Photoluminescence image evaluation of solar cells based on implied voltage distribution

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ABSTRACT

All previous methods for quantitatively evaluating photoluminescence (PL) images of solar cells assumed a laterally constant short circuit current density Jsc. Moreover, they had to subtract a Jsc PL image from all other PL images for considering the diffusion-limited carriers. Here a more realistic PL evaluation method is introduced, which is based on a recently published alternative model of the illuminated solar cell. In this model an analytic expression is derived by considering the illuminated current as a diffusion process between bulk and the pn-junction and linking the implied voltage in the bulk with the local pn-junction voltage under illumination. This model does not assume a laterally constant Jsc but a constant light absorption rate, and it leads to a prediction of the Jsc distribution solely based on PL imaging results. Moreover, it regards the shadowing of the cell by the busbars and grid lines. This model is applied to the quantitative evaluation of PL images of an industrial multicrystalline silicon solar cell. The resulting series resistance and saturation current density images are compared with that of an established PL evaluation method, and the resulting distribution of Jsc is compared with LBIC results. The results of the new method appear slightly more realistic than that of the old one, since they consider the inhomogeneity of Jsc.

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1. Introduction

In the last decade photoluminescence (PL) imaging of solar cells has been established as a successful and fast method for quantitatively imaging the distribution of the local series resistance and of the local saturation current density, see e.g. [2–4]. All these methods are based on the model of independent diodes, each being connected with the terminals via an independent series resistance, which is expressed in this model area-related in units of Ω cm². Moreover, most of the previous methods assume an injection intensity-independent lifetime by assuming an ideality factor of unity for the diode current. Only in [4] this ideality factor may be assumed to be larger than unity for the whole area, which enables a fit of the simulation results to the global illuminated characteristic.

All previous PL evaluation methods for solar cells have another point in common: they need to subtract a PL image taken under short circuit (Jsc) condition from all other PL images for obtaining a ‘net’ PL image for further evaluation. This procedure goes back to a proposal of Trupke et al. [1] and was justified theoretically by Glatthaar et al. [3], who showed that the carrier concentration in the bulk under illumination and current extraction is the sum of one voltage-dependent but illumination-independent and one voltage-independent but illumination-dependent part, the latter one dominating under short circuit condition. The physical reason for this procedure is the well-known fact that, for the same pn-junction voltage below the open circuit voltage Voc, the carrier concentration in the bulk is higher under illumination and current extraction than that in the dark. These additional carriers, which have to diffuse to the pn-junction for generating the illuminated cell current, are called “diffusion-limited carriers” [1]. By subtracting the Jsc PL image from the other PL images, the illuminated case is reduced to the un-illuminated case, as it would hold e.g. for an electroluminescence (EL) investigation. After this correction the net luminescence intensity depends exponentially on the pn-junction voltage, as in the EL case.

This approach works fine as long as the lifetime remains independent of the excitation intensity. In reality the luminescence intensity is caused by the excess carrier concentration in the bulk, hence it depends exponentially on the so-called implied voltage Vimpl in the bulk, which we here define as the separation between the electron and the hole quasi-Fermi level in the middle of the bulk, divided by the electron charge q. In all previous PL evaluation methods the implied voltage did not appear at all. Any PL evaluation method, which wants to consider an injection intensity-dependent lifetime, must be based on the implied...
voltage. Moreover, as mentioned above, all previous PL evaluation methods assumed a homogeneous value of $J_{sc}$ even below the busbars and grid lines, which is a strong simplification.

The PL evaluation method introduced here, which we name “PL evaluation based on implied voltage distribution (PL-imp)”, also uses the model of independent diodes, but it is explicitly based on the implied voltage distribution, and it does not assume a constant $J_{sc}$. Instead, it assumes a constant rate of generated carriers per area in the non-shadowed regions, which appears to be more realistic. From the $J_{sc}$ signal a measure of the bulk recombination rate at short circuit condition is derived, which allows to predict the $J_{sc}$ distribution solely from the evaluation of PL images. Moreover our method does not rely on the assumption of no lateral voltage gradients at low injection conditions, which can lead to errors in the final results as shown in [5]. In this contribution, the lifetime is still assumed to be independent of the excitation intensity, but this method provides the base for a future extension to regard an injection-dependent lifetime.

2. Physical model

The PL evaluation method introduced here is based on an alternative one-diode model for illuminated solar cells published in detail elsewhere [6]. Therefore, only the basic ideas and results of this theory will be reported here. The main content of this contribution is the application of this theory to PL image evaluation. The diode theory is described here without any series contribution is the application of this theory to PL image evaluation. Therefore, only the basic ideas and results of this theory will be reported here. The main content of this contribution is the application of this theory to PL image evaluation. The diode theory is described here without any series resistance will be considered. As in [6] only the dark and illuminated currents of the p-doped bulk are considered here.

As mentioned above, the alternative one-diode model assumes that the generation current density $J_{gen}$ describes the total amount of light-generated carriers per unit area and time, is locally constant and independent of the local pn-junction bias $V_{pn}$. Provided that the texturing is sufficiently homogeneous, this is certainly a better approach than assuming $J_{sc}$ to be homogeneous, in particular for multicrystalline silicon cells. Under short circuit condition, this current density splits into the extracted short circuit current density $J_{rec}$ and a current density describing the bulk recombination under short circuit, which is called here as $J_{rec,0}$:

$$J_{gen} = J_{sc} + J_{rec,0}$$  \(1\)

The magnitude $J_{rec,0}$ is a new diode parameter introduced for this theory. The alternative diode theory [6] assumes that the excess carrier concentration in the largest part of the bulk is constant across the depth. If some current is extracted under illumination, only in a so-called drift region close to the pn-junction a carrier concentration gradient exists, which leads to the illuminated current flow. According to PC1D simulations of a typical crystalline solar cell, this drift region has an extension of about 20 μm [6]. As in the previous theories, the excess carrier concentration at the pn-junction is given by the local voltage there. The basic idea of the new model is that under illumination the extracted current density is proportional to the difference between the excess carrier concentration in the bulk $n_{bulk}$ and that at the pn-junction $n_{pn}$ and can be described formally by an effective diffusion coefficient $D_{eff}$ ($n_{i}$=intrinsic carrier concentration, $N_{A}=\text{effective bulk acceptor concentration, } V_{T}=\text{thermal voltage}$):

$$J = qD_{eff}(n_{bulk} - n_{pn}) = \frac{qD_{eff}n_{i}^{2}}{N_{A}}(\exp(V_{impl}/V_{T}) - \exp(V_{pn}/V_{T}))$$  \(2\)

In contrast to the usual definition of a diffusion coefficient, $D_{eff}$ has the unit of cm/s. Thus, it also could be named a carrier extraction velocity. On the other hand, the extracted cell current is the difference between $J_{gen}$ and the bias-dependent recombination rate in the bulk, which may be expressed by the saturation current density of the bulk recombination $J_{01}$:

$$J = J_{gen} - J_{01} \exp\left(\frac{V_{impl}}{V_{T}}\right)$$  \(3\)

For $V_{pn}=0$ (short circuit) $J_{rec,0} = J - J_{gen}$ holds. Then Eq. (3) allows to calculate $V_{impl}$ under short circuit condition:

$$V_{impl,0} = V_{T} \ln\left(\frac{J_{rec,0}}{J_{01}}\right)$$  \(4\)

This allows to calculate $D_{eff}$ after Eq. (2):

$$D_{eff} = \frac{qD_{impl}}{\left(\frac{N_{i}}{N_{A}} - \frac{n_{i}^{2}}{n_{pn}^{2}}\right) \left(\frac{J_{rec,0}}{J_{01}}\right) V_{T}}$$  \(5\)

The latter relation in Eq. (5) holds due to the second basic equation, which is also used in all other PL evaluation methods, is described in [6]. Thus, the alternative one-diode model does not change the standing of the pn-junction physics and provides a simple way to express $V_{impl}$ by $V_{pn}$ analytically.

3. PL evaluation method

All previous luminescence imaging methods are based on the equation:

$$\Phi_{i} = C_{i}\exp\left(\frac{V_{impl}}{V_{T}}\right)$$  \(8\)

here $C_{i}$ is the so-called luminescence scaling parameter, which depends e.g. on the local surface conditions and recombination properties, and $i$ is the position index. Eq. (8) holds directly for un-illuminated (EL) measurements, since there $V_{impl} \approx V_{pn}$ holds. For previous PL evaluation methods, however, Eq. (8) only holds for the ‘net’ PL signal after $J_{sc}$ correction [1]. In our contribution $V_{impl}$ and $V_{pn}$ are two separate variables, which are connected by Eq. (6). Therefore our PL evaluation is based on:

$$\Phi_{i} = C_{i}\exp\left(\frac{V_{impl}}{V_{T}}\right)$$  \(9\)

The second basic equation, which is also used in all other PL evaluation methods, is the calculation of $V_{pn}$ in the model of independent diodes regarding a local series resistance $R_{s}$. Regarding Eq. (7) this equation reads here:

$$V_{pn} = V + R_{s}J_{i} = V + R_{s} \left(\frac{J_{sc,1}}{J_{gen}} \exp\left(\frac{V_{impl}}{V_{T}}\right)\right)$$  \(10\)
A major difference between this and previous PL evaluation methods is the new local diode parameter \( J_{rec,0,i} \), which describes the local bulk recombination rate under short circuit condition. This means that a PL signal \( \Phi_{(sc)} \) measured under short circuit condition provides information to \( J_{rec,0,i} \). Combining Eq.(3) for the short circuit case with Eq. (9) leads to:

\[
J_{rec,0,i} = J_{01,i} - \frac{\Phi_{(sc)}^{(i)}}{C_i}
\]  

(11)

Since the global currents of the cell are the sum of all pixel currents, the global generation current is the global sum of \( I_{sc} \) and the sum of the \( I_{rec,0} \) of all pixels. Here the influence of the light shortcircuiting by the busbars and grid lines has to be considered, otherwise the simulated local short circuit current density becomes too low. Note that \( I_{sc} \) of the cell always refers to the whole cell area, but locally (between the grid lines) the averaged \( J_{sc} \) is larger than \( I_{sc}/A \) (\( A= \)cell area). This influence is considered here by dividing \( I_{sc}/A \) by a factor of \( (1 - f_{met}) \), with \( f_{met} \) being the fraction of metallized area. Expressed as current densities, this leads with \( X \) and \( Y \) being the dimensions of the image to:

\[
J_{gen} = \frac{I_{sc}}{A(1-f_{met})} \frac{1}{XY} \sum \left( J_{rec,0,i} \right)
\]  

(12)

This equation allows to calculate the value of \( J_{gen} \), assumed here to be homogeneous between the grid lines, if \( I_{sc} \) is known and \( J_{rec,0,i} \) is measured after Eq. (11).

The two possible ways to evaluate PL images are either to evaluate the same number of images as the number of local diode parameters (which are usually \( J_{01}, R_s, \) and \( C_i \)), plus at least one \( J_{sc} \) PL image for performing the above mentioned PL data correction [2,3]. The second way is to evaluate a larger number of PL images and to perform a linear regression procedure for obtaining the local diode parameters [4]. Here the first way will be used. Since our local diode parameters are \( J_{01,i}, J_{rec,0,i}, R_{s,i}, \) and \( C_i \), for our procedure we have to evaluate four PL images. For obtaining these diode parameters, we are looking for a simultaneous solution of Eqs. (9) – (12) regarding Eq. (6) applied to these PL images. Our strategy is to optimize the imaging conditions for these PL measurements so that each of them reacts most sensitively to one of the diode parameters. Then an iterative loop procedure is used for fitting Eq. (9) – (12) with Eq. (6) simultaneously to all PL results. We propose to perform the following PL measurements:

- \( \Phi(1) \) measured under \( V_{sc} \) condition at low intensity \( I^{(1)} \) (e.g. 0.1 sun) used for fitting \( C_i \) after Eq. (9)
- \( \Phi(2) \) measured under \( J_{sc} \) condition at high intensity \( I^{(2)} \) (e.g. 1 sun) used for fitting \( J_{rec,0,i} \) after Eq. (11) and \( J_{gen} \) after Eq. (12)
- \( \Phi(3) \) measured with weak load (e.g. 25% of \( I_{sc} \)) at high intensity \( I^{(3)} \) (e.g. 1 sun) used for fitting \( J_{01,i} \) after Eq. (10)
- \( \Phi(4) \) measured with stronger load (e.g. 75% of \( I_{sc} \)) at high intensity \( I^{(4)} \) (e.g. 1 sun) used for fitting \( R_{s,i} \) after Eq. (10)

We have developed a software package performing this iterative fitting procedure named “PL-imp”, since this procedure is based on the analysis of the implied voltage. On a usual PC the evaluation of four 1024 \( \times \) 1024 pixel sized PL images using 20 iterations takes about 4 s.

4. Results

This PL evaluation method was applied to a typical industrial multicrystalline silicon solar cell with a standard size of 156 \( \times \) 156 mm\(^2\). For comparison, the same PL images were evaluated by a “Coupled Voltage Calibration” (C-VC) method [3], which also regards the voltage drop at series resistances for the calibration measurement, but assumes a homogeneous \( J_{sc} \). Also here the shadowing effect was considered by assuming a slightly increased \( J_{sc} \), see Eq. (12). Fig. 1 shows the resulting images of \( C, J_{01}, \) and \( R_s \) for both methods. This comparison shows that the results of both methods regarding these parameters are very close to each other.
This proves that the iterative fitting procedure is generally working as expected. Looking more into the details we see that the maximum values of $J_{sc}$, in the poor crystal quality regions are slightly higher in the C-VC method than in the PL-imp method, here they differ by about 9%. This is due to an overestimation of $J_{sc}$ in these regions by C-VC. Altogether, though the differences between the C-VC and the PL-imp results are weak, the latter procedure seems to be more realistic from a physical point of view.

Fig. 2 (a) shows an image of the PL-simulated $J_{sc}$ data, in comparison to a light beam-induced current (LBIC) image (b) scaled to a nominal excitation intensity of 1 sun as at the same excitation wavelength as used for PL imaging of 780 nm. In addition, an artificially blurred version of the LBIC image of (b) is shown in (c). It is visible that the PL-based $J_{sc}$ image (a) shows a clearly worse spatial resolution than the directly measured one (b). This is due to the lateral spreading of the local voltage in a solar cell due to the horizontal balancing currents in the emitter and the grid. Note that this PL evaluation procedure is based on the model of independent diodes, which neglects any lateral interaction between neighboring pixels. In reality, the series resistance is a distributed one, which is not considered here. If the LBIC image is artificially blurred (c) it looks very similar to the simulated one (a). Note that the scaling limits are not exactly the same but close to each other. Thus, it can be judged that our PL evaluation method leads to a good modeling of $J_{sc}$. The remaining quantitative differences to the direct measurement may be due to the very different excitation processes between (a) and (b, c) or due to natural limitations of this relatively simple physical model, e.g. to the assumption of a depth-independent carrier concentration, an excitation intensity-independent lifetime, or the independent diode model.

5. Summary and discussion

In this contribution a novel photoluminescence evaluation method is introduced (PL-imp), which is based on the evaluation of the local implied voltage instead of the local pn-junction voltage. Moreover, this method does not assume a homogeneous short circuit current density but only a homogeneous density of absorbed photons, and it considers the shadowing by metallized areas. Therefore, in contrast to all previous PL evaluation methods, PL-imp leads to a realistic prediction of a $J_{sc}$ image for the wavelength used for PL excitation. The comparison of such an image with a conventionally measured LBIC image shows a high degree of conformance, in spite of the relatively coarse physical model underlying this PL-imp procedure. Except the simulation of $J_{sc}$ data, the results of PL-imp do not deviate significantly from that of previous PL evaluation methods, which all had to subtract a $J_{sc}$ PL image from the others. However, in contrast to the previous PL evaluation methods, only PL-imp is able to be extended to evaluate intensity-dependent lifetimes. It also appears physically more meaningful than the previous methods, since it evaluates the PL signal directly and regards an inhomogeneous $J_{sc}$.

It has to be mentioned that PL-imp is more demanding with respect to light filtering than previous PL evaluation methods. If some amount of reflected excitation light reaches the camera used for PL detection, this amount is canceled out by the usual subtraction of the $J_{sc}$ PL image. This is not the case for the PL-imp method.

References


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1 In this work we define a 1 sun equivalent in the context of luminescence measurements as an incident photon flux of $2.55 \times 10^{17}$ photons/(cm$^2 \times$ s)