in mc-Si not only the presence of grain boundaries and dislocations by themselves induces pre-breakdown but especially the decoration of these defects influences the breakdown behaviour strongly. In our investigation we found that the specific impurity element is not of importance but only the impurity concentration. Metal containing precipitates are thus likely candidates as the origin of local breakdown irrespective of the specific metal element investigated.

In order to substantiate this perception further investigations were carried out with the help of a PL-/EL-mapping tool with high spatial resolution. This time a damage etched standard industrial solar cell from the bottom of a mc ingot made from solar grade feedstock was investigated. The breakdown light of type II is generally emitted within a spot of 3 to 5 µm in diameter and shows a continuous spectrum in the visible range, peaking at around 700 nm [6], see Figure 3. At the same position, we measured reduced photoluminescence, indicating that breakdown sites coincide within sub-micrometer precision with recombination-active defects. On the same solar cell, micro-XRF measurements were performed at two soft breakdown sites found within two grain boundaries [13] shown in Figure 4. Iron precipitate colonies were detected at the position of both breakdown spots. Utmost care was taken to exactly transfer position information between the different measurements. Further µ-XRF measurements along the grain boundary (labelled with A) revealed no other metal clusters. The one to one concurrence of the precipitates and breakdown gives strong evidence that metal clusters in or close to the p-n junction induce variations in the space charge region which causes pre-breakdown which now experimentally confirms earlier conjections [11, 12].

TC-DLIT measurements in soft breakdown regions reveal a temperature coefficient which is zero or slightly negative. This means that the breakdown mechanism probably involves avalanche multiplication, although the mechanism is not a mere classical avalanche breakdown. One possible explanation may be the superposition of the electric field in the space charge region with the field generated around precipitates due to the Schottky contact between the silicon matrix and the metal silicide. Another possibility are trap-assisted tunneling or avalanche mechanisms [7].

2.3 Hard pre-breakdown at etch pits (type III)

The third type of pre-breakdown is the last to set on at reverse bias around -13 V. Above this reverse voltage, it governs the global *I-V* curve (see Figure 1 (a)). Therefore, most of the reverse current is then transported across type III breakdown regions. This leads to a large heat development, which can be seen in the DLIT image in Figure 5. In these regions, the local TC is strongly

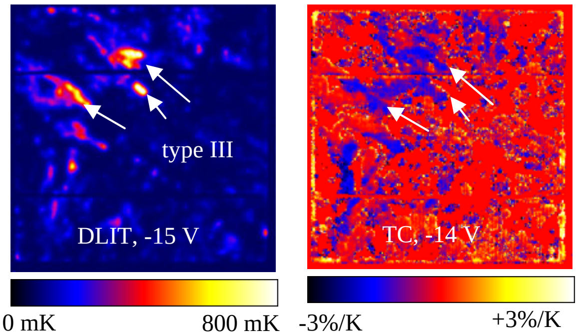

Figure 5: In the regions of high DLIT intensity (left) at high reverse bias, a strongly negative TC (right) is found, indicating avalanche breakdown.

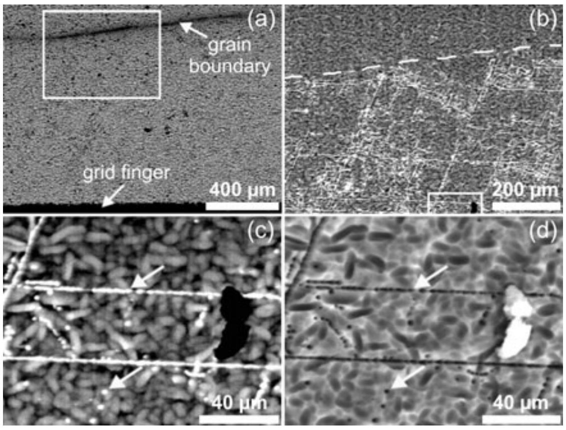

Figure 6: Lock-in EBIC image at 0 V (a) and at -15 V (b) at low magnification, showing breakdown spots in bright color. Second row: Close up of the region marked by the white rectangle in image (a). Lock-in EBIC image at -15 V (c) and corresponding SE image (d) at higher magnification, showing that breakdown occurs in deep surface pits.

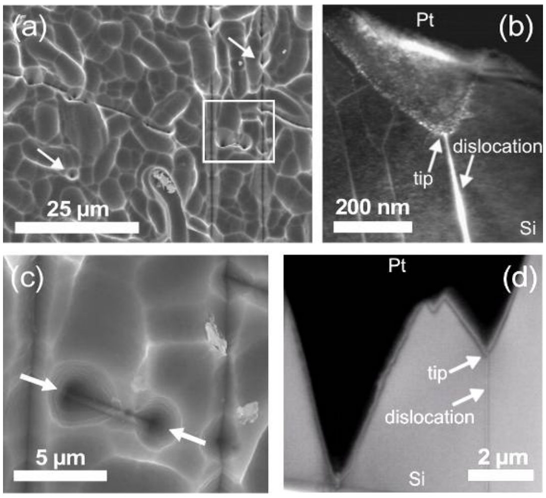

Figure 7: SE images (a, c) and TEM images (b, d) of etch pits where avalanche breakdown appears [14]. Image (d) shows the longitudinal cut of the region marked by the arrows in image (c).

negative (Figure 5, right) which clearly indicates avalanche breakdown.

Investigations with SEM/TEM and Lock-In EBIC revealed deep pits in the wafer surface (see Figure 6 and Figure 7). Dislocations at the bottom of the pits can be discerned in the TEM images. We therefore infer that during the acidic texturization, certain dislocations or other defects are selectively etched. In the following phosphorous diffusion, the emitter is forced to follow closely the wafer surface. Thus, at the bowl-shaped bottom of the etch pits, a very narrow junction radius evolves which induces a strong electric field due to the electrostatic field tip effect. The enhanced electric field in turn is responsible for early avalanche breakdown [14].

4 DISCUSSION AND CONCLUSION

Hot spots usually occur only when a high reverse current is localized within a small spot. Then, the local power density can become large enough to develop a significant amount of heat which may destroy the cell encapsulation.

While in general, soft (type II) and hard (type III) breakdown are detected in clusters dispersed over the entire cell area, early pre-breakdown (type I) demonstrates highly localized light emission and heat development, making it potentially dangerous for solar modules. It is likely to occur in every module because it sets on at very low reverse bias which means that only a few solar cells within a string are needed to generate the necessary breakdown voltage. According to our DLIT measurements, however, the heat which is developed within the breakdown spots remains relatively low in the voltage range up to -15 V and therefore it is likely to be harmless.

We presented clear indications that the soft pre-breakdown (type II), which is related to recombination-active defects, is caused by metal clusters in or close to the space charge region. The local as well as the global breakdown voltage of this type depends strongly on the impurity concentration in the wafer. This indicates that the inferior diode breakdown behaviour observed in UMG silicon [1] can be attributed to the increased metal contamination level. However, it is still possible that the breakdown behaviour is additionally governed by the significantly higher B- and P-doping level in this material and the resulting different base resistance and subsequently differing solar cell parameters like the V_{OC}. This matter still calls for clarification. A conclusion of high practical relevance from our work is, that the soft reverse characteristic and the appearance of the soft pre-breakdown sites over a large part of the cell area can easily account for the increased global reverse current of contaminated silicon. Yet the local heat generation due to this breakdown type stays most likely below the critical limit within the voltage-current range produced in a standard module since the reverse current does not flow through highly localized spots, but is strongly distributed. Whether this is true for the soft breakdown of every solar cell can only be decided when more data has been gathered with different feedstock materials. Until then, cells rejected on the basis of a high global reverse current may be qualified as uncritical on the basis of additional images of breakdown site distribution.

Avalanche breakdown (type III) shows a hard *I-V* characteristic which soon governs the global *I-V* curve. DLIT measurements show that this pre-breakdown type leads to large heat development within a small voltage range. In addition, the etched defects are often found in clusters. At their centers, high temperatures can occur because lateral heat transport due to the temperature gradient basically takes place only at the edges of the clusters. If the solar cells in a string are able to generate the necessary high reverse voltage, this breakdown type appears to be the most dangerous.

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