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Defect induced non-ideal dark I–V characteristics of solar cells

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ABSTRACT

The non-ideal behavior of the dark current–voltage (I–V) characteristics of typical silicon solar cells is characterized by (1) an unexpectedly large recombination current, often characterized by an ideality factor larger than 2, (2) an ohmic characteristic at low reverse bias, and (3) pre-breakdown at a reverse bias far below the expected breakdown voltage. Experimental evidence, especially from lock-in thermography results, shows that all these features are due to currents flowing locally in the edge region, or at certain extended crystal defects like grain boundaries. Detailed investigations on local breakdown sites in industrial solar cells are introduced. Though a realistic theory of these processes is still missing, a unified explanation of non-ideal dark I–V characteristics is presented and several theoretical approaches to explain different aspects of this non-ideal behavior are discussed.

1. Introduction

In 2007, silicon solar cells filling an area of about 30 km^2 have been produced worldwide (4.2 GW, assuming a module efficiency of about 140 W/m^2). One should expect that the electronic behavior of these cells, which are basically large-area silicon p–n junctions, has been well-known for decades. However, even such a simple thing as the dark current–voltage (I–V) characteristic is still not fully understood. Ideally, the dark forward I–V characteristic of a p–n junction should be exponential with an ideality factor below 2, there should be no ohmic shunting, and the reverse characteristic should be saturating in the low microampere region up to a breakdown voltage above 50 V [1]. In reality, however, ideality factors of 3 to 4 are often measured for industrial solar cells, the magnitude of the recombination current (given by its prefactor J_{02}) is usually orders of magnitude larger than expected

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for this material, and the reverse characteristic is linear (ohmic) at low and superlinear at higher reverse bias. In particular, this pre-breakdown behavior is a serious reliability problem in solar cell industry, since a high pre-breakdown current disqualifies cells from being used in solar modules. Thus, a complete understanding of the dark I–V characteristic of solar cells is very desirable, but still lacking. This work describes some recent success of this research, both experimental and theoretical.

The so-called recombination current of a p–n junction is due to electron–hole recombination in its depletion region. Already in 1962, Queisser had observed the non-ideal behavior of silicon solar cells, especially the large J_{02} and ideality factor of the recombination current, and had proposed to attribute it to metal precipitates crossing the p–n junction [2]. However, such metal precipitates are usually not found in solar cells. Later on, several authors observed that the recombination current of differently sized cells is proportional to the circumference rather than to the area of the cells [3–5]. So obviously the edge region, where the p–n junction crosses the crystal surface, is a major source of the recombination current, which may, but need not, show ideality factors larger than 2. Generally, an ideality factor larger than 2 means that, with increasing forward bias, the recombination rate increases slower than the p–n product. Hence, the recombination should be limited by any kind of saturation effect. Several proposals have been made to explain large ideality factors, such as resistance-limited recombination [4], single-level trap-assisted tunneling [6] and two-level trap-assisted tunneling [7]. However, resistance-limited recombination can only account for large ideality factors at forward biases larger than 0.3 V, whereas in reality they are observed already below 0.2 V. Trap-assisted tunneling is also not sufficient to describe the observed magnitude of recombination currents for defect concentrations usually found in solar silicon material, at least not if one assumes homogeneously distributed point defects to be responsible. These proposals also did not explain the ohmic and pre-breakdown reverse characteristic of the cells.

From the three aspects of non-ideal diode behavior (1) large ideality factor and J_{02} of the recombination current, (2) ohmic behavior at low reverse bias, and (3) pre-breakdown at large reverse bias, the first two aspects have been presented in detail already earlier [8–11]. Therefore, we will only briefly summarize these results here. This contribution will focus on latest results of pre-breakdown investigations, which imply special dark and illuminated lock-in thermography (DLIT and ILIT) investigations, as well as, for investigating local avalanche multiplication, electron beam-induced current (EBIC) investigations performed under large reverse bias in the avalanche regime. Models for the interpretation of these results are discussed. The presentation of a unified explanation of the non-ideal I–V characteristics of silicon solar cells will also be attempted.

2. Experimental

Lock-in thermography (LIT) is based on thermal infrared (IR) imaging of a device which is subjected to periodically pulsed heat introduction. By digitally lock-in processing and averaging the IR images, an image of the local heat dissipation is formed [12–14]. Depending on the measurement conditions and on the data evaluation procedure, different special LIT techniques exist. For investigating pre-breakdown phenomena, we have used "TC-DLIT" for imaging the relative temperature coefficient (TC) of breakdown sites, "Slope-DLIT" for imaging the relative steepness (slope) of such sites, and "MF-ILIT" for imaging the local avalanche multiplication factor (MF) at a certain reverse bias. These techniques are described in detail elsewhere [15]. TC-DLIT and Slope-DLIT both rely on the evaluation of a set of LIT images taken in the dark at different temperatures and for different reverse biases. MF-ILIT measures the local heat dissipation at constant reverse bias under pulsed homogeneous light illumination, which may be scaled to image the local multiplication factor quantitatively. All LIT results have been obtained by using a TDL 640 M 'Lock-in' thermography system by Thermosensorik GmbH (Erlangen), which was extended by an LED array for illuminating the sample at $\lambda = 840$ nm.

The EBIC investigations have been performed in a JEOL JSM 6400 scanning electron microscope at an acceleration voltage of 30 kV. At high reverse bias in the avalanche regime a considerable d.c. reverse current already flows, which would overload the EBIC amplifier. Therefore an R-C separation circuit was switched between the biased sample and the current amplifier, similar to that already described by Heydenreich et al. [16] for performing "microplasma imaging". Since this circuit

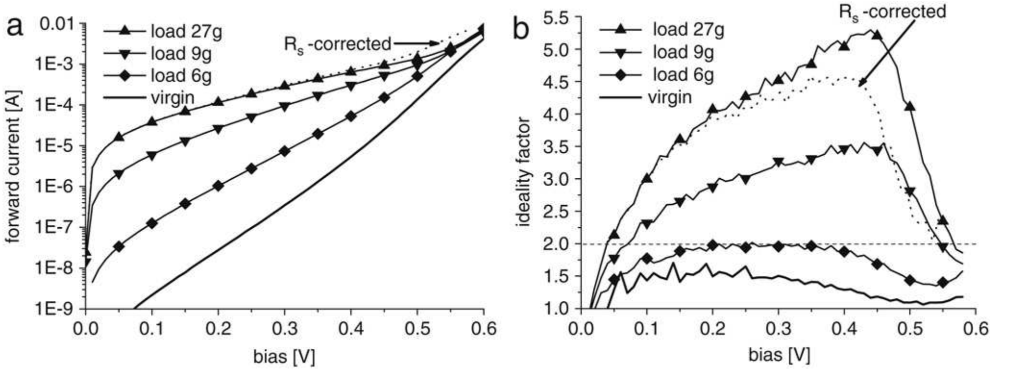

Fig. 1. Dark I–V characteristics (a) and bias-dependent ideality factor (b) of an "ideal" (virgin) cell and of 3 equivalent cells, which are diamond scratched with different loads. Dotted: R_s-corrected curves for the 27 g load cell.

transmits only the a.c. component of the EBIC signal to the amplifier, the electron beam was pulsed at 1 kHz and the EBIC signal was lock-in processed by using a home made lock-in amplifier.

3. Results

3.1. The recombination current and ohmic behavior

In this section only the most important results presented in [8–11] will be reviewed for obtaining a complete picture of the non-ideal behavior of silicon solar cells. Many LIT investigations have shown that the dominant part of the recombination current, being characterized by its prefactor J_{02} and its ideality factor n, is not flowing homogeneously in silicon solar cells, but in local positions, where extended defects are crossing the p–n junction. The most prominent defect of this type is the outer edge (circumference) of the cell where the p–n junction comes to the surface. This surface is usually prepared either by plasma etching or laser grooving. In any case, it is highly disturbed. Only if the edge of a p–n junction is well-passivated using a thick field oxide, does it generate a negligible edge leakage (recombination) current [8].

Mechanical scratches are also very efficient sources of recombination current. Hence, such scratches may serve as "model defects" for studying the recombination current caused by extended defects. By comparing diamond scratches performed with different loads into previously ideally behaving cells, we have found that the magnitude of the scratch-induced recombination current and its ideality factor both increase with increasing load, hence with an increasing degree of disturbance of the crystal, which is shown in Fig. 1 [9].

Since the geometry of the current flow was well-known here (scratch in the middle between two grid lines in an emitter layer of well-defined sheet resistance), the influence of the series resistance could be explicitly corrected, which is shown in Fig. 1 for the highest load. We see that, here, the series resistance further increases the ideality factor, but the large ideality factor is definitely not only series resistance-induced, but has an intrinsic origin. We attribute this behavior to multi-level recombination in the highly disturbed material caused by the scratch. Indeed, using the coupled defect level model of Schenk [7] and assuming pair recombination via deep donor–acceptor pairs with distance-dependent inter-level recombination probability [9], we were able to model large ideality factors already at low biases. Though these models are still far from being realistic, they show that the implementation of multi-level recombination may lead to intrinsic saturation of the recombination, which might explain the large ideality factors. Depending on the local density of states of an extended defect crossing the p–n junction, its recombination current may show an ideality factor of 2 or below (for low densities, e.g. a cleaved edge) or above 2 for high densities. This is exactly what has been found experimentally on our scratches of different load, where the weakest scratch did not cut the p–n junction yet [9].

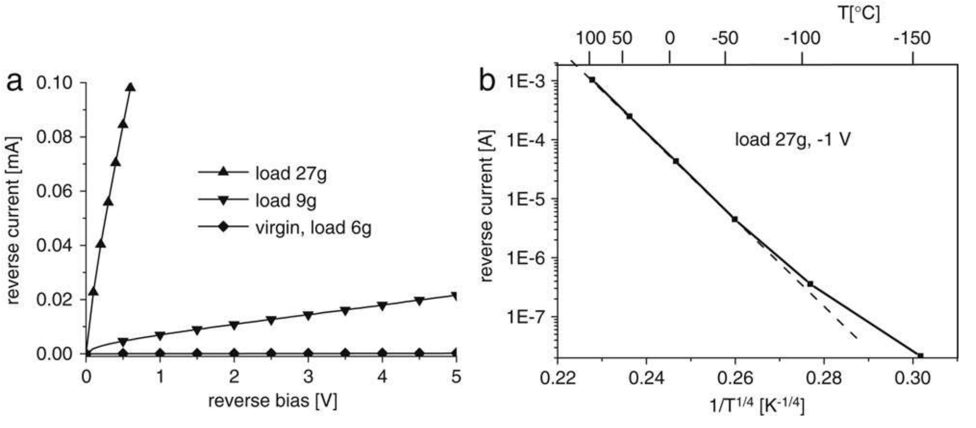

Fig. 2. Reverse I–V characteristics (a) of the cells used for Fig. 1 and temperature dependence of the reverse current of the 27 g load cell (b).

An ideal diode shows no ohmic parallel resistance. However, this does not mean that there is no linear part in the I–V characteristic at very low bias. A recombination current of $J_{rec} = J_{02} * (\exp(eV/nkT) - 1)$ [1] may be developed in a power series around V = 0, leading to $J_{rec} = J_{02}eV/nkT$, which is equivalent to an (area-related) parallel resistance of $r_p = nkT/J_{02}e$. Hence, not every linear part in the characteristic around $V = 0$ is allowed to be interpreted as an ohmic parallel resistance. However, this recombination current should saturate for a reverse bias larger than 3 kT/e to a value of J_{02}. Hence, if a linear behavior is measured for reverse biases up to several V, this cannot be explained by the recombination current any more. Fig. 2 shows reverse bias I–V characteristics of the cells investigated in Fig. 1, together with the temperature dependence of the reverse current of the cell with the strongest scratch [9]. We see that, with increasing load of the scratch, the ohmic reverse current increases dramatically. Between $-50\,°C$ and $+100\,°C$, $\log(I_{rev})$ varies linearly over $1/T^{1/4}$. This temperature dependence is characteristic for variable range hopping conduction in a constant density of states near the Fermi level, according to Mott's theory [17]. This is a strong proof for our hypothesis that, in absence of stronger shunts, the linear part of the reverse I–V characteristic at intermediate reverse bias is due to hopping conduction across the same defects that are also responsible for the recombination current.

In multicrystalline (mc) silicon cells, strong ohmic shunting is often observed that cannot be attributed to hopping conduction any more. This is usually due to the presence of SiC filaments, some μm in diameter and hundreds of μm long, that are often lying in grain boundaries and are crossing the whole cell [10]. By performing microscopic 4-probe measurements, we have shown that these filaments are highly n-doped, most probably by nitrogen [11]. So they are in ohmic contact with the emitter and may also be in contact with the base contact, thus producing serious shunts.

3.2. Pre-breakdown

3.2.1. LIT investigations

Reverse-bias breakdown of p–n junctions may be due to two different mechanisms, which are impact ionization (avalanche breakdown) or internal field emission (Zener effect) [1,18]. Avalanche breakdown means that residual carriers in the depletion region are accelerated by the field to such an energy that they generate a new electron–hole pair by impact ionization. Since the chance of the carriers to gain high kinetic energy is higher at lower than at higher temperature because of phonon scattering, the temperature coefficient of an avalanche current (at fixed voltage) is negative, hence the avalanche breakdown voltage (for a given current) has a positive temperature coefficient. For a base net doping concentration of 10^{16} cm^{-3}, as is usual for industrial silicon solar cells, the avalanche breakdown voltage should be above 50 V [1]. As a rule, avalanche breakdowns show a

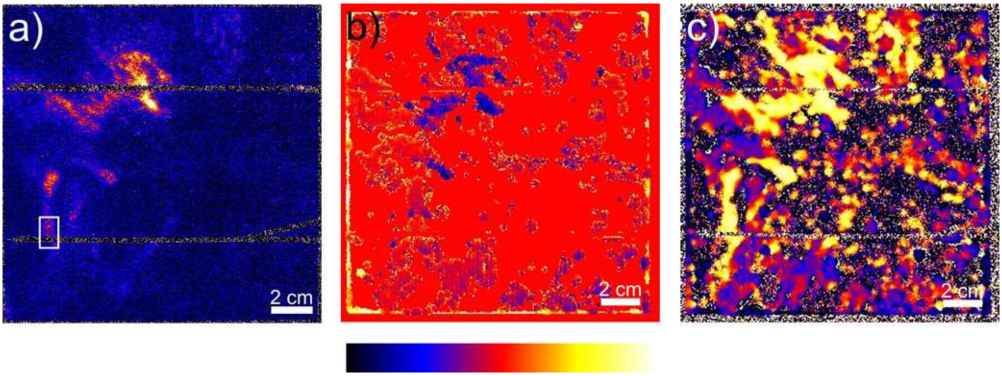

Fig. 3. (a) MF-ILIT image measured at room temperature at 15 V, scaling from $MF = 1$ to 4, (b) TC-DLIT image displaying the relative temperature coefficient at 13 V and 50 °C, scaling from −3% to 3%/K, (c) Slope-DLIT image displaying the relative slope at $T = 60$ °C and $V = 13.5$ V, scaling from 0 to 200%/V. The region indicated in (a) is that investigated in Fig. 4.

very high slope of the I–V characteristic in the breakdown region [18]. For internal field emission (IFE), on the other hand, the carriers are horizontally tunneling through the energy gap. Since the gap energy has a negative temperature coefficient, the IFE current at fixed voltage shows a positive one, hence this current increases with increasing temperature. IFE breakdown is known to show a smaller slope of the breakdown characteristic than avalanche breakdown. For clean silicon material, IFE breakdown occurs only at very high doping concentration, where the breakdown voltage is below 6 V [1]. Multiplication of photo-induced carriers occurs only for avalanche breakdown but not for IFE breakdown. Thus, the temperature coefficient (TC) of the breakdown characteristic, its slope, and the avalanche multiplication factor (MF) are important parameters indicating the nature of a local breakdown current. All these parameters can be imaged by special lock-in thermography techniques [15]. Fig. 3 shows an MF-ILIT image (a), a TC-DLIT image (b), and a Slope-DLIT image (c) of a typical industrial multicrystalline silicon solar cell. It should be noted that most of the breakdown sites occurring below the avalanche threshold of about 14 V are in the positions of grown-in crystal defects like grain boundaries and dislocations [15].

In Fig. 3(a) we observe significant avalanche multiplication already at 15 V reverse bias. Up to 13 V reverse bias, this kind of image looked very homogeneous, hence there was no avalanche multiplication. The local avalanche multiplication factor is distributed very inhomogeneously. In Fig. 3(b) the temperature coefficient (TC) is displayed at a reverse bias of 13 V. Here, the signal in the regions outside of breakdown sites has been blanked artificially to zero to remove the disturbing noise. This image (b) shows that most breakdown sites show a negative TC (dark contrast), which is strongest in the avalanche breakdown sites. Only the laser-opened edge and two small sites in the area show a positive TC (bright contrast). Note, however, that this measurement was done at 13 V reverse bias, where no avalanche multiplication was observed yet. The Slope-DLIT image (b), measured between 13 and 14 V, shows that there are breakdown sites with very different slopes. The largest slope between 13 and 14 V is found in regions where also the highest MF was found at 15 V, but not all regions of high slope also show a large MF. The edge region, which showed a positive TC, shows a rather weak slope (about 20%/V). Altogether, these results cannot be interpreted completely in the frame of previous breakdown models.

3.2.2. *Avalanche-EBIC investigations*

Even if only a small region is imaged, MF-ILIT does not allow localization of single avalanche breakdown sites because of the limited spatial resolution of this thermal technique. Thus, for investigating avalanche breakdown sites more microscopically, we have performed EBIC in lock-in mode under high reverse bias on a selected sample cut out of the cell shown in Fig. 3 in the position marked in (a). In the past, this type of investigation has been called "microplasma imaging" [16]. Fig. 4 shows lock-in EBIC images measured at zero bias (a, d) and at 15 V reverse bias (b, e), together with

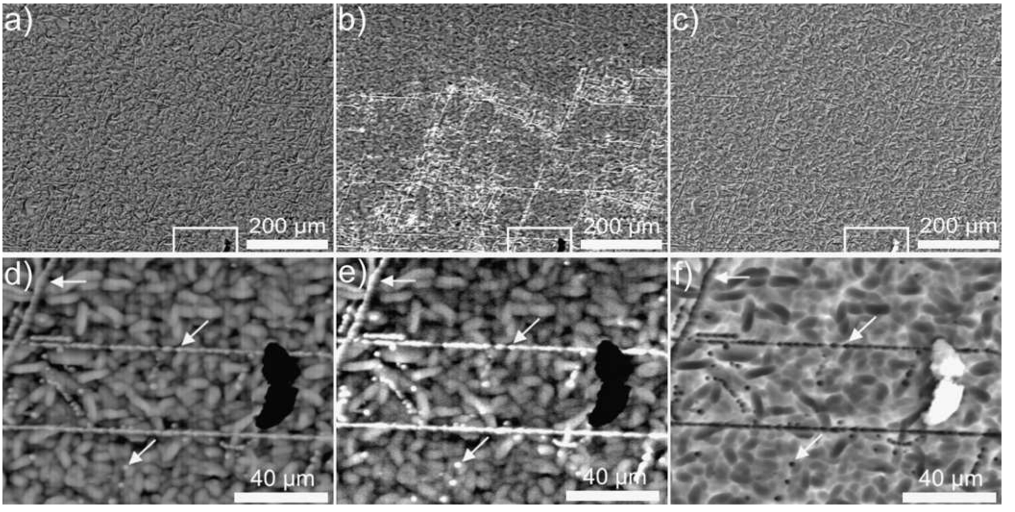

Fig. 4. (Lock-in) EBIC images at zero bias (a, d) and at 15 V reverse bias (b, e) and SE-images (c, f) of the region indicated in Fig. 3(a) imaged in two magnifications.

secondary electron (SE) images of the surface (c, f), in two magnifications. 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. We see that this is the case in many very local sites, some of them being arranged in lines, as can be seen in Fig. 4(b, e). 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. 4(d, e, f) 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 texturization etch. The p–n junction is lying about 0.3 microns below the surface, hence it also completely covers these cone-shaped holes. At the tip of these holes the electric field should be strongly enhanced due to the electrostatic "tip effect". Hence, obviously the avalanche breakdown occurring at this unexpected low voltage of 15 V is caused by the existence of cone-shaped holes, which are generated by the acid texturization etch.

4. Discussion and conclusions

Though a complete theoretical description of the non-ideal behavior of the dark I–V characteristics of industrial silicon solar cells is still missing, all aspects of this non-ideality are at least qualitatively well understood. The unexpectedly large magnitude and the unexpectedly large ideality factor of the recombination current can both be explained by taking into account that this current is not flowing homogeneously, as assumed in classic diode theory, but flows locally in the position of extended defects crossing the p–n junction. The most important defect of this type is the edge of the cell, where the surface crosses the p–n junction. Only if this edge is well-passivated by a field oxide and if there are no other extended defects, do the solar cells show an ideal I–V characteristic. It should be mentioned that very large values of J_{02} of 2-dimensional extended defects can only be explained by considering the electrostatic band bending at the defects, which leads to preferred electron injection from the emitter into the defect plane and thus increases the region where recombination takes place [3,5,8]. Besides the edge region, other extended defects generating the recombination current are grain boundaries, dislocations, precipitates, and also scratches. Scratches made at different loads are very useful "model defects" for studying the physical nature of the recombination current. The higher the load, the larger is the magnitude of the recombination current, and the higher is its ideality factor. This behavior can be explained by an increasing participation of multi-level recombination in addition to the well-known Shockley–Read–Hall single level recombination. Obviously, multi-level recombination may imply certain intrinsic saturation effects, which are the final reason for large ideality factors. Qualitatively, these saturation effects have already been modelled within the coupled defect level model of Schenk et al. [7] and within the deep donor–acceptor-pair recombination model [9], but a realistic theory is still missing.

The linear characteristic at intermediate reverse bias should be due to the same kinds of extended defects. Obviously the local density of gap states may be so high in these defect regions that hopping conduction occurs via these levels [17]. The measured temperature dependence of the reverse current induced by a scratch strongly supports this hypothesis. Strong ohmic shunts in multicrystalline cells have been already explained previously to be due to n-conducting SiC filaments crossing the cells in the position of grain boundaries [10,11]. For explaining the pre-breakdown phenomena at unexpectedly low voltages, avalanche breakdown and IFE may be considered. Both MF-ILIT and avalanche-EBIC investigations have shown that, in our sample, avalanche multiplication already occurs above 13 V reverse bias. The mechanism of avalanche breakdown at such a low bias has been identified to be a field enhancement at the tips of deep cone-shaped holes in the surface, which are generated in the acid texture etching process. However, breakdown with negative TC, which would be characteristic for avalanche breakdown, already occurs well below 13 V reverse bias, where no avalanche multiplication takes place. These breakdown sites are correlated with local accumulations of grown-in crystal defects in this multicrystalline material, like grain boundaries and dislocations [15]. We propose that IFE, via defect states, might be responsible for this kind of breakdown. In the simplest case, from a midgap state, an electron and a hole may alternately tunnel into the conduction and the valence band, respectively, leading to the breakdown current. Since, for these tunneling events, a triangle barrier with only half of the height of the gap energy has to be tunneled through, these single tunneling events should be more probable than tunneling across the whole gap by many orders of magnitude. If, at very high local defect density, more than one level is participating in the tunneling process, this process should become even more probable. This "trap-assisted tunneling", which was discussed previously mostly to occur under forward bias [6,7], may also work under relatively low reverse bias and probably may explain the distinct pre-breakdown behavior in the positions of recombinative defects below 14 V, where avalanche breakdown begins. However, the observed negative TC of this effect has yet to be explained.

Also, hopping conduction across extended defects like the edge region, which should be responsible for the ohmic behavior under low reverse bias, is expected to lead to superlinear characteristics at higher bias with a positive TC [17]. Maybe the pre-breakdown observed in the laser-opened edge region is due to this effect, since it shows a low slope and a positive TC. In fact, the junction between trap-assisted tunneling and hopping conduction is floating and depends only on the local defect level concentration.

Another interesting aspect is the generation of light in breakdown sites. This light emission is a standard failure analysis technique for integrated circuits. It has also been observed for monocrystalline silicon solar cells [19]. The general explanation of light emission under high field conditions is bremsstrahlung, which is light emission due to acceleration or deceleration of carriers. We have also found light emission in breakdown sites of the cell investigated here. Whether light is generated only under avalanche conditions or also in other breakdown sites, is under investigation. Altogether, the research about electric breakdown in silicon solar cells has only just begun. Different lock-in thermography techniques and beam-induced techniques like MF-ILIT and avalanche-EBIC are very useful in this field.

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