The reliability of thermography- and luminescence-based series resistance and saturation current density imaging

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1. Introduction

Solar cells, in particular wafer-based multicrystalline silicon cells, are large-area devices and exhibit unavoidable inhomogeneities. For example the excess carrier lifetime is affected by grain boundaries, dislocations, metallization and edge effects. Also the local voltage is inhomogeneous since the current has to be transported from the local region to the contacts and suffers from the series resistance of the grid and the emitter series resistance. Such inhomogeneous cells can be understood in detail only by applying appropriate imaging methods, which allow extracting e.g. the local saturation current density J01 or the effective series resistance R s [1,2]. J01 is a measure for the current loss within the device due to recombination within the emitter, the bulk and at both surfaces and Rs gives the resistance for the current transport from the local region to the contacts.

Until now two types of camera measurements, dark lock-in thermography (DLIT) and luminescence imaging using either electrical (EL) or optical (PL) charge carrier generation have been introduced leading to images of J01 and Rs when analysing solar cells at different operation conditions [3–8]. From these local diode parameter images, images of locally expected cell efficiency parameters like the open circuit voltage Voc, the fill factor FF, or the locally expected efficiency η may be calculated [9,10]. While the PL analysis directly leads to images of J01 and Rs, the pure DLIT analysis has to be supported with series resistance information. For this purpose DLIT can be combined with EL imaging [3], called DLIT–EL analysis in the following. Alternatively, if no series resistance image is required, a homogeneous value for Rs can be assumed. Thus, the pure DLIT analysis provides only images of J01.

All DLIT-, EL- and most of PL-based imaging methods are based on the “model of independent diodes”, because a realistic analysis of measured data in a 2-dimensional device model and their...
conversion into local $J_{01}$ and $R_s$ data is really hard to accomplish. Hence, it is assumed that each pixel is connected to the terminals by an independent series resistance and is electrically isolated from the neighbouring pixel [11], which is most easy to evaluate. In reality, however, the solar cell represents a resistance-diode network where neighbouring pixels are electrically connected to each other by the emitter layer and the grid. Hence, the series resistance is distributed and the independent diode approach does not properly consider horizontal balancing currents, which exist in inhomogeneous solar cells due to a laterally varying local diode bias. When in the past the same solar cell was analysed both by DLIT–EL and PL, it was regularly found that the results agree only qualitatively, but quantitatively they are inconsistent to each other [12,13]. Only in one case, where at the PL analysis the ideality factor was used as an additional fitting parameter, the agreement was reasonable [14]. The question is which of the methods delivers the most correct results, in particular of the $J_{01}$ distribution? In this work this question will be answered for DLIT, DLIT–EL, and PL.

It should be noted that there are two different definitions of the local series resistance $R_s$ in the literature. The most common definition, which is also used by most previous DLIT, EL, and PL methods [1–14], is to define $R_s$ in units of $\Omega \cdot \text{cm}^2$ as the local voltage drop between the terminals and the local diode, divided by the local diode current density. This definition corresponds to the equivalent model of isolated diodes for each position, which neglects the distributed character of the resistive network of the device. There is another PL-based $R_s$ evaluation method, which uses a linear response approach for the description of the solar cell [15,16]. This method is also used in the light-beam-induced current-based measurement technique CELLO (solar cell local characterization, [17]). Here $R_s$ is defined as the local voltage drop divided by the global cell current, therefore it is given in units of $\Omega$. This approach corresponds to a model of nearly perfectly interconnected local diodes. However, it does not allow to determine the local diode properties ($J_{01}$) in a straightforward way. The different definitions of $R_s$ complicate a direct comparison of the results of DLIT–EL, PL, and CELLO. In the only attempt of such a direct comparison [18] it was found that the results of DLIT–EL and CELLO agree qualitatively, but not quantitatively, as for the comparison between DLIT–EL and PL [12,13].

In this work DLIT, EL, and PL images of solar cells with known parameter distributions are realistically simulated, and then these data are back-converted into $R_s$ and $J_{01}$ images by applying acknowledged methods for evaluating measured DLIT, EL, and PL images. We apply a dedicated 2-dimensional resistance-diode network simulation tool [19] to model a symmetry element (1/4 of the free area between two busbars and two gridlines) of a typical industrial solar cell. Two different geometries are investigated, both containing certain defects.

The first has three different types of local shunts ($J_{01}$-type, $J_{02}$-type and ohmic-type) and the second has extended regions of increased $J_{01}$ values, see Section 2 for more details. The results of the 2-dimensional simulations are images of the local diode voltages and local currents under various biasing and illumination conditions. From these images DLIT, EL, and PL signal images are calculated and then evaluated according to generally accepted quantitative DLIT, DLIT–EL, and PL evaluation methods [4,5]. These evaluation methods, which are all based on the model of independent diodes, lead to predicted images of the effective series resistance $R_s$ and of $J_{01}$, which are compared to each other and to the $J_{01}$-distribution which was entered into the simulation. The differences between the input $J_{01}$ distribution and the calculated $J_{01}$ images are discussed by regarding the independent diode model approximation, horizontal balancing currents and thermal blurring.

### Table 1

| $R_s$ | Area-related local series resistance [$\Omega \cdot \text{cm}^2$] |
| $J_{01}$ | 1st Diode saturation current density, here 1 pA/cm²; 10 resp. 3 pA/cm² in $J_{02}$-shunt regions |
| $J_{02}$ | 2nd Diode saturation current density, 0.867 $\mu$A/cm² in $J_{02}$-type shunt, zero otherwise |
| $G_p$ | Parallel conductance, 0.132 $\Omega / \text{cm}^2$ (7.58 $\Omega \cdot \text{cm}$) in ohmic shunt, zero otherwise |
| $V$ | Applied bias |
| $V_{V1} = V_{V2}$ | Base potential below pn-junction (corresponds to voltage difference between point 1 and 2 as shown in Fig. 1) |
| $V_{V1} = V_{V2}$ | Diode voltage |
| $V_{V1} = V_{V2}$ | Emitter potential |
| $J_p$ | Photocurrent density, here 38 mA/cm² |
| $R_i$ | Back contact and base resistance for current flow into the depth, here 0.04 $\Omega \cdot \text{cm}^2$ |
| $R_{bdl}$ | Bulk resistance, here 1.5 $\Omega \cdot \text{cm}$ |
| $R_{em}$ | Emitter sheet resistance, here 50 $\Omega / \text{sq}$ |
| $R_{gr}$ | Grid resistance, here 0.4 $\Omega / \text{cm}$ |
| $R_{ct}$ | Grid contact resistance, here 1.5 m$\Omega \cdot \text{cm}^2$ |
| $V_T$ | Thermal voltage, here 0.0257 V at 25 °C |
| $i$ | Position index |
| $I$ | Total device current |
| $C_p$ | PL/EL scaling factor |
to this $J_{01}$-type shunt. All shunts have a size of $520 \times 520 \mu m$ ($4 \times 4$ pixel), and their magnitudes are chosen so that at the highest applied forward bias of 0.6 V they show about the same current density. For geometry B three extended regions with $J_{01} = 3 \, pA/cm^2$ are introduced, two of them lying close to the busbars and the third lying in the middle between the busbars. These regions will be called “spatially extended $J_{01}$-shunts” in the following. This second geometry is similar to multicrystalline solar cells, which usually contain low lifetime regions.

Fig. 1 shows the electronic circuits assumed for one pixel within the free cell area (a) and below a grid line (b). The ground point at the base represents the connection to the full-area back contact, which is assumed here to have negligible series resistance. All resistances and diode parameters are converted from their area-related values given in Table 1 to the device values of the circuits in Fig. 1 by regarding the correct geometrical relations. The vertical resistances $R_{c1}$ represent the contact resistance of the back contact plus the bulk resistance for current flow into the depth. The horizontal resistances $R_{bulk}$ describe the lateral current flow in the bulk. Here an active depth of $130 \mu m$, corresponding to the pixel size, is assumed. The local diode is characterized by its saturation current density $J_{00}$ and by its photocurrent density $J_{Ph}$. In general, low lifetime regions with increased $J_{00}$ also have a reduced $J_{Ph}$. Deliberately, $J_{Ph}$ is assumed as constant here to better separate the effect of the local diode $J_{00}$ from the effects of an inhomogeneous $J_{Ph}$. Moreover, all previous DLIT-EL and PL evaluation methods (except [7]) are assuming a homogenous $J_{Ph}$. The second diode $J_{02}$ and the ohmic parallel resistor $G_p$ exist only in the corresponding shunt regions. The horizontal emitter resistance $R_{em}$ represents the emitter sheet resistance, which is assumed here to be $50 \, \Omega/sqr$.

In the metallized area shown in Fig. 1(b) $R_{c2}$ is the contact resistance to the grid contact and $R_{gr}$ represents the grid resistance. Note that the symmetry element considered here contains at the edges only half of a grid line and half of a busbar, the other halves belong to the neighbouring regions. This was regarded in the dimensioning of the components. Note also that in reality half the width of a gridline (typically $65 \mu m$, half of $130 \mu m$) is smaller than one pixel row ($130 \mu m$). Nevertheless, for keeping the calculations simple, the grid lines on the top and the bottom are assumed here to have a width of 1 pixel. The grid resistances $R_{gr}$ are chosen to lead to a realistic grid resistance of $0.4 \, \Omega/cm$ for the complete grid line [21] ($0.8 \, \Omega/cm$ for the half grid). Also the contact resistances $R_{c2}$ are chosen to match the contact resistance of the real (half) grid acting on this pixel line. Within the busbar region the horizontal resistances within the metallization layer were chosen to be zero. We assume beneath the metallized regions the same photocurrent $J_{Ph}$ as in the free area. This is a simplification but also in a real PL experiment, the impinging light in the free area is refracted and also enters the shadowed regions. Moreover, due to light scattering within the detector, also the signal of one camera pixel contains contributions of the neighbouring pixels [22]. In the PL evaluation procedures the shadowing of the PL signal in these regions is attributed to a reduced luminescence scaling factor $C_i$. With our chosen device parameters we have tried to match a conventional industrial solar cell as good as possible, but the goal of this work is not a 100% realistic solar cell modeling. Instead, we model the local diode voltage distribution around $J_{01}$-type and other shunts in a solar cell in a 2D model, thereby realistically regarding the distributed character of the series resistance.

3. Simulated voltage and current images

Fig. 2 shows the main results of the 2D device simulations. The left images correspond to geometry A and the right images to geometry B. The different scaling limits are indicated for each image. Each image shows one window between two busbars and two gridlines. Fig. 2(a) shows the two $J_{01}$ distributions assumed for the simulations. In geometry A (left part), the diode in the middle is the $J_{01}$-type shunt, the two shunts left and right of it are the $J_{02}$-type shunts, and the two shunts near the left and right edges, close to the busbars, are the ohmic-type shunts. Fig. 2(b) and (c) show the local diode voltage distributions and (d) and (e) the local current densities for applied biases of 0.55 and 0.6 V in the dark. Fig. 2(f) and (g) shows the local diode voltage distributions under 1 sun equivalent illumination and current extraction for biases of 0.525 and 0.575 V. These two applied biases are both lying below the open circuit voltage of this cell, hence these are current extraction conditions and $V_{oc}$ is lying above the applied bias $V$ here, in contrast to the dark simulation in Fig. 2(b) and (c). In Fig. 2(h) and (i) the lateral balancing currents appearing in the emitter of geometry A and B under illumination at a bias of 0.575 V are visualized. They are calculated as the horizontal resp. vertical gradient of the emitter potential divided by the emitter sheet resistivity (here $50 \, \Omega/sqr$). In the horizontal balancing current images bright contrast corresponds to current flow from left to right and vice versa, and in the vertical current images bright contrast corresponds to current flow from top to bottom and vice versa. At the applied bias of 0.575 V all local shunts in geometry A draw nearly the same dark current, as can be seen in the balancing current images. Under these conditions, the mean current density outside of the shunts is about $-30 \, mA/cm^2$, whereas in the shunt positions it is above $+50 \, mA/cm^2$, hence here the current direction was reversed. This can nicely be seen in the vertical balancing current image (i) of geometry A. This image is dominated by the photocurrent flow to the top and bottom gridline. However, in the shunt positions, the direction of the vertical current flow reverses. In geometry B the net photocurrent in the $J_{01}$ shunt regions is reduced to one half, which also reduces the vertical balancing currents. The horizontal balancing currents react to the horizontal steps in the emitter potential, which are also visible in Fig. 2(g).

4. Conversion to DLIT, EL and PL signal images

For the DLIT and EL simulations the 2D equivalent circuit of one symmetry element of the solar cell was calculated for applied biases of $V_{oc} = 0.5 \, V$, $0.55 \, V$, $0.6 \, V$, and $-1 \, V$ assuming no illumination, hence with $J_{Ph} = 0$. The main results of these simulations were the local values of the diode voltages $V_{di}$ across the local diodes ($i=position$ index), which are characterized by their assumed saturation current densities $J_{01,i}$, $J_{02,i}$, the local conductance $G_i$, and the local base
potential $V_{cl,i}$. Then these local voltages are used to calculate the dark current densities $J_i$ according to the two-diode model ($V_T$ is the thermal voltage):

$$J_i = J_{01} \exp \left( \frac{V_{di}}{V_T} \right) + J_{02} \exp \left( \frac{V_{di}}{2V_T} \right) + G_i V_{di}$$  \hspace{1cm} (1)

Knowing $J_i$, the total device current $I$ is calculated for each applied bias by summing up over all pixel currents. Then, for each bias, the local emitter voltage $V_{e,i}$ is calculated as the sum of $V_{cl,i}$ and $V_{di,i}$,

$$V_{e,i} = V_{cl,i} + V_{di,i}$$  \hspace{1cm} (2)

leading to the locally dissipated power density for vertical current flow (into the depth),

$$P_{i}^{\text{verm}} = J_i V_{e,i}$$  \hspace{1cm} (3)

Note, while this dissipated power density is visible in DLIT images resulting from the heat generation of the current flow through $R_{sh}$, and the diode, the net luminescence emission is fully determined by the local diode voltage $V_{di}$, which is a measure of the quasi Fermi level splitting, see below. In addition, here also the power densities dissipated by the lateral current flow in the emitter and the gridline, as well as the Joule heating for the vertical current flow across the grid resistance $R_{sh}$, have been regarded. However, it has turned out that these additional heat contributions amount everywhere to less than $10^{-6}$ of the heat caused by the vertical current flow. Hence, the usually made assumption that the vertically flowing current dominates the total heat dissipation [3,4] is correct for these solar cells. The total dissipated local power density $p_i$ is then artificially blurred by convoluting it with the $90^{\circ}$ point spread function of a thermally thin sample, for details of this convolution procedure see [1]. For reducing the blurring radius of the local shunts to the window region investigated here, a relatively high lock-in frequency of 30 Hz has been assumed. This results in simulated DLIT images for all applied biases.

For the PL image simulation the 2D equivalent circuit of one symmetry element of the solar cell was calculated for two applied biases of $V = 0.525$ and $0.575$ V under illumination condition of 1 sun equivalent, and in addition at 0.1 sun illumination under $V_{oc}$ condition (0.563 V for geometry A and 0.561 V for geometry B). From the $V_{di}$ data resulting from our 2D device simulation under illumination, images of the PL signal $\Phi_{PL}(V_{di})$ are calculated assuming the long-wavelength detection range as [19]:

$$\Phi_{PL}(V_{di}) = \Phi_{EL}(V_{di}) + \Phi_{PLSC} = C_i \exp \left( \frac{V_{di}}{V_T} \right) + \Phi_{PLSC}$$  \hspace{1cm} (4)

Details for calculating $C_i$ and $\Phi_{PLSC}$ for different conditions can be found in [19]. Note that the latter equation holds for EL and PL at all operation conditions, i.e. the EL-only case is obtained by setting $\Phi_{PLSC} = 0$, which gives the simple relation $\Phi_{EL} \propto \exp(V_{di}/V_T)$. Eq. (4) contains the superposition principle: At a certain local diode voltage $V_{di}$, the PL signal can be described as the sum of the “equivalent EL” signal at this voltage $\Phi_{EL}(V_{di})$ and the PL signal under short circuit condition $\Phi_{PLSC}$ [2,5,19]. Only the “equivalent EL” or “net PL”, which is the PL signal minus the $J_{sc}$-PL signal, is exponentially dependent on the local diode voltage and can be used for quantitative PL evaluation. Thermal blurring does not occur here; this is expected to be one of the advantages of EL and PL compared to DLIT imaging [8].

Fig. 3(a) and (b) shows images of the simulated DLIT signal of geometries A and B for applied biases of 0.55 and 0.6 V in arbitrary units. Fig. 3(c) shows the assumed distribution of the scaling constant $C_i$ according to [19]. Fig. 3(d)-(f) shows the simulated PL images for $V_{oc}$ condition at 0.1 sun (scaling measurement) and 1 sun for the applied bias of 0.525 and 0.575 V. We see in (d) that the $J_{02}$- and ohmic-type shunts show a reduced PL signal in the scaling measurement, which is translated later on into minima of $C_i$, see Section 6. Fig. 3(g) and (h) shows the simulated EL images for 0.55 and 0.6 V bias, which are used later on for DLIT-EL analysis, see next section.

5. DLIT and PL evaluation procedures

The DLIT-based data evaluation was performed by using the “Local I–V” method [4], which, if $n_2 = 2$ is assumed, as here, evaluates the DLIT signal distributions simulated for two forward and one reverse bias (3 DLIT images). In this evaluation the local DLIT signal is fitted for all three applied biases $V$ to the locally dissipated power density by using Eqs (1)–(3), and

$$V_1 = V - R_{sh}J_i$$  \hspace{1cm} (5)

The result of this fit are images of $J_{01}$, $J_{02}$, and $C_{p1}$. Note that for the DLIT images only the relative and not the absolute values of
the temperature modulation are required, since the quantitative scaling occurs via the flowing total device current \( I \). This analysis needs \( R_s \) as an input parameter, hence it does not lead to an \( R_s \) image. The preferred option is to calculate \( R_s \) according to the so-called “RESI” method [3]. In this method, which only evaluates the first diode \( J_{01} \) contribution of the dark current, the local voltage is obtained by evaluating two EL images for two biases after the independent diode model according to (4) and (5) with \( J = J_{01} \exp (V_{d,j}/V_T) \). This evaluation leads to EL-based images of \( C_i \) and of the product \( J_{01} \times R_s \), which allows to calculate the local diode voltage \( V_{d,j} \) at these two biases after (5) [23]. The evaluation of the local diode voltage distribution and the DLIT signal at the highest forward bias leads to the DLIT–EL–\( R_s \) image, which can be used for the DLIT–EL-based “Local \( I–V \)” evaluation [3,4]. Alternatively, a PL-based \( R_s \) image can be used for the DLIT analysis or a homogeneous value for \( R_s \) can be assumed. It has been found that the DLIT–EL analysis leads to most realistic values for efficiency-related parameters like the fill factor or the locally contributing efficiency, which are strongly influenced by the local \( R_s \) [9]. However, it will be shown below that for imaging \( J_{01} \) the pure DLIT analysis assuming a homogeneous value of \( R_s \) is sufficient.

For the PL data evaluation the local diode voltages under illumination are calculated from the PL signal after Eq. (4). The evaluation of an open circuit net PL image at reduced intensity (here 0.1 sun) is used to calculate the local scaling constant \( C_i \) [22]. This evaluation assumes that, under this condition, the local diode voltage \( V_{d,j} \) equals everywhere the (global) open circuit voltage \( V_{oc} \) because at open-circuit conditions the current flow is zero and thus also the voltage drop from the contacts to the local position. It will be discussed in Section 6 that this expectation only holds in the model of isolated diodes, but not in a real solar cell containing local shunts.

Within the model of independent diodes and assuming only \( J_{01} \)-type currents, as usual in most previous PL evaluation methods, the local diode voltages \( V_{d,j} \) obtained from Eq. (4) are evaluated after [5], in analogy to Eq. (5):

\[
V_i - V = R_s (J_p - J_{01}) \exp (V_{d,j}) \exp (V_{d,j}/V_T)
\]  

(6)

For performing the so-called “C-DCR” PL evaluation method (“coupled determination of the dark saturation current and the series resistance” [5]), altogether five PL images are needed: one at reduced intensity under \( V_{oc} \) condition (scaling measurement), two at full intensities for two different loading conditions, and two PL images under \( I_{sc} \) condition for reduced and full intensity, respectively. From the scaling measurement and \( I_{sc} \)-PL under reduced intensity, the image of \( C_i \) is obtained after (4) by assuming \( V_{d,j} = V \). Then (4) is used to calculate the images of \( V_{d,j} \) for the two loading conditions. Then (6) has to be solved for each pixel \( i \) for the two applied biases \( V \), leading for each pixel \( i \) to calculated values of \( R_s \) and of \( J_{01} \). In our 2D-simulations we have directly evaluated net PL images after (4), hence we did not need the \( J_{01} \)-PL images. Again, this whole analysis is based on the simple model of independent diodes, whereas the local values of \( V_{d,j} \) for calculating the DLIT, EL and PL images were calculated here by applying a realistic 2D diode-resistance network. Hence deviations are expected because of the electrical connection from pixel to pixel, which is not considered for in the independent diode model.

6. Scaling factor and series resistance results

It was mentioned in the last section that the pure DLIT analysis does not lead to an \( R_s \) image. Only the combined DLIT–EL analysis generates an \( R_s \) image by evaluating an EL-based image of \( V_{d,j} \) at the highest used forward bias. This EL evaluation, just as the PL evaluation, is based on the model of independent diodes and does not consider any \( J_{02} \)- or ohmic-type current contributions. Hence, if such contributions are present, as in geometry A, these regions \( C_i \) and with it also the local diode data are expected to be erroneous. Also if in the considered cell strong local shunts are present and significant lateral balancing currents are flowing even in the PL scaling measurement \( (V_{oc} \text{ image at } 0.1 \text{ sun}) \), the assumption \( V_{d,j} = V \) might fail there. Indeed, Fig. 4 shows that, for geometry A, the PL-obtained \( C_i \) (b) shows local minima also in \( J_{02} \)- and ohmic-type shunt positions, where the assumed \( C_i \) did not show any minima. This is due to the fact that in the scaling measurement the local diode voltage also under low illumination and open circuit condition does not coincide with the applied bias, see Fig. 3(d). Note that at this low voltage the \( J_{02} \)- and ohmic-type shunts draw more current than the \( J_{01} \)-type shunt in the middle, see Fig. 2(b). Therefore the minima of the PL signal in the \( J_{02} \)- and ohmic-type local shunt positions (see Fig. 3(f) are wrongly attributed by the PL evaluation procedure to local minima of PL–\( C_i \) see Fig. 4(b). The same occurs in the EL
evaluation, see Fig. 4(c). In geometry B, which is dominated by $J_{01}$ and does not show local shunts, PL–$C_i$ and EL–$C_i$ closely match the assumed $C_i$. Hence, in these regions, at the assumed applied biases, the PL and EL-measured local diode voltages agree with the simulated ones within 1 mV accuracy.

Fig. 4(d) and (e) shows the distribution of the series resistance as obtained by DLIT–EL at 0.6 V bias (d) and by PL (e) for both geometries. The DLIT–EL $R_s$ image at 0.55 V is very similar to (d) and not shown here. Around the regions of $J_{01}$- and $J_{02}$-type shunts of geometry A and in the extended $J_{01}$-shunt regions of geometry B, the DLIT–EL–$R_s$ images show local minima, but in the local shunt positions of geometry A local maxima. This will be discussed in Section 10. The PL–$R_s$ images are nearly undisturbed by the local shunts and by the $J_{01}$ distribution. In the regions outside of the shunts PL–$R_s$ closely matches DLIT–EL–$R_s$. The average values of $R_s$ for the DLIT–EL evaluation is 0.5 Ω cm² and that of the PL evaluation 0.51 Ω cm².

Note that the PL image for the lower applied bias (here 0.525 V), where the dark current is lowest and usually negligible compared to the photocurrent, mainly determines the value of PL–$R_s$. On the other hand, the PL image for the higher applied bias (here 0.575 V), where the total current is already significantly influenced by the dark current, mainly determines PL–$J_{01}$. Hence, in PL evaluation the series resistance is measured essentially under homogeneous current density condition. This is the main reason why PL–$R_s$ is nearly undisturbed by local shunts. This is also the reason why even in multicrystalline solar cells the Trupke method for measuring $R_s$ [2], which assumes a homogeneous $J_{01}$ distribution, leads to the same results as the C-DCR method [5]. In DLIT and EL, on the other hand, only the dark current flows, which is inhomogeneous in most solar cells, in particular in multicrystalline ones. Therefore the DLIT–EL–$R_s$ is stronger influenced by the distribution of the dark current. This does not mean that the DLIT–EL–$R_s$ results are erroneous. In the model of independent diodes, for this inhomogeneous dark current distribution they exactly describe the local diode voltages $V_{di}$, as good as in the case of homogeneous photocurrent density $PL–R_s$ describes them. However, only the PL–$R_s$ image is proportional to the so-called point-to-point or geometrical series resistance [21], which would be measured by a local probe in position $i$ towards the busbars at zero bias. This type of resistance, which is obtained e.g. by the FFT impedance analysis of CELLO [17], can be interpreted intuitively much better than DLIT–EL–$R_s$, which is influenced by $J_{01}$.

7. Saturation current density results

The saturation current density results are shown in Fig. 5. For the pure DLIT analysis a homogeneous $R_s$ of 0.5 Ω cm² was assumed, which corresponds to the average value obtained in the DLIT–EL $R_s$ analysis, see Section 6. We show results of a “low-current regime” evaluation using DLIT results of 0.5 V, 0.55 V, and −1 V and a “high-current regime” evaluation using DLIT results of 0.5 V, 0.6 V, and −1 V, since it is expected that possible errors of this procedure may depend on the magnitude of the currents used in the DLIT measurements. Also the combined DLIT–EL analysis was performed as a low-current analysis, based on DLIT images at 0.5, 0.55 and −1 V and on the EL-based $V_{di}$ at 0.55 V, and a high-current analysis based on DLIT images at 0.5, 0.6, and −1 V and on the EL-based $V_{di}$ at 0.6 V. For geometry B, which does not contain any ohmic-type currents, the DLIT images at −1 V are not necessary. For PL, the simulated PL images at 0.525 V and 0.575 V at 1 sun illumination and PL–$C_i$ of
Fig. 4(b) are used for calculating the PL-based $V_{01}$ at 0.525 and 0.575 V, which are used in the analysis after (6).

Since for all DLIT-based analysis results thermal blurring is present, Fig. 5(a) and (b) shows the original and the artificially thermally blurred assumed $J_{01}$ distribution. Calculated DLIT–$J_{01}$ distributions for the low- and the high-current regime evaluations are shown in (c) and (d) and DLIT–EL–$J_{01}$ distributions in (e) and (f), respectively. Generally, these DLIT-based $J_{01}$ images match the blurred assumed $J_{01}$ distribution (b) well. The homogeneous value of $J_{01}$ of 1 pA/cm$^2$ is correctly imaged everywhere with deviations below 10%. Both for the DLIT- and for the DLIT–EL evaluation the low-current $J_{01}$ results fit the blurred assumed input $J_{01}$ distribution better than the high-current results. In the high-current DLIT–$J_{01}$ result of geometry A the $J_{01}$-type shunt is somewhat underestimated (1.38 instead of 1.56 pA/cm$^2$ in the maximum), and in geometry B the extended $J_{01}$ shunts left and right are overestimated (3.7 instead of 2.8 pA/cm$^2$). These are mainly effects of the assumed homogeneous $R_s$, which mainly affects the high-current results. In the DLIT–EL evaluation in geometry A, in particular in the high-current evaluation (f), also the $J_{02}$-shunts are slightly visible. This, just as the other current-dependent errors, has to be considered as an artifact of the evaluation, caused by the used model of independent diodes. For geometry B the high-current DLIT–EL result (f) is significantly closer to the expected distribution (b) than the pure DLIT high-current result (d). This means that, at least under high-current conditions, the implementation of the local $R_s$ image after [3] in DLIT–EL indeed improves the accuracy of the analysis. The origin of the artifacts of the DLIT–EL analysis will be further discussed in Section 10. The maxima of $J_{01}$ in the low-current DLIT evaluation (c) (1.51 pA/cm$^2$ geometry A and 2.94 pA/cm$^2$ geometry B) closely match that of the blurred input $J_{01}$ distribution (b) (1.56 pA/cm$^2$ geometry A and 2.84 pA/cm$^2$ geometry B). The $J_{02}$ and $G_n$ results of the DLIT evaluation of geometry A, which are not shown here, closely match the assumed distributions if they are thermally blurred. It can be summarized that DLIT and DLIT–EL provide a good to reasonable imaging of $J_{01}$, whereby the accuracy improves for lower current densities used for the measurement.

Fig. 5(g) shows the PL–$J_{01}$ images of both geometries. As in the DLIT case the homogeneous value of 1 pA/cm$^2$ is correctly imaged, at least in the middle of the undisturbed regions. Towards the grid lines $J_{01}$ increases by up to 40%. In geometry A the maximum in the shunt position is also here significantly too weak (1.49 pA/cm$^2$ instead of the expected 10 pA/cm$^2$) and appears slightly blurred. We attribute this directly to the simple model of independent diodes since there is no thermal blurring in PL imaging, see Section 10. As for DLIT–EL, the $J_{02}$-type shunts in geometry A are interpreted by this PL evaluation as weak $J_{01}$-type shunts. The ohmic shunts are not visible in the PL–$J_{01}$ image. This is probably due to the weak voltage dependence of their current, therefore the method identifies them completely as a $C_i$ variation.

Also the extended $J_{01}$ shunts in geometry B appear in PL significantly weaker than expected. Here the deviation of the determined $J_{01}$ values depends on the position in the cell. In the central region PL–$J_{01}$ is only 1.83 pA/cm$^2$ instead of the expected 3 pA/cm$^2$, and in the center of the two outer regions it is 2.25 pA/cm$^2$. Here the detected PL–$J_{01}$ signal depends on the distance to the grid lines, towards the grid lines the PL–$J_{01}$ value increases to 2.48 pA/cm$^2$. The reasons for these dependencies will be discussed in Section 10.

8. The influence of the ideality factor

For all simulations of this work an ideality factor of the first diode current of $n_1=1$ has been assumed. However, if the recombination properties of the lifetime-limiting defects are dependent on the excitation intensity (injection-level), this ideality factor may be larger than 1. This may also hold for dislocations and grain boundaries, which dominate the bulk lifetime of multicrystalline solar silicon material, as it has been shown e.g. by Macdonald et al. [24] and Rißland et al. [25]. Shen et al. [14] have used $n_1$ as a fitting parameter for improving the agreement between the globally measured illuminated $I-V$ characteristic and that simulated after a PL analysis of this cell. In this work an optimum value of $n_1=1.15$ has been found, which also leads to an improvement of the correspondence between PL-based and DLIT-based local efficiency images. Here we will check how a possibly wrongly assumed ideality factor influences the results of the DLIT–EL and PL-based local analysis. Hence, we use the DLIT and PL images, which are simulated for $n_1=1$, and evaluate them by assuming $n_1=1.1$. Since, for a given dark current density at 25 °C, the values of the saturation current density are strongly influenced by the chosen value of $n_1$, we will normalize the resulting saturation current densities $J_{01}$, which belong to $n_1>1$, to the original $J_{01}$ by dividing them by the factor [25]:

$$ J_{01} = \frac{\exp(V/V_i)}{\exp(V/n_1V_i)} = \frac{(1-(1/n_1)V)}{V_i} $$

For the voltage $V$ in (7) a value of 0.6 V is assumed, leading for $n_1=1.1$ to a correction factor of 8.35. Fig. 6 shows the results of this procedure. For the DLIT analysis (a) the results are nearly identical to that in Fig. 5(f). This shows that the DLIT analysis is only weakly influenced by a possibly wrongly chosen value of $n_1$. The PL–$J_{01}$ data (b), on the other hand, are strongly influenced by the assumed value of $n_1$. For the chosen $n_1=1.1$ the $J_{01}$-corrected values of $J_{01}$ show a larger local variation than before, and they go into the negative. Therefore Fig. 6(b) is scaled from $-1$ to $+2$ pA/cm$^2$. In the black regions $J_{01}$ goes deep into the negative. In this evaluation, in the regions with nominally homogeneous $J_{01}$, the apparent $J_{01}$ values strongly correlate with the local $R_s$. In regions with high $R_s$ the values of $J_{01}$ become larger and in regions of low $R_s$ smaller, up to becoming negative. In the busbar regions at the left and right edge, where $R_s$ is very small, extreme values of $J_{01}$ between $-110$ and $+40$ pA/cm$^2$ appear, which are clearly artifacts. Reasons for these errors will be discussed in Section 10. This investigation shows that the PL–$J_{01}$ evaluation becomes strongly disturbed, if a wrong value of $n_1$ is assumed for the data evaluation.

9. Comparison to measured results

The findings of our simulations agree well with previous comparisons of lock-in thermography and luminescence investigations.
[12,13]. Fig. 7 shows the comparison of experimentally obtained DLIT–EL based $J_{01}$ (a), PL-based $J_{01}$ (b), DLIT–EL-based $R_s$ (c), and PL-based $R_s$ (d) images from the same multicrystalline silicon cell, taken from the data of [12]. While the average value of $J_{01}$ is about the same for both methods, the relative differences are much more pronounced in DLIT–EL–$J_{01}$ (a) than in PL–$J_{01}$ (b). According to the simulation results of this paper, DLIT–EL–$J_{01}$ has to be considered as the more realistic $J_{01}$ distribution. In the DLIT–EL–$R_s$ image (c) the predicted local minima in the positions of extended $J_{01}$-type shunts are clearly visible. The PL–$R_s$ image (d), on the other hand, is not disturbed by any lifetime inhomogeneities, as predicted. Moreover it shows a clearly better spatial resolution and signal-to-noise ratio. Therefore, for the evaluation of solar cells, the PL–$R_s$ image is clearly more meaningful than the DLIT–EL–$R_s$ image.

10. Discussion

This contribution has shown that PL imaging leads to reliable data for the local effective series resistance $R_s$, but not for the local saturation current density $J_{01}$. Only in the case of a homogeneous distribution of $J_{01}$ over a large region, and if the correct value of $n_1$ is chosen, PL-based $J_{01}$ data are reliable. However, local maxima of $J_{01}$, as they appear in local regions of recombination-active bulk defects, are generally imaged significantly too weak. In the DLIT- and DLIT–EL-based analysis, on the other hand, the resulting $J_{01}$ distribution appears thermally blurred, but its quantitative influence is described correctly. The reason for this difference is that the PL analysis reacts much more critical to the wrongly assumed model of independent diodes than the DLIT analysis. Note that PL basically measures the local diode voltage. If there would be no series resistance, this local voltage would everywhere be equal to the applied bias. Then Eq. (6) would not allow one to obtain any information on local dark current densities described by $J_{01}$, since lateral balancing currents would completely equalize the local potential. The information on $J_{01}$ can be obtained in PL only by evaluating the bias-dependent voltage drops at $R_s$. Only if $R_s$ is constant, strictly independent of the flowing current, and if the local diodes are separated from each other, this evaluation may be successful. If, however, the device is a 2D resistive network, but the evaluation is based on the independent diode model, the network tends to equalize the local potentials and the local voltage drops are not strictly proportional to the local current densities.
independent of the local and DLIT diodes, which de-PL as long as the investigated cell has no serious

However, as these simulations have shown, these errors are small when the investigated cell has no serious Rs problem.

In the regions with homogeneous J01, the DLIT–EL–Rs and the PL–Rs images nicely agree with each other. This proves that, for homogeneous solar cells like monocrystalline ones, both Rs imaging methods are equivalent. However, the DLIT–EL–Rs image is influenced by the presence of local shunts, in contrast to the PL-based one. This is again a result of the applied model of independent diodes, which defines Rs as the local voltage drop defined by the local current density. Note that, due to the lateral resistive coupling in the 2D network, the local diode voltage in shunt position does not drop as much as expected for independent diodes. Therefore, in extended shunt positions like in geometry B, the local voltage drop is lower than expected for this local current density, leading to a reduced DLIT–EL–Rs there. The local maximum of DLIT–EL–Rs in the positions of very local shunts in geometry A and the weak vertical profile of J01 in the high-current DLIT–EL analysis are due to another effect, which is the different spatial resolution of the EL-based local diode voltage distribution and the DLIT-based local current density distribution. Therefore the very local voltage drop in a shunt position, which is mainly due to the voltage drop at Rs, is not accompanied by a corresponding local current density maximum and leads to the observed relative maximum of DLIT–EL–Rs in very local J01- and J02-shunt positions of geometry A. This different spatial resolution is also responsible for the weak vertical profile of DLIT–EL–J01 in the extended J01 shunts in geometry B in the high current regime (Fig. 5f), which is influenced by the vertical parabolic local diode voltage profile there (Fig. 2c). In this region, close to the grid lines the high current DLIT–EL–J02 appears smaller than expected, and in the middle between the grid lines it appears larger. This profile is invisible or even slightly inverted in the pure DLIT–J01 signal in Fig. 5(d). Note, however, that the EL simulations, where the EL–V data are based on, assume very idealized conditions. They assume that the photon signal detected in one camera pixel stems only from luminescence out of this imaged pixel. In reality, there is light scattering in the detector chip as well as in the sample, and there are optical scattering and blurring effects, which reduce the spatial resolution of EL imaging [22]. In fact, in local J01-shunt positions like recombination-active grain boundaries [26], local maxima of DLIT–EL–Rs have not been observed yet.

The conclusion of this work is that the conventional PL evaluation is most reliable for Rs imaging but cannot replace DLIT or DLIT–EL with respect to J01 imaging and local current type identification. A reliable PL evaluation method, which leads to a meaningful J01 image, independent of the local Rs, and which even may identify J02- and ohmic shunts reliably, must consider the influence of local balancing currents, hence it must go beyond the model of independent diodes.

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Appendix

The results of this work may nicely be visualized by considering a chain of 7 resistance-interconnected single diodes to ground as a model device. The leftmost diode No. 1 and the rightmost No. 7 are assumed to be connected with the busbars. The coupling resistors R between the diodes, which are all the same, are chosen together with the values of I01 of the diodes in such a way that, at the applied bias of 0.6 V, the voltage drop between the busbars and the middle diode is between 15 and 20 mV. For simplicity here only the dark case is considered. The illuminated case behaves in the same way, except that then the voltages of the inner diodes are lying above the busbar bias. Two cases are simulated: (A) all diodes show the same value of I01 (homogeneous I01 case), and (B) only the outer 6 diodes show this I01, but the central diode shows three times this I01 (inhomogeneous I01 case). Case (B) is the 1-dimensional analog to geometry B considered in the previous simulations. Fig. 8 shows the results of these simulations, with the homogeneous case (A) shown as a full line and the inhomogeneous case (B) as a dashed line. In Fig. 8(a) the local diode voltages are shown and in (b) the simulated local currents. We see that, in the central diode No. 4, the current in (b) increases by 140% by increasing I01 of the central diode, but the voltage drop in (a) increases only by 37%. This is a direct consequence of the lateral interconnection of diodes, as discussed above. In the following we assume that PL and EL are able to measure the local diode voltages exactly. Then, since DLIT–EL measures the local current (density) by measuring the local power (density), divided by the local diode voltage, this current profile in (b) is exactly that measured by DLIT–EL. Thermal blurring is not considered here.

Fig. 8(c) shows the profiles of the local DLIT–EL series resistances, which are calculated after (5). In addition (c) shows the PL–Rs profile, which was obtained by assuming the same currents through all diodes and dividing the local voltage drops by this current. This profile is exactly parabolic, whereas in the DLIT–EL–Rs profile of the homogeneous I01 case it is slightly non-parabolic. This comes from the fact that, as Fig. 8(b) shows, even for a homogeneous I01 the local current is position-dependent. The same departure from the parabolic shape was reported in [21] in the high-current regime. In the inhomogeneous I01 case (B) we see that the DLIT–EL–Rs is locally reduced in the central shunt region and slightly increased around. Exactly the same has been simulated in Fig. 4(d) in Section 6 for geometry B. As already discussed there, this is a natural consequence of the model of independent diodes applied for defining this Rs if the real device shows a distributed Rs and an inhomogeneous current distribution. The reduction in shunt position is due to the fact that, as Fig. 8(a) and (b) shows, the relative current increase in shunt position is larger than the relative increase of the voltage drop. The Rs increase around the shunt is due to the fact that, around the shunt, the diode current decreases but the voltage drop increases.

Fig. 8(d) shows the luminescence-based current obtained applying the PL procedure (6) to this dark case. Hence, here the current is calculated as the local voltage drop divided by the local Rs, for which here the PL–Rs was assumed. In this simulation the currents for diodes 1 and 7 could not be calculated since there (at the busbars) both the voltage drop and Rs are zero. For the homogeneous I01 case (A) the luminescence-based current in (d) exactly matches the real current in (b). In the inhomogeneous case (B), however, this luminescence-measured current increases in the middle only by 49% instead of the expected 140% by increasing I01 of the central diode, in qualitative accordance with our simulations of Fig. 5. We also see a clear blurring...
around, which is due to the fact that the single shunt diode also influences the potentials of the surrounding diodes due to the lateral resistive coupling, see Fig. 8(a). Herewith we propose to call this kind of blurring, which also affects PL imaging results, “resistive blurring”, since it is caused by the resistive interconnection of the local diodes.

References


