Evaluation of luminescence images of solar cells for injection-level dependent lifetimes

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1. Introduction

Electroluminescence (EL) and photoluminescence (PL) imaging are versatile tools to image local variations of the effective diffusion length \( L_{\text{diff}} \) in solar cells [1] as well as of the lateral series resistance \( R_s \) and the dark saturation current density \( J_{01} \) [2–6]. All these methods describe the dark current–voltage \((I–V)\) characteristic of the investigated solar cell by a one-diode model regarding the diffusion current density with an ideality factor \( n_1 \) of unity. This assumption implies that the effective minority carrier lifetime in the bulk is independent from the injection level. Very often, however, this is not the case. This holds e.g. for oxidized surfaces [7] and also for multicrystalline solar cells [8], which then have to be described by an ideality factor larger than unity. The aim of this work is to include the concept of an injection-level dependent lifetime in the quantitative evaluation of EL and PL images.

If the lifetime is governed by a single Shockley–Read–Hall (SRH) recombination center, and the recombination channel is saturable (low capture cross section for majority carriers), in the low-injection regime \((n < \text{net doping concentration})\) the lifetime \( \tau \) depends in the following way on the minority carrier concentration \( n \):

\[
\tau(n) = \tau_0 + A n
\]

(1)

here \( \tau_0 \) is the lifetime for low carrier concentration, and \( A \) is a constant, which depends on the electronic properties of the level. For sufficiently high carrier concentration \( \tau \) becomes proportional to \( n \). Since the diode saturation current density \( J_{01} \) is proportional to \( 1/\sqrt{n} \), and thus in this regime to \( 1/\sqrt{n} \), with \( n \sim \exp(eV/kT) \) the local dark current density becomes

\[
J_{\text{dark}}(V_i) = J_{01,i}(V_i) \exp \left( \frac{V_i}{V_T} \right) = J_{01,i} \exp \left( \frac{V_i}{2V_T} \right) = J_{01,i} \exp \left( \frac{V_i}{n_1 V_T} \right)
\]

(2)

\((V_T = kT/e = \text{thermal voltage}, i = \text{local position index}, n_1 = \text{ideality factor})\) \( J_{01,i} \) is the voltage-independent saturation current density parameter, if the ideality factor \( n_1 \) is regarded. Hence, if the lifetime is governed by a single SRH-center, in the low-voltage limit the ideality factor of the dark characteristic is unity and the lifetime is constant \((\tau = \tau_0)\), but with increasing voltage and current the lifetime increases and the ideality factor approaches \( n_1 = 2 \). This has not to be confused with depletion region recombination, which for non-saturated SRH-recombination also predicts an ideality factor of \( n_2 = 2 \) in the whole voltage range. \( J_{01,i}(V_i) \) in (2) may be expressed as

\[
J_{01,i}(V_i) = J_{01,i} \exp \left( \frac{V_i}{V_T} \left( \frac{1}{n_1} - 1 \right) \right)
\]

(3)

In many cases, in the injection regime of interest (usually the range between the maximum power point \( V_{\text{mpp}} \) and the open circuit voltage \( V_{\text{oc}} \)), the SRH-level is only partly saturated, or there are several SRH-centers and/or other recombination channels acting in parallel [8]. Then, in this limited voltage range, the lifetime increases sub-proportional to \( n \), and the ideality factor \( n_1 \) in (2) is lying between 1 and 2. Assuming a voltage-independent ideality factor \( n_1 \), this can be expressed by a carrier- resp. voltage-dependent lifetime of

\[
\tau_i = \tau^* \left( \frac{n_i}{N_c} \right)^{-2(2/n_1)} = \tau^* \exp \left( \frac{V_i}{V_T} \left( 2 - \frac{2}{n_1} \right) \right)
\]

(4)

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(\(N_c\)—effective density of electron states, \(n_m\)—minority carrier concentration in position \(i\), \(\tau^0\)—voltage-independent lifetime parameter). For \(n_1 > 1\) the lifetime increases with increasing voltage. Regarding an injection-level dependent lifetime in EL and PL evaluations consists in replacing the parameters \(J_{01,i}\), \(\tau_i\) and the usual expression for \(J_{\text{dark}}(V)\) by Eqs. (3), (4), and (2), respectively, with \(n_1\) being the parameter describing the magnitude of the effect. For \(n_1 = 1\) the lifetime \(\tau\) is constant, \(J_{01,i}\) becomes independent of \(V_i\), and \(f_{01,i}^2\) is the usual saturation current density \(J_{01,i}\). Since for \(n_1 > 1\) the values of \(f_{01,i}^2\) are significantly higher than that of the real (voltage-dependent) saturation current density \(J_{01,i}\), (3) allows the calculation of \(J_{01,i}\) for any voltage \(V_i\).

The evaluation of luminescence data is based on the fact that the local luminescence intensity \(\Phi_i\) strongly depends on the minority carrier concentration and therefore on the local voltage \(V_i\). In the low injection regime holds:

\[
\Phi_i = C_i \exp \left( \frac{V_i}{V_T} \right)
\]

(5)

\(C_i\) is a local proportionality factor, which depends on the local lifetime and includes the surface properties and the depth-dependence of the minority carrier concentration, but is independent of \(V_i\) as long as the lifetime is constant [6]. Let us first briefly review the evaluation of PL and EL luminescence data for a carrier-independent lifetime. Note that for all PL evaluations a PL image under short circuit condition has to be measured and subtracted from all other images to account for the luminescence due to the minority carrier concentration under illumination at short circuit [5,6], see also [9]. If \(C_i\) is known, (5) allows the measurement of the local voltage \(V_i\) from \(\Phi_i\). In many cases, a first “scanning” measurement is made with low \(J_n\), where the voltage drop across \(R_s\) is negligible and \(V_i = V\) holds everywhere. Then \(C_i\) is directly obtained by (5). This condition is realized for EL by applying a relatively low voltage \(V\) [3], and for PL by operating under open circuit condition, often at reduced illumination intensity [5]. If a local current density \(J_i\) is flowing in the considered pixel position, this local voltage \(V_i\) differs from the applied voltage \(V\) by the voltage drop at the local series resistance \(R_{s,i}\):

\[
V_i = V - R_{s,i}J_i
\]

(6)

Note that this definition of an area-related series resistance (given in unit of \(\Omega \text{cm}^2\)) actually assumes that each region (pixel) is connected to the cell terminals by an individual series resistance, which is only a coarse approximation. For EL imaging \(J_i\) is given by (2), and for PL imaging the local short circuit current density \(J_{0c,i}\) has to be subtracted from (2), leading to negative current values of \(J_i\) for \(V < V_{sc,i}\). If PL is performed at full illumination intensity with current drain, leading e.g. to \(V_{\text{mpp}}\) at the terminals, the local voltages obtained after (5) directly lead to \(R_s\) at \(V_{\text{mpp}}\) after [6], see [5]. For EL imaging, both \(R_{s,i}\) and \(J_{01,i}\) are unknown, and only the product of both can be determined by (6). This problem can be solved by applying the Fuyuki approximation, claiming that the calibration factor \(C_i = f J_{01,i}\) scales inversely with the local saturation current density [1,3]. Here \(f\) is an unknown factor, which finally may be fitted e.g. to the average value of \(R_s\) [3] or \(J_{01,i}\) [4]. This approximation leads from (5) and (6) to the following formula for \(V_i\), which allows the determination of \(R_{s,i}\) and \(J_{01,i}\), independently according to the procedures described in [3,4]:

\[
V_i = V_{\text{mpp}} \ln \frac{\Phi_i}{\Phi_{01,i}} + \frac{R_{s,i}J_{01,i}}{f}
\]

(7)

All above considerations hold for an injection-independent lifetime, leading to constant values of \(J_{01}\) and \(C\). If the lifetime is carrier-dependent, \(J_{01}\) is according to (3) voltage-dependent, and also \(C\) becomes voltage-dependent. If we assume a certain value of \(n_1\), we know the voltage-dependence of \(J_{01,i}\) according to (3). However, then we do not know the voltage-dependence of \(C\) yet, since this also depends on the experimental and geometrical parameters. For example, if we neglect light absorption in the bulk, for a bulk thickness larger than the diffusion length, and for electroluminescence resp. optical excitation close to the emitter, \(C_i\) should be proportional to the diffusion length, which is proportional to \(1/\tau_i\), resp. \(\sqrt{\tau_i}\) corresponding to the Fuyuki approximation [1]. This approximation, which may be valid in the defect regions of multicrystalline cells showing a low diffusion length, is also underlying (2) and (4). However, if the diffusion length is large compared to the bulk thickness, \(J_{01,i} \sim 1/\tau_i\) holds (the saturation current density is a measure of the bulk recombination rate), and the luminescence intensity (resp. \(C_i\)) becomes independent of the lifetime, since the carrier depth profile does not depend on \(\tau_i\) anymore. Hence, assuming a certain ideality factor \(n_i\) for the dark current does not mean generally knowing the voltage dependence of \(C_i\).

Since EL and PL imaging is used mainly for investigating recombination-active defects, in the following we assume again the validity of the above mentioned Fuyuki approximation, now formulated voltage-dependent:

\[
C_i = \frac{f}{J_{01,i}(V_i)}
\]

(8)

Combining the left part of (2), (5) and (8) leads to

\[
J_{\text{dark},i} = \Phi_i \left( \frac{J_{01,i}(V_i)^2}{\Phi_i} \right) = \Phi_i \frac{J_{01,i}^2 \exp \left( \frac{2V_i}{V_T} \frac{1}{n_1} \right)}{\Phi_i} = \frac{v_i \ln \frac{\Phi_i}{\Phi_{01,i}} \exp \left( \frac{2V_i}{V_T} \frac{1}{n_1} \right)}{f}
\]

(9)

Inserting this into (6), together with (3), (5), and (6), this leads in analogy to (7) to

\[
R_s = \frac{f}{\Phi_i} \frac{\Phi_i^2 \exp \left( \frac{2V_i}{V_T} \frac{1}{n_1} \right)}{\Phi_i} = \frac{v_i \ln \frac{\Phi_i}{\Phi_{01,i}} \exp \left( \frac{2V_i}{V_T} \frac{1}{n_1} \right)}{f}
\]

(10)

For \(n_1 > 1\) the direct evaluation of (10) is not possible anymore, since \(V_i\) is unknown, which also depends on \(R_s\). For the same reason also the analytic procedure proposed in [6] is not applicable in this case anymore, since the coefficients in the equation system now depend on the local voltages. However, (10) may be used as one of the equations implied in the iteration procedure for evaluating EL images described in [4], which does not need any scaling measurement at low current. Regarding the left part of (2) and (3), and (6), the other two equations used in the iteration cycle of [4] read:

\[
J_{01,i}^2 = \frac{f}{\Phi_i} \exp \left( \frac{V_i}{V_T} \frac{2 - 1}{n_1} \right) \quad \text{and} \quad V_i = V - R_{s,i}J_{01,i} \exp \frac{V_i}{n_1 V_T}
\]

(11)

As described in [4], Eqs. (9)–(11) can be solved by an iteration procedure, leading to self-consistent values of \(R_{s,i}\), \(f_{01,i}\), and the local voltages \(V_i\) belonging to the two EL biases \(V_i\) and \(V_2\) used for evaluation. The extension of this procedure regarding an injection-intensity dependent lifetime by introducing \(n_1 > 1\) described here is now implemented in the EL evaluation software “EL-Fit”, as well as in the local solar cell efficiency analysis software “Local I–V 2” [10], which are both available [11].

For demonstrating the significance of this new evaluation procedure, a typical commercial multicrystalline solar cell, measured and evaluated at 28 °C, has been investigated, the results are shown in Table 1. The dark characteristic could be analyzed with sufficient accuracy by assuming both \(n_1 = 1\) and \(n_1 = 1.13\), but the measured value of \(V_{sc} = 0.611\) V was only compatible with the simulation from the dark characteristic by assuming \(n_1 = 1.13\), see also [12]. EL images of this cell taken at 0.56 and 0.598 V at
The consideration of a carrier-dependent lifetime for PL image evaluation will be described in a later publication.

One limitation of the method described here is that it has to assume a fixed value of $n_1$, holding for the whole area of the cell. In reality, since the effective bulk lifetime e.g. of a multicrystalline silicon cell is governed by several factors (crystal defects like dislocations and different types of grain boundaries, rear surface recombination), it may be assumed that also $n_1$ is position-dependent. Therefore the approach described here is only able to consider the influence of the dominating bulk recombination mechanism.

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