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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 J_{sc}. Moreover, they had to subtract a J_{sc} 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 J_{sc} but a constant light absorption rate, and it leads to a prediction of the J_{sc} 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 J_{sc} 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 J_{sc}.

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 [1] 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 $\Omega\,cm^2$. 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 (J_{sc}) 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 V_{oc}, the carrier concentration in the bulk is higher under illumination and carrier 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 J_{sc} 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 V_{impl} 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

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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} PL 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 resistances, but for the application of the results to PL evaluation a local series resistance will be considered. As in [6] only contributions of 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}, which 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_{sc} and a current density describing the bulk recombination under short circuit, which is called here as $J_{rec,0}$:

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

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 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=effective bulk acceptor concentration, V_T=thermal voltage):

$$J = qD_{eff}(n_{bulk} - n_{pn}) = \frac{qD_{eff} n_i^2}{N_A}\left(\exp\left(\frac{V_{impl}}{V_T}\right) - \exp\left(\frac{V_{pn}}{V_T}\right)\right) \tag{2}$$

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}:

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

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:

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

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

$$D_{eff} = \frac{J_{sc}}{q\left(\frac{n_i^2 J_{rec,0}}{N_A J_{01}} - \frac{n_i^2}{N_A}\right)} \approx \frac{J_{sc} J_{01} N_A}{q n_i^2 J_{rec,0}} \tag{5}$$

The latter relation in Eq. (5) holds due to $J_{rec,0} \gg J_{01}$, since $J_{rec,0}$ is typically in the low mA/cm^2 region, see Section 4. Hence, by Eq. (5) the formally introduced effective diffusion coefficient D_{eff} can be expressed by measurable diode parameters. If Eq. (5) is inserted into Eq. (2), this leads together with Eq. (3) to the major result of this theory, which expresses V_{impl} by V_{pn} under illumination:

$$V_{impl}(V_{pn}) = V_T \ln\left(\frac{J_{rec,0}}{J_{01}} + \frac{J_{sc}}{J_{gen}}\exp\left(\frac{V_{pn}}{V_T}\right)\right) \tag{6}$$

Here the material parameters n_i and N_A cancel and only measurable diode parameters remain. If Eq. (6) is inserted into Eq. (3) for calculating the illuminated current density, the result is basically the same as for the conventional diode model:

$$J(V_{pn}) = J_{sc} - \frac{J_{sc}}{J_{gen}} J_{01}\exp\left(\frac{V_{pn}}{V_T}\right) \tag{7}$$

The factor (J_{sc}/J_{gen}) in Eq. (7) is due to the fact that, in the new model, the open circuit condition is established by balancing J_{gen} to the dark current, instead of J_{sc} in the conventional diode model [6]. Thus, the alternative one-diode model does not change the solar cell physics significantly, it only provides a deeper understanding 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:

$$\Phi_i = C_i \exp\left(\frac{V_{pn,i}}{V_T}\right) \tag{8}$$

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:

$$\Phi_i = C_i \exp\left(\frac{V_{impl,i}}{V_T}\right) \tag{9}$$

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:

$$V_{pn,i} = V + R_{s,i} J_i = V + R_{s,i}\left(J_{sc,i} - \frac{J_{sc,i}}{J_{gen}} J_{01,i}\exp\left(\frac{V_{pn,i}}{V_T}\right)\right) \tag{10}$$