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Differences in reverse bias voltage behavior of n-type and p-type multicrystalline solar cells

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Abstract

The use of n-type, instead of p-type, silicon wafers for the production of mc-Si solar cells has a clear effect on the pre-breakdown behavior under reverse bias conditions. In p-type solar cells, material related breakdown patterns that are commonly observed in luminescence and thermography images. These patterns do not appear in the investigated n-type mc-Si solar cells, at least not down to a reverse bias of -16V. To the best of our knowledge, this difference between p-type and n-type mc-Si solar cells has not yet been described in literature before and could provide important information for the understanding of this type of wafer related breakdown.

Keywords: breakdown; electroluminescence; thermography; n-type; multicrystalline; silicon solar cells

1. Introduction

When a cell is shadowed or broken in a module, it becomes reverse biased by the other cells in the string. At reverse bias voltages below -10 Volt, p-type mc-Si solar cells can display breakdown patterns, that consist of many microscopic breakdown spots through which a local leakage current flows. If the leakage current through one of these spots is very large, the dissipated power can lead to a local heat-up, a ‘hot spot’, that can damage and even destroy the module [1]. One type of breakdown is spatially correlated with crystal defects, like dislocations or grain boundaries [2], [3] and the pattern of spots where it occurs shows a clear overlap with the non-radiative recombination pattern of reduced luminescence areas in forward biased electroluminescence (EL) images.

So far, most breakdown studies have focused on p-type mc-Si solar cells and much less is known on the reverse bias behavior of n-type mc-Si solar cells. Monocrystalline n-type silicon wafers have an

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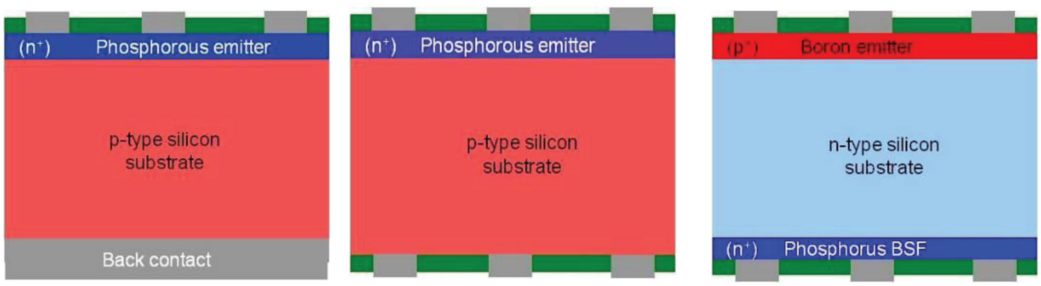
advantage over p-type doped wafers due to the higher achievable bulk lifetime [4], and are therefore used in high efficiency cell concepts [5], [6]. For multicrystalline wafers the difference in bulk lifetime between p-type and n-type is less prominent [7]. However, in this paper it will be demonstrated that n-type mc-Si solar cells can have some significant advantages over p-type mc-Si solar cells in a module, based on their pre-breakdown behavior.

2. Experimental details

The cell processing schemes of the cells in this paper are not identical, since the cells were selected from different experiments that have been performed in our lab over the past years. In particular, the processes used for the mc-Si n-type cells, are not representative for the 2012 state-of-the-art, but the conclusion is independent of the applied cell process, emphasizing its universality. All p-type cells have got a diffused P-emitter contacted by a screenprinted Ag grid and a fired Al-BSF contacted by screenprinted Al-paste. All n-type cells have got a diffused B-emitter and P-BSF and screenprinted Ag/Al and Ag at the front and rear side of the cell, respectively. Surface passivation and antireflection was in all cases achieved by deposition of a SiN_x coating by PECVD. In total 23 n-type and 15 p-type solar cells made with different processing schemes and wafers from different suppliers were investigated.



a) b) c)

Fig. 1. Schematic representation of the cell types used in this study. The green layer represents a (SiOx)/SiNx passivation layer and antireflection coating. a) p-type cell with Al rear contact. b) p-type cell with passivated open rear side. c) n-type cell with diffused B emitter and P-BSF and passivated open rear side

The electroluminescence (EL) images were taken with a VIS-IR camera in the range of 280 to 1100 nm. The two busbars at the front side of the cell were contacted by two multi-pin probes, the rear side was contacted by placing the cell on a brass chuck. Forward and reverse biased electroluminescence images were taken at an equal exposure time of 30 seconds. For the Dark Lock-in Thermography (DLIT) images, a long wavelength IR camera and a 15 Hz modulated bias voltage signal was used.

3. Reverse breakdown behavior in multicrystalline solar cells

3.1. Solar cells from non-contaminated wafers

In the first column of figure 2, forward biased band-to-band recombination electroluminescence [3] images of both p-type and n-type mc-Si solar cells are shown. At several locations on the cell dark spots can be observed where the luminescence is reduced. The pattern, that is formed by the reduced luminescence sites, consists of a mixture of dark clusters and fine lines. This reduced luminescence pattern is typical for p-type mc-Si solar cells and was attributed in literature to non-radiative recombination active sites such as stacking faults and dislocations, decorated by impurities or impurity clusters [3]. Cells from neighbouring wafers (not shown) display nearly identical recombination patterns, which confirms its material related origin. In n-type multicrystalline cells (4th and 5th row of fig. 2) a similar pattern can be observed, although commonly the dark clusters appear darker.

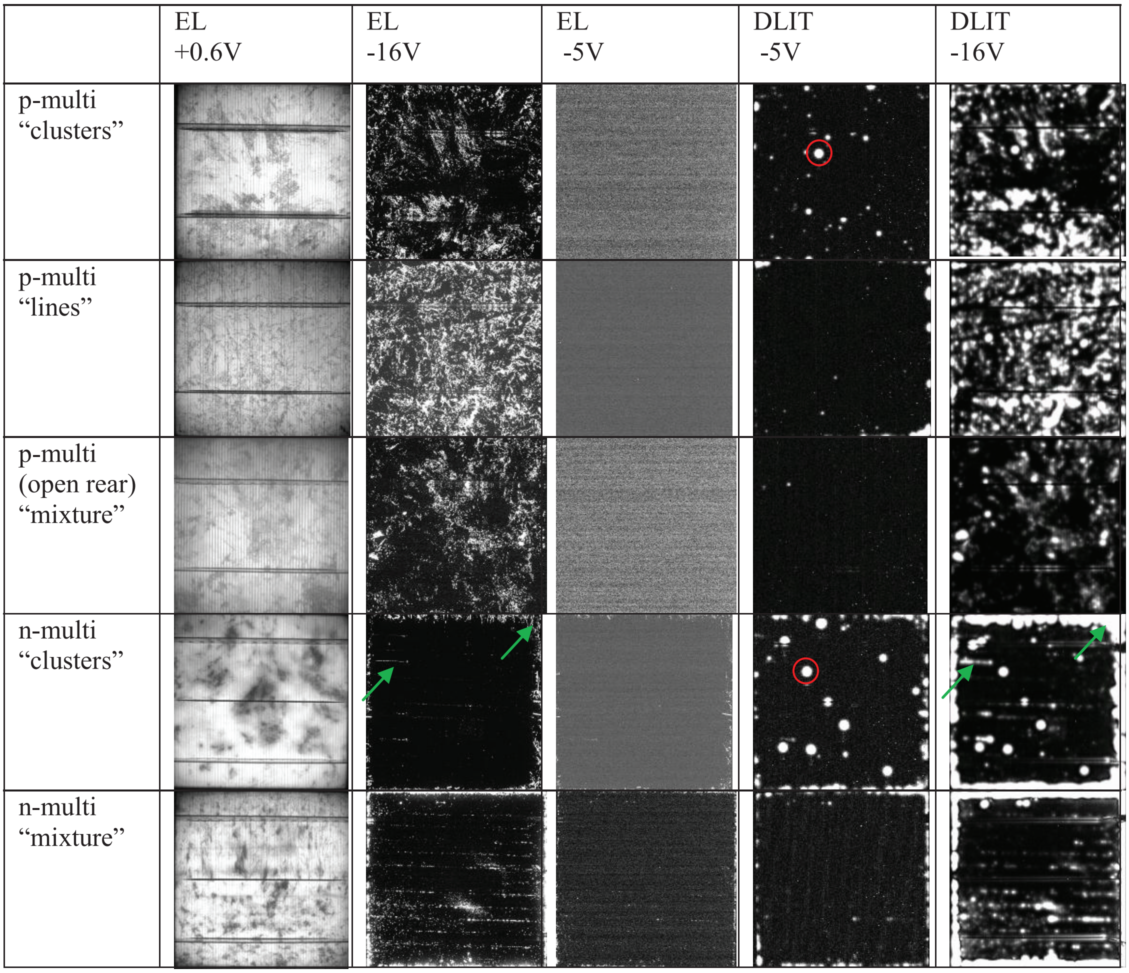


Fig. 2. EL images and DLIT thermal radiation images at different forward & reverse bias voltage values for the cells that are described in the text. The scale of the EL images is from black (low) to white (high) in arbitrary units (but equal exposure time). The scale of the DLIT images is from +0 mK (black) to +10 mK (white) for the -5V images, and from +0 mK (black) to +100 mK (white) for the -16V images. Examples of shunts and processing effects are marked by red circles and green arrows, respectively

For p-type solar cells a spatial correlation between the reduced recombination pattern in forward EL and the reverse breakdown pattern in reverse EL at -16V is evident, both for a fully metalized rear side and for an open rear concept, which is more similar to the n-type concept. For n-type multicrystalline solar cells, however, this correlation cannot be found. The much lower density of breakdown spots in the reverse biased images of n-type cells, can be traced back to process induced effects. In the n-type cells in row 4 and 5, breakdown luminescence of process related defects, like parasitic diffusion, can be observed already at -5V and are a side-effect of the non-optimized process scheme that has been used. That the presence of these effects depends on the applied process, is confirmed by their absence in the reference n-type cell in figure 3 (discussed in the next section), which was processed following a different scheme and only displays some fingerprints and minor defects. Breakdown sites with such low breakdown voltage were attributed by e.g. Lausch et al. [8] to the formation of very local p+-n+ junctions, which can likely occur at the observed processing defects.

By comparison of the DLIT and EL images at -5V of both p-type and n-type cells with clusters in forward EL, individual hot spots related to local shunts can be identified. In the last column of figure 2 the total picture of all discussed effects, breakdown and shunts is given by the thermography images at -16V. From these images it becomes clear that the total reverse current for p-type mc-Si solar cells, envisioned by its heat production, is dominated by wafer related effects, while for n-type cells the total reverse current is related to processing induced effects only. Unfortunately, due to the high reverse current that results from the process induced effects in the n-type cells, it was not yet possible to test whether a similar material related breakdown would occur in n-type cells at higher reverse bias voltages.

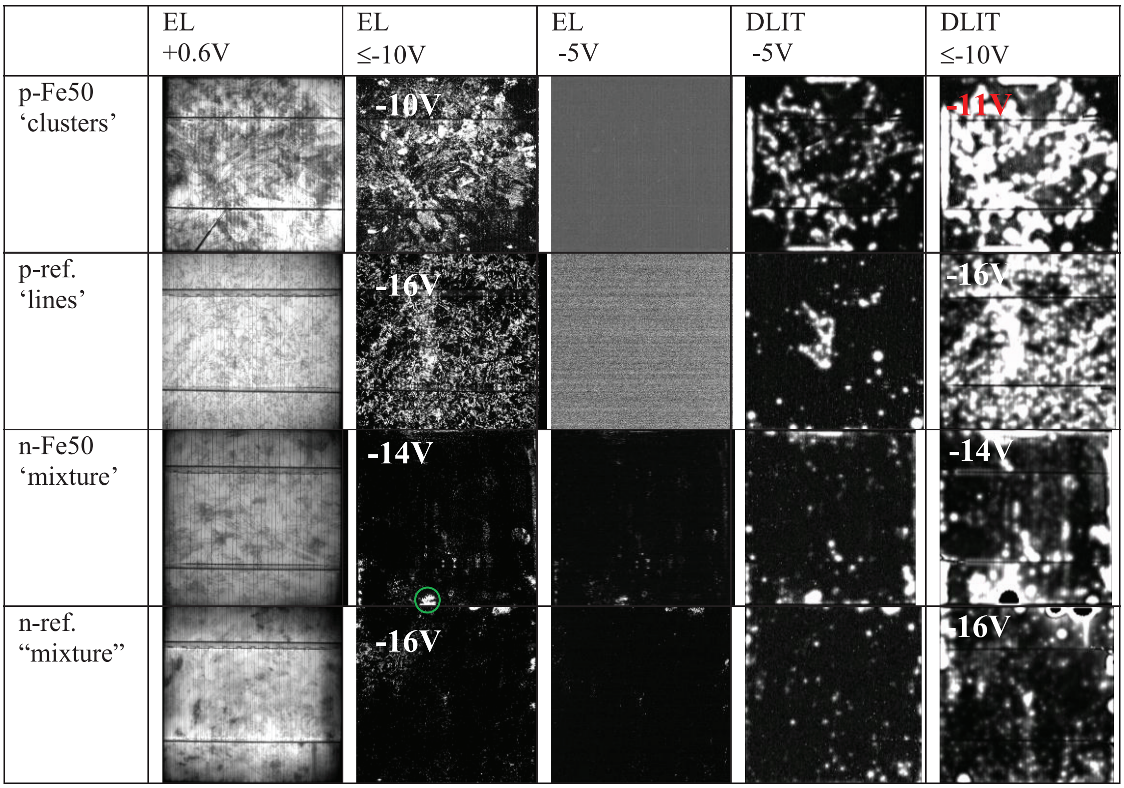


Fig. 3. EL images and DLIT thermal radiation images at different forward & reverse bias voltage values for n-type and p-type cells from an ingot that was intentionally contaminated with 50 ppm wt of Fe (p-Fe50 an n-Fe50) and reference cells from the same casting furnace made from uncontaminated silicon (p-ref and n-ref). The scale of the EL images is from black (low) to white (high) in arbitrary units (but equal exposure time). The scale of the DLIT images is from +0 mK (black) to +10 mK (white) for the -5V images, and from +0 mK (black) to +200 mK (white) for the -16V images.

3.2. Solar cells from Fe contaminated wafers

It is known that Fe contamination lowers the onset voltage of local pre-breakdown in p-type mc-Si solar cells [2]. In the first row of figure 3, a p-type cell from a small ingot that was intentionally contaminated by addition of 50 ppm wt of Fe is shown. A roughly circular breakdown pattern can be recognized clearly in all images of this cell except for the -5V EL image. Since the pattern does also occur in DLIT at -5V, also shunts must be present. A similar circular shunt pattern has been correlated to the presence of SiN filaments and sheets on the grain boundaries of cells from metal contaminated ingots [9], and also on this cell SiN filaments were observed. Because of the high reverse current at -10V, this p-type cell was not tested below -11V. The EL and DLIT images of a non-contaminated p-type reference cell, which ingot was cast in the same furnace, are comparable to the images in figure 2. For this cell, and for the p-type cells in figure 2, no significant breakdown was observed at -10V, confirming that the pattern was related to the metal contamination.

Also an intentionally contaminated n-type ingot was cast in the same furnace by adding 50 ppm wt Fe to clean feedstock. Except for some process induced damage (mainly fingerprints), no breakdown or shunt pattern can be observed for the Fe contaminated n-type cell up to -14V. The reverse current could not be tested for lower voltages due to the very high reverse current through a fingerprint at the edge of the cell. Qualitatively, no difference can be observed between the contaminated n-type cell and its reference. SiN filaments were observed at some grainboundaries in the Fe contaminated n-type cell as well, but apparently, these do not cause shunts in this n-type cell.

4. Discussion

The fine-structured breakdown patterns that are observed in p-type mc-Si wafers and are correlated to recombination patterns in forward EL, have a ‘soft’ breakdown characteristic which gradually increases with decreasing bias voltage. Breakdown patterns with this characteristic and an onset voltage between -8V and -13V were defined as type 2 breakdown by Kwapil et al. [2], who demonstrated that for wafers from Fe, Cr or Ni contaminated p-type ingots the onset voltage is lowered due to an increased impurity decoration of breakdown sites. In a later publication, Breitenstein et al. [10], attributed type 2 breakdown to the breakdown of a Schottky barrier between a metal silicide particle in the junction and the bulk. For all tested n-type mc-Si solar cells, no type 2 breakdown pattern could be observed both in DLIT and reverse biased EL down to -16V. Also a ‘hard’ type 3 breakdown [2], at bias voltages below -13V, was not observed, but due to the large current flowing through the process induced sites and the lack of direct correlation with the material structure this is hard to confirm.

Apparently, type 2 breakdown does not occur in n-type mc-Si cells down to -16V or cannot be observed with these methods. If a breakdown current is present in a reverse biased solar cell, it is highly unlikely that it is not detected both in EL and in DLIT. According to Bothe et al. [3], all 3 main breakdown types display a voltage dependent trend that is similar in EL and in DLIT and any measurable current flow passing through a microscopic site will dissipate a significant enough amount of power to be detected by DLIT imaging. Also, if the applied reverse voltage is stable and the current of the power source is not limited within the measured range, all parts of the cell (at equal distance to the cell terminals) are exposed to the same voltage in both methods. Therefore, the local breakdown behavior depends on the local sensitivity to the high bias voltage and cannot be influenced by shunts or breakdown currents through other parts of the cell. A large breakdown effect, like the one responsible for the reverse current in p-type, can therefore not remain unnoticed both in DLIT and EL.

Electroluminescence in high reverse bias conditions is always a result of acceleration of carriers in high electric fields with subsequent scattering or recombination of carriers [10]. If pre-breakdown is observed in the reverse IV-curve, it is expected to be luminescent [3] and the accelerated carriers form a local current that will locally heat up the cell. In n-type cells, type 2 pre-breakdown related local heating and luminescence were not observed. In p-type cells, some authors (e.g. [2], [10]) attribute type 2 breakdown to the presence of metal precipitates in the junction. A large metal silicide precipitate can form an ohmic contact to the emitter region and a Schottky contact to the bulk with a reduced barrier height, which can lead to a locally lowered breakdown voltage of the junction [10]. In the Fe-contaminated n-type cell, many Fe precipitates must be present, but also here no increased type 2 breakdown was observed, which indicates their significantly different impact on n-type. Other authors attribute type 2 breakdown to trap assisted tunneling (e.g. [3]). For both proposed mechanisms, it is not yet clear why they should not occur in n-type cells, but the change of base and emitter dopant type and concentration would certainly have an impact on both mechanisms. At least, the results in this paper demonstrate that whatever mechanism causes type 2 pre-breakdown in a reverse biased n+-p junction might not be present or create pre-breakdown in a reverse biased p+-n junction down to -16V.

5. Conclusion

Material related breakdown patterns, that are commonly observed for p-type mc-Si solar cells and are correlated to the crystal structure, were not observed in a large set of n-type mc-Si solar cells, down to a reverse bias voltage of -16V. The breakdown effects that were observed in n-type mc-Si cells, are processing related. Even in case of high Fe contamination, which lowers the breakdown voltage in p-type mc-Si solar cells, the type 2 breakdown pattern remains absent down to high reverse bias in n-type mc-Si solar cells. This observation can provide new insight into the mechanism behind type 2 breakdown.

Acknowledgements

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