Evaluation of recombination velocities of grain boundaries measured by high resolution lock-in thermography

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Abstract

Multicrystalline silicon solar cells include a high amount of crystal defects such as dislocations and grain boundaries, which are featured by different degrees of recombination activity. This contribution presents a method to investigate the recombination velocity at grain boundaries (GBs) by means of dark lock-in thermography (DLIT). The local diffusion current density $j_{01}$ at the GB is evaluated by applying a spatial deconvolution algorithm and separating the dark current contributions due to their different voltage dependencies. Adopting a model of the GB developed by Lax enables an analysis of the recombination velocity from the local $j_{01}$. In this contribution we firstly present an explicit expression for this calculation. It is shown that the dominant contribution to $j_{01}$ at the investigated sample is caused by the recombination active GBs and that the intra-grain defects such as dislocations have just a lower influence.

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1. Introduction

The performance of multicrystalline (mc) silicon solar is mainly limited by recombination-active defects. In contrast to monocrystalline solar cells they contain a high amount of crystal defects such as dislocations and grain boundaries (GB), which act as recombination centers. Thus they lower the local carrier lifetime and therefore increase the local diffusion current density described by its saturation current density $j_{01}$. For a deeper understanding of the corresponding recombination effects and their influence on the global cell performance, it is necessary to measure the local recombination activity at the different

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defects. Since GBs have a macroscopic dimension, their recombination activity becomes visible in beam-injection methods like electron beam-induced current or light beam-induced current, and the recombination velocity of the GBs can be evaluated quantitatively by these methods [1,2]. Also dark lock-in thermography (DLIT) permits the investigation of these defects [3], because it facilitates a direct quantitative measurement of the dark current density caused by the recombination active defects [4].

In this contribution we demonstrate the approach for measuring the local diffusion current at the GBs by DLIT in combination with spatial deconvolution. The adoption of a 2-dimensional model of a GB proposed by Lax [5], which was already described in [3], allows the calculation of the corresponding recombination velocity by the evaluated results. We will evaluate the errors due to the assumptions made by this approach and present an empirically found correction factor, which leads to an explicit expression of the recombination velocity according to the locally increased diffusion current density.

2. Experimental

A 3×3 cm² sized piece of an industrial multicrystalline silicon solar cell (15.6×15.6 cm², $j_{sc} = 32.9$ A/cm², $V_{oc} = 618$ mV, $FF = 78.3$%) containing a high amount of GBs was investigated by DLIT measurements at 10 Hz. This frequency leads to a thermal diffusion length of 1.6 mm in the 200 μm thick sample. The sample was sucked to a thermostatted measurement chuck (25 °C) and is connected to a four-quadrant power supply by a four-probe contacting scheme at the busbar and the rear side metallization. The surface of the cell was covered with black paint to assure a homogeneous emissivity. Measuring DLIT images at biases of 550 and 600 mV enables the separation of the different dark current contributions by an algorithm and software called “Local I-V” [6]. Here the assumption of an ideality factor of two for the depletion region recombination current was chosen and the ohmic shunt components were neglected. Although the lifetime in mc material might be injection-level dependent [7], we assume a constant lifetime ($n_1 = 1$) in simplest approximation. To limit the errors made by this assumption, we measure at an injection level comparable to the operation conditions of the solar cell.

The “Local I-V” procedure requires a local series resistance ($R_s$) image, which is evaluated by the RESI-method, which is a combination of electroluminescence (EL) imaging and DLIT imaging [8]. First, the distribution of the local voltage at 600 mV is calculated by applying the code “EL-Fit” [9] on two EL images taken at 550 and 600 mV. Together with the DLIT results at 600 mV the software “Local I-V” evaluates the local $R_s$ according to [8].

3. High resolution DLIT-measurement

The out-of-phase (-90°) DLIT-signal is proportional to the locally dissipated power, but has just a limited spatial resolution due to the thermal blurring (see Fig. 1(b)). The in-phase (0°) DLIT-signal (Fig. 1(a)) has a better spatial resolution, but is not directly proportional to the dissipated power. Therefore a clear correlation of the measured values to individual GBs, as they are visible in the EL-image (Fig. 1(c)), is not possible without applying a 2-dimensional deconvolution algorithm to the measurements. The used FFT-formalism, which is implemented into a code called “DECONV” [4], enables the conversion of the in-phase (0°) and out-of-phase (-90°) image (Figs. 1(a) and (b)) into a distribution of the locally dissipated power density $p$ (Fig. 1(d)). Since this procedure is very sensitive to the noise of the measured data, the deconvolution is performed with a Wiener filter, which allows choosing a compromise between spatial resolution and signal-to-noise ratio. An artificial overshoot of the power density into the negative caused by this algorithm is corrected by applying an additional Gaussian blurring of 4 pixels to the result.
It has been checked that this deconvolution and subsequent smoothing procedure does not falsify the quantitative results, neither the intra-grain current density nor the current per unit length of the GBs. The full width at half maximum of the grain boundaries’ signal has improved from 3.4 mm (-90° DLIT image) to 400 μm (deconvoluted power density). Therefore the signal can be directly correlated to the different GBs.

Evaluating the local power density $p$ at 550 and 600 mV by using the procedure described above allows separating the (depletion region) recombination current density $j_{\text{rec}}$ and the diffusion current density $j_{\text{diff}}$ by applying the “Local I-V” algorithm [6]. The recombination current density $j_{\text{rec}}$ in Fig. 1(e) mainly occurs at the edges of the cell, where the p-n junction crosses the surface of the cell. This is consistent to former investigations of the local current-voltage characteristic [6]. In the inner part of the cell, except of one spot in the middle, only a weak noisy pattern was measured, which is mainly caused by the noise increase due to the deconvolution procedure. Hence, at a bias of 600 mV the dominant current contribution is given by the diffusion current density $j_{\text{diff}}$ (f). All recombination active GBs, which appear dark in the EL-image (c) can be clearly correlated to increased $j_{\text{diff}}$-values. The improved spatial resolution allows describing the properties of the GBs by a diffusion current line density $J_{\text{01 line}}$ (in units of A/cm) and the diffusion current density of the adjacent grains $j_{\text{01 back}}$ (in units of A/cm$^2$). For this purpose linescans perpendicular to the grain boundaries were fitted by a Gaussian function with an independent baseline, as it is visualized in the upper part of Fig. 2(a).

Fig. 1. (a) In-phase and (b) out-of-phase DLIT-image at 600 mV; (c) electroluminescence intensity (arbitrary units); (d) deconvoluted DLIT image; (e) recombination current density and (f) diffusion current density at 600 mV (the positions of the evaluated GBs are marked in (d) and (f)).
The additional $j_{\text{diff}}$ at the GBs directly increases the global diffusion current and thus decreases the open circuit voltage of the solar cells under illumination. Also the light induced current is diminished at the GB and declines the global $j_{\text{sc}}$ of the cell. Therefore all these local phenomena affect the global cell parameters directly.

4. Analytical model

The influence of the recombination at the grain boundaries in multicrystalline solar cells can be described in term of its recombination velocity by the 2-dimensional model developed by Lax [5]. Several assumptions are included:

- GB is specified by an injection independent recombination velocity $v_s$
- GB is perpendicular to the surface and located at $x = 0$ (see Fig. 2a))
- Negligible recombination in the depletion region and emitter
- Adjacent grains have same properties
- Carrier density at the p-side of the depletion layer is constant under forward bias

The corresponding differential equation with the boundary conditions described above was analytically solved by Lax and results in a description of $J_{01}^{\text{line}}(v_s)$ [5]. Since this result is an implicit expression, the assumption $(2D_n)/v_sL_n << 1$ has been supposed to obtain an explicit term for $v_s(J_{01}^{\text{line}})$ as it is already described in [3].

$$v_s = \frac{j_{01}^{\text{back}} N_A}{q n_i^2} \exp\left(\frac{J_{01}^{\text{line}} \pi N_A}{2D_n n_i^2 q} + 1\right)$$

(1)

$D_n$ is the diffusion constant for electrons in silicon, $q$ is the elementary charge, $N_A$ the doping level, $n_i$ the intrinsic carrier density, and $L_n$ the effective diffusion length in the adjacent grains. To evaluate the error made by this expression, if the assumption of $(2D_n)/v_sL_n << 1$ is not achieved, we compare the results evaluated by (1) with the implicit analytical solution calculated by Lax. Thus for given values of $j_{01}^{\text{back}}$, $N_A$, and $D_n$, the $J_{01}^{\text{line}}$-values for different recombination velocities were calculated by equation (4.8) in [5]. The resulting pairs of values are plotted in Fig. 3 by squares labeled as ‘$v_s$ exact’. Recalculating the obtained $J_{01}^{\text{line}}$ to $v_s$ with equation (1) results in the straight dashed line labeled with ‘$v_s$ approximation’. It is clearly visible that for recombination velocities lower than 3000 cm/s (resp. $J_{01}^{\text{line}} < 5 \times 10^{-14}$ A/cm) the correlation becomes quite poor for the chosen parameters. For values higher than $J_{01}^{\text{line}} > 1 \times 10^{-13}$ A/cm the approximation describe the default data very good. Introducing an empirical found correction factor $C_i$ (see eq. (2)) results in a much better correspondence of the exact solution calculated by Lax and the reversible approximation presented here. This is indicated by the solid blue line labeled with ‘$v_s$ corrected approximation’, which is calculated by eqn. (3), being the product of (1) and (2):

$$C_i = 1 - \exp\left(-\frac{J_{01}^{\text{line}} \pi N_A}{2D_n n_i^2 q}\right)$$

(2)

$$v_s = \frac{j_{01}^{\text{back}} N_A}{q n_i^2} \cdot \exp(1) \left[\exp\left(\frac{J_{01}^{\text{line}} \pi N_A}{2D_n n_i^2 q}\right) - 1\right]$$

(3)
Fig. 2. (a) Electrons injected into the p-side of a p-n junction diffuse towards the grain boundary (GB) with a rate determined by the recombination velocity of the GB and thus increase the local diffusion current density \( j_{01} \) (from \([3]\));

(b) Comparison of the analytical solution of the used model by Lax \((J_{line}^{n}(v_{s}))\) \([5]\) (black squares), the approximation based on the assumption \((2D_{n})/v_{s}L_{n} << 1\) developed in \([3]\) (red dashed line), and the approximation with the correction factor (solid blue line).

As already described in section 3, the corresponding \( j_{01} \) of an investigated GB is measured by a linescan perpendicular to the GB, which is evaluated by a Gaussian function fit as indicated in the upper part of Fig. 2(a). Since the dark current separation has indicated that \( j_{diff} \) is the dominant current contribution at a bias of 600 mV in the inner part of the cell, the power density image at 600 mV was interpreted as a pure \( j_{diff} \)-distribution. Thus the intra-grain diffusion current density can be interpreted without problems caused by the noisy pattern due to the deconvolution process.

Table 1 contains the results of four different recombination-active GBs marked by A through D in Fig. 1(d) and (f), which were evaluated by the above mentioned procedure under the assumption of \( N_{A} = 10^{16} \text{ cm}^{-3} \). A wide range of more than 3 orders of magnitude can be figured out for \( v_{s} \). Comparing results obtained from (d) and (f) results in almost the same values. Nevertheless the uncertainness of the calculated \( v_{s} \) rises with increasing \( J_{01}^{line} \)-values due to the exponential dependency of \( v_{s} \) on \( J_{01}^{line} \).

Table 1. Evaluation of recombination velocity of the GBs marked in Fig. 1(d) under the assumption \( N_{A} = 10^{16} \text{ cm}^{-3} \), \( D_{n} = 28.25 \text{ cm}^{2}/\text{s} \) according to equation (3)

<table>
<thead>
<tr>
<th></th>
<th>( j_{back}^{01} ) [A cm(^{-2})]</th>
<th>( j_{line}^{01} ) [A cm(^{-1})]</th>
<th>( v_{s} ) [cm s(^{-1})]</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>( 3.26 \times 10^{-13} \pm 1.22 \times 10^{-14} )</td>
<td>( 4.22 \times 10^{-14} \pm 2.33 \times 10^{-15} )</td>
<td>( 1.24 \times 10^{3} \pm 1.67 \times 10^{2} )</td>
</tr>
<tr>
<td>B</td>
<td>( 5.53 \times 10^{-13} \pm 2.43 \times 10^{-14} )</td>
<td>( 6.55 \times 10^{-14} \pm 3.69 \times 10^{-15} )</td>
<td>( 5.07 \times 10^{3} \pm 8.78 \times 10^{2} )</td>
</tr>
<tr>
<td>C</td>
<td>( 5.48 \times 10^{-13} \pm 2.80 \times 10^{-14} )</td>
<td>( 1.19 \times 10^{-13} \pm 4.03 \times 10^{-14} )</td>
<td>( 2.84 \times 10^{4} \pm 5.00 \times 10^{3} )</td>
</tr>
<tr>
<td>D</td>
<td>( 4.74 \times 10^{-13} \pm 3.59 \times 10^{-14} )</td>
<td>( 2.70 \times 10^{-13} \pm 5.48 \times 10^{-14} )</td>
<td>( 2.43 \times 10^{6} \pm 5.85 \times 10^{5} )</td>
</tr>
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</table>
For comparing the data with results published by other authors it has to be mentioned that the recombination velocity might be injection dependent [2]. For that reason the given results can just be related to data acquired under the same injection conditions. By averaging the $j_{01}\text{back}$ of altogether 25 linescans in this investigated defect rich region it could be estimated that only 40 % of the $j_{\text{diff}}$ stems from the intra-grain regions and about 60 % are caused by the grain boundaries. Thus, without the recombination-active GBs, $V_{oc}$ of this region would rise by more than 20 mV, if a homogeneous $j_{sc}$ of 32.9 mA/cm$^2$ is assumed, as it was measured at the original solar cell.

5. Conclusion

The aim of this work was to indicate the feasibility of measuring the recombination velocity of grain boundaries by means of DLIT and to present an explicit expression for $v_s(J_{01}\text{line})$. Thus a 3×3 cm$^2$ sized piece of an industrial solar cell was evaluated by lock-in thermography measurements and a subsequent deconvolution algorithm was used to improve the spatial resolution of the acquired images up to a FWHM of 400 μm. The interpretation of the obtained results was based on a model of the GB adopted from Lax [5], which was extended by an empirically found correction factor. This new application of DLIT imaging offers a deeper insight to the recombination activity of GBs and extends the possibilities in dark current characterization of solar cells. The codes of the used procedures “Local I-V”, “EL-Fit”, and “DECONV” are available from one of the authors (O.B.).

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