PRE-BREAKDOWN MECHANISMS IN MULTICRYSTALLINE SILICON SOLAR CELLS

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ABSTRACT: Solar cells showing too large pre-breakdown currents, which might flow for unintentional reverse biasing by local shading, cannot be used since they would lead to thermal damage of the module. To be able to reduce the number of off-specification cells, the origin of the reverse current needs to be investigated. Pre-breakdown mechanisms in semiconductors exhibit characteristic temperature dependences. We present temperature-dependent lock-in thermography (LIT) measurements as well as illuminated LIT investigations under reverse bias that facilitate the identification of the type of breakdown observed at certain sites. There are both local regions with positive and with negative temperature coefficient of the breakdown current. It turns out that grown-in recombination defects lead to regions of local soft pre-breakdown sites. However, outside of these regions there are often some additional sites where a hard breakdown occurs which may even dominate at higher reverse bias. Lock-in EBIC images show that in the latter regions the cell surface, as a result of the acidic texturization etch, contains cone-shaped holes which act as avalanche breakdown sites.

Keywords: EBIC, Electrical Properties, Lock-in Thermography, Multicrystalline Silicon, Pre-Breakdown, Shunts, Silicon Solar Cell

1 INTRODUCTION

According to their net doping concentration of about $10^{18}$ cm$^{-3}$ and assuming an ideal n$-$p junction, standard multicrystalline (mc) Si solar cells should show a breakdown voltage beyond $-50$ V [1]. In reality, however, pre-breakdown may appear already for voltages of about $-10$ V. Since solar cells may unintentionally be reverse biased by local shading to about $-13$ V, this pre-breakdown may damage the module. To prevent this, only a certain maximum reverse current is allowed in the cell specification. Therefore, the investigation of pre-breakdown sites and avoiding their formation is necessary to reduce the number of off-specification cells.

The basic mechanisms responsible for the pre-breakdown currents occurring at a reverse-biased p$-$n junction are internal field emission (Zener effect) and impact ionization (avalanche effect). Both mechanisms are known to be possibly enhanced by the presence of material defects [2] or impurities [3, 4]. They possess different temperature coefficients: Whereas for internal field emission the current increases slightly with rising temperature due to the band-gap lowering, it decreases considerably for impact ionization due to increased phonon scattering. Also, multiplication of generated carriers takes place only for impact ionization.

For regions of high defect densities another possible pre-breakdown mechanism exists which is related to hopping conduction. It was observed for reverse-biased cells that were deliberately damaged by scratches [5]. Also for this type of conduction the current increases with temperature. Obviously, all pre-breakdown mechanisms mentioned above exhibit a characteristic temperature dependence, which can be used for their identification.

2 EXPERIMENTAL

We have imaged the breakdown current of standard mc-Si cells that don’t show ohmic shunts, applying various reverse biases and different temperatures, by lock-in thermography (LIT), both in the dark (DLIT) and under illumination (ILIT). On the same cells, both DLIT and electroluminescence (EL) imaging under forward bias have been performed. In addition, the crystal defects appearing in different breakdown sites are investigated by transmission electron microscopy (TEM) and lock-in electron-beam-induced current (EBIC) measurements in order to correlate the observed breakdown behavior with the defects in the silicon material.

In order to determine relevant physical parameters of pre-breakdown sites, newly proposed LIT techniques [6] are used. For DLIT measurements, images of the current density distribution can be obtained from the total cell current $J$ by scaling the $-90^\circ$ LIT signal $S$ according to

$$J = S \frac{I}{S_n A},$$

where $S_n$ is the $-90^\circ$ LIT signal [7] averaged over all image pixels. From several of such current density images, $J_n$, taken for varying temperature $T_i$ and at a given reverse bias, the corresponding temperature coefficient mapping can be obtained by dividing the difference of subsequent images (with the cell always exactly at the same place) by the temperature difference and normalizing to the average current. The result is called Temperature-Coefficient-DLIT (TC-DLIT) image:

$$\text{TC-DLIT} = \frac{2(J_n - J_{n-1})}{(J_n + J_{n-1})(T_n - T_{n-1})}.$$  

Due to the normalization to the average current density, the TC-DLIT image represents a central-difference derivative giving the relative slope at the midpoint temperature $T_{mid}$ between $T_{i-1}$ and $T_i$. It allows to distinguish between different values and different signs of the local temperature coefficient, independent of the magnitude of the current.

For studying avalanche effects it is useful to image the carrier multiplication factor, which is defined as the ratio of the photocurrent at a given reverse voltage to its (constant) value at small reverse bias [8]. To obtain this image, we perform ILIT at a constant reverse bias but with a pulsed homogeneous illumination of the cell, using a wavelength of 850 nm at an intensity of about 0.1 sun.
Under this measurement condition the dominant pulsed heat source is the thermalization of the photocurrent in the reverse-biased depletion region, where it can become locally increased by impact ionization. Since in this case the total cell current (originating from both the constant dark current and the pulsed photocurrent) cannot be used for the conversion of the LIT images into current density images, a value proportional to the current is obtained by dividing the (reverse-voltage-dependent) LIT signal $S(U)$ by the total voltage corresponding to the heat dissipation processes involved, which here is given by the sum of the excess thermalization voltage of the photogenerated carriers $U_{th}=(h\nu-E_g)/e$ (here about 0.35 V) and the barrier height, which is the sum of the (built-in) diffusion voltage $U_D$ and the applied voltage $U$. The Multiplication-Factor-ILIT (MF-ILIT) image is then obtained by dividing the image proportional to the photocurrent at the desired (reverse) voltage $U$ by another one taken at a low reverse bias $U_{low}$ where no avalanche effect occurs:

$$MF-ILIT = \frac{S(U)(U_{th}+U_D+U_{low})}{(U+U_D+U_{low})S(U_{low})}.$$  

This definition ensures that the value obtained for regions without avalanche multiplication equals one and that it is larger when impact ionization occurs. Additionally, it leads to a correction of any inhomogeneities of the photocurrent.

3 RESULTS AND DISCUSSION

3.1 Forward bias

A qualitative lifetime mapping of the cell is obtained from an EL measurement, shown in Fig. 1a. Areas of long and short lifetime are clearly separated, and in some parts the cell is free from recombinative defects. The corresponding DLIT image for a forward bias of 0.6 V, where the local heating of the cell due to the diffusion current can be seen (Fig. 1b), shows that the diffusion current flows preferably in areas having a short lifetime. Except for the better spatial resolution of the EL image, the +0.6 V DLIT image therefore also allows to identify areas with short carrier lifetimes.

3.2 Reverse-bias DLIT

For reverse biases of –5 V and –8 V (Fig. 2a, 2b) reverse currents show up at the edge and in locations with short carrier lifetimes (cf. Fig. 1), respectively. Increasing the reverse bias further more, the number and intensity of (pre-)breakdown sites continually increases. All these sites exhibit a more or less soft breakdown characteristic. At –12 V reverse bias, the image of the reverse current distribution (Fig. 2c) looks quite similar to the +0.6 V forward bias image, hence the breakdown currents are still found predominantly in regions with short carrier lifetime. However, when going from –12 V to –13 V (Fig. 2d), the total reverse current doubles, and in the DLIT image additional bright spots appear in areas previously identified to have a large lifetime (see circles). The reverse current doubles again when going from –13 V to –13.6 V, and the DLIT image is dominated by these newly appearing signals. This indicates a “hard” characteristic for the respective breakdown sites.

3.3 Temperature coefficient

Temperature-dependent measurements of the total reverse current showed a slightly positive temperature coefficient (TC) of the current in the soft-breakdown region (before reaching –12.5 to –14 V) and a strongly
negative coefficient in the hard-breakdown region (beyond \(-12.5\) to \(-14\) V), the point of zero TC shifting with increasing temperature from \(-13\) to \(-13.5\) V.

The TC-DLIT images (Fig. 3) were obtained by using the current density images of this cell taken at 25°C and those taken at 40°C, the result therefore applying to \(T_{\text{mid}} = 32.5°C\). Regions with positive temperature coefficient of the pre-breakdown current appear bright and that with negative coefficient appear dark. Regions with very weak thermal signal are blanked to zero. At \(-10\) V bias (Fig. 3a), except for some parts of the cell edge, all pre-breakdown sites show a negative TC (compare Figs. 3a and 2c; the bright rim of most such regions is probably an artefact of the measurement resulting from temperature-dependent lateral heat diffusion [6]). This negative TC is surprising, both because of the positive TC of the total reverse current and because of a lack of indication for avalanche multiplication (as will be shown below). The reason for the positive TC of the total reverse current is found from a rescaling of the DLIT images (not shown): The weak currents flowing in the areas that have been blanked in the TC image increase with temperature. This increase is nearly homogeneous over the whole cell area.

At \(-13\) V bias (Fig. 3b), only the newly appearing breakdown regions (cf. Fig. 2d) show a strongly negative TC, most other breakdown regions show just a slightly negative TC. Only the edge shows a clearly positive TC. In general, the TC-DLIT images are strongly dependent both on bias and on temperature. However, the edge almost always shows a markedly positive TC, indicating tunnelling or hopping processes as conduction mechanism.

3.4 Multiplication factor

For the MF-ILIT image shown in Fig. 4, a reverse bias of \(-7\) V has been chosen as reference \((U_{\text{low}})\), since up to that voltage no carrier multiplication was found. Even at \(-10\) V there is no indication for multiplication as pre-breakdown mechanism. At \(-13\) V, some cell areas show multiplication up to a factor of 1.5, and at \(-14\) V (Fig. 4) a pronounced MF-ILIT signal is obtained in those regions marked in Fig. 2 where hard breakdown occurred. For these regions, being of good material quality (cf. Fig. 1), a strongly negative TC of the current was found (cf. Fig. 3b). Altogether, it can be concluded that impact ionization (avalanche) is the dominating breakdown mechanism in the regions of hard breakdown (cf. Fig. 2).

**Figure 4:** MF-ILIT image of the cell shown in Fig. 1, taken at 25°C, obtained from measurements at reverse biases of \(-14\) V and \(-7\) V. Scale: 1.0 (black) to 2.0 (white). The bus bars appear as stripes of a noisy signal (being found also outside the cell area).

**Figure 5:** Comparison of TEM images of twin boundaries in “bad” (a) and “good” (b) regions of a similar cell, taken with beam directions of [111] (a) and [110] (b). Typically, only the “bad” region shows stacking faults.

**Figure 6:** Comparison of TEM images of dislocation-rich sites in “bad” (a) and “good” (b) regions of a similar cell, both taken with a beam direction of [111] but with slightly different spatial resolution (note the different scales given). Typically, only the “bad” region shows dislocation networks.

3.5 Transmission electron microscopy

In order to correlate the observed breakdown behaviour with the defects in the silicon material, small pieces from typical short-lifetime (“bad”) regions
(showing mainly soft pre-breakdown) and from long-lifetime ("good") regions (showing mainly hard pre-breakdown) of a similar cell were used for TEM investigations, the results being shown in Figs. 5 and 6.

Both in "bad" and "good" regions, twin boundaries are found (Fig. 5), but with a much higher abundance in the "bad" region. There, additionally many stacking faults and dislocations are present directly at the twin boundaries, whereas in the "good" region, twin boundaries are mainly free from dislocations. Also, dislocation-rich sites are found in both regions (Fig. 6), typically either in a fence-like arrangement or more isolated, however with a much higher local density of the single dislocations in the "bad" region (note the slightly different scales of the two parts of Fig. 6). In the "bad" region, also more of those "fences" can be found than in the "good" region. A typical feature of the "bad" region is the occurrence of dislocation networks (Fig. 6a), whereas in the "good" region, mainly isolated dislocations are found. The TEM results allow the conclusion that the "bad" regions are probably caused by plastic deformation in the cooling phase of the ingot.

3.6 Lock-in EBIC

Even if only a small region is investigated, an MF-ILIT image does not allow localization of single avalanche breakdown sites because of the limited spatial resolution of this thermal technique. For studying avalanche breakdown sites more microscopically, we have performed EBIC in ac-coupled lock-in mode on a selected sample cut out of a similar cell in a position where a non-negligible MF-ILIT signal was observed [9]. Figure 7 shows lock-in EBIC images taken at zero (a) and at –15 V bias (b, d; in two different magnifications), together with a secondary electron (SE) image of the surface (c). The surface of this cell was acid-etched to obtain a rough texture.

Avalanche multiplication occurs in all sites where the EBIC signal at –15 V is significantly larger than at zero bias (where the image shows a nearly homogeneous intensity). This is the case for many specific local sites, some of them being arranged in lines. These lines consist of single dots, and at each of these dots a microplasma occurs. Examples of those lines and dots are marked in Fig. 7 (c, d) by arrows. The SE images show that in all these sites cone-shaped holes exist, being many microns deep, which are etched into the surface by the texturizationetch. The p–n junction is lying about 0.3 microns below the surface, hence it completely covers also these cone-shaped holes. At the bottom of these holes the electric field should be strongly enhanced due to the electrostatic "tip effect". Hence, the avalanche breakdown occurring unexpectedly at this reverse voltage of –15 V is obviously caused by the existence of cone-shaped holes, which are generated by the acidic texturization etch.

4 CONCLUSIONS

Using the newly introduced LIT techniques to obtain the temperature coefficient (TC-DLIT) and the carrier multiplication factor (MF-ILIT) image [6], the pre-breakdown behaviour of standard mc-Si cells was investigated. Grown-in recombinative crystal defects lead to regions of local soft pre-breakdown sites. In regions of short carrier lifetime, stacking faults and dislocation networks were found. The TC-DLIT images have shown that regions of positive and of negative TC may exist in parallel, which we interpret as follows: The positive TC of the current may correspond to trap-assisted tunneling (internal field emission) or to hopping conduction. For a large reverse bias chosen beyond the crossover point of the TC, the negative TC and the multiplication factor of the current indicate that impact ionization (avalanche multiplication) is the dominating breakdown mechanism. It has been demonstrated in the literature that also this breakdown mechanism can be influenced by the presence of traps and dislocations [10, 11]. Interestingly, here we have found by lock-in EBIC investigations that cone-shaped holes at the surface are the origin of the hard pre-breakdown sites (tip effect). Altogether, temperature- and bias-dependent LIT investigations prove to be a very successful tool for studying pre-breakdown phenomena.

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REFERENCES


