



Letter

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

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ABSTRACT

If the minority carrier lifetime in a semiconductor is dependent on the injection level, the dark current–voltage characteristic of solar cells may show an ideality factor n_1 larger than unity. This modifies the evaluation of photoluminescence and electroluminescence imaging data for obtaining the distribution of the local series resistance and saturation current density of solar cells. In this contribution these modifications are summarized and applied to an iterative method for evaluating electroluminescence images. It is found that even a small increase of n_1 leads to substantial variations of the resulting series resistance values.

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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_{eff} 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 τ depends in the following way on the minority carrier concentration n :

$$\tau(n) = \tau_0 + An \quad (1)$$

here τ_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 τ becomes proportional

to n . Since the diode saturation current density J_{01} is proportional to $1/\sqrt{\tau}$, and thus in this regime to $1/\sqrt{n}$, with $n \sim \exp(eV/kT)$ the local dark current density becomes

$$J_{\text{dark}}(V_i) = J_{01,i}(V_i) \exp \frac{V_i}{V_T} = J_{01,i}^{\#} \exp \frac{V_i}{2V_T} = J_{01,i}^{\#} \exp \frac{V_i}{n_1 V_T} \quad (2)$$

($V_T = kT/e$ = thermal voltage, i = local position index, n_1 = 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

$$J_{01,i}(V_i) = J_{01,i}^{\#} \exp \left(\frac{V_i}{V_T} \left(\frac{1}{n_1} - 1 \right) \right) \quad (3)$$

In many cases, in the injection regime of interest (usually the range between the maximum power point V_{mpp} and the open circuit voltage V_{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

$$\tau_i = \tau^{\#} \left(\frac{n_i}{N_c} \right)^{(2-(2/n_1))} = \tau^{\#} \exp \left(\frac{V_i}{V_T} \left(2 - \frac{2}{n_1} \right) \right) \quad (4)$$

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(N_c =effective density of electron states, n_i =minority carrier concentration in position i , $\tau^\#$ =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} , τ , 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 τ is constant, $J_{01,i}$ becomes independent of V_i , and $J_{01,i}^\#$ is the usual saturation current density $J_{01,i}$. Since for $n_1 > 1$ the values of $J_{01}^\#$ are significantly higher than that of the real (voltage-dependent) saturation current density J_{01} , (3) allows the calculation of J_{01} for any voltage V .

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

$$\Phi_i = C_i \exp\left(\frac{V_i}{V_T}\right) \quad (5)$$

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 Φ_i . In many cases, a first “scaling” measurement is made with low J_i , where the voltage drop across $R_{s,i}$ 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 $R_{s,i}$:

$$V_i = V - R_{s,i} J_i \quad (6)$$

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 $J_{sc,i}$ has to be subtracted from (2), leading to negative current values of J_i for $V < V_{oc,i}$. If PL is performed at full illumination intensity with current drain, leading e.g. to V_{mpp} at the terminals, the local voltages obtained after (5) directly lead to $R_{s,i}$ at V_{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} [4]. This approximation leads from (5) and (6) to the following formula for V , which allows the determination of $R_{s,i}$ and $J_{01,i}$ independently according to the procedures described in [3,4]:

$$V = V_T \ln \frac{\Phi_i J_{01,i}}{f} + \frac{\Phi_i R_{s,i} J_{01,i}^2}{f} \quad (7)$$

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} 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 $1/J_{01,i}$ 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 τ_i anymore. Hence, assuming a certain ideality factor n_1 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:

$$C_i = \frac{f}{J_{01,i}(V_i)} \quad (8)$$

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

$$J_{\text{dark},i} = \frac{\Phi_i}{f} (J_{01,i}(V_i))^2 = \frac{\Phi_i}{f} J_{01,i}^{\#2} \exp\left(\frac{2V_i}{V_T} \left(\frac{1}{n_1} - 1\right)\right) \quad (9)$$

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

$$R_{s,i} = \frac{f}{\Phi_i J_{01,i}^{\#2} \exp(2V_i/V_T((1/n_1)-1))} \left(V - V_T \ln \frac{\Phi_i J_{01,i}^{\#} \exp(V_i/V_T)((1/n_1)-1)}{f} \right) \quad (10)$$

For $n_1 > 1$ the direct evaluation of (10) is not possible anymore, since V_i is unknown, which also depends on $R_{s,i}$. 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:

$$J_{01,i}^\# = \frac{f}{\Phi_i} \exp\left(\frac{V_i}{V_T} \left(2 - \frac{1}{n_1}\right)\right) \quad \text{and} \quad V_i = V - R_{s,i} J_{01,i}^\# \exp\left(\frac{V_i}{n_1 V_T}\right) \quad (11)$$

As described in [4], Eqs. (9)–(11) can be solved by an iteration procedure, leading to self-consistent values of $R_{s,i}$, $J_{01,i}^\#$, and the local voltages V_i belonging to the two EL biases V_1 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 $V_{oc}=0.611$ 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

Table 1

Results of the I – V characteristic analysis and EL image evaluation of a typical commercial multicrystalline silicon solar cell.

Ideality factor n_1	J_{01} resp. $J_{01}^{\#}$ (A/cm^2)	J_{01} at 0.6 V (A/cm^2)	V_{oc} (simulated) (mV)	$\langle R_s \rangle$ (Ωcm^2)	R_s (min) (Ωcm^2)
1	3.62×10^{-12}	3.62×10^{-12}	596	0.220	–0.013
1.13	2.87×10^{-11}	2.01×10^{-12}	611	0.961	0.31

28 °C were evaluated according to [4] by the extended iterative procedure described here. For both assumed values of n_1 the factor f was fitted so that the global values of J_{01} resp. $J_{01}^{\#}$ in the EL evaluation equal that of the dark characteristic. The qualitative appearance of the resulting R_s and J_{01} images was the same for assuming $n_1=1$ and $n_1=1.13$, respectively. However, depending on whether $n_1=1$ or 1.13 was assumed, the average of the resulting local R_s values differed by a factor of more than four, while the saturation current density at 0.6 V differs only by less than a factor of 2, see Table 1. The difference of J_{01} close to V_{oc} is due to the fact that the I – V fitting procedure regards the lower steepness of the characteristic by increased the values of R_s and J_{01} . Table 1 also contains the minimum R_s value, which is measured close to the bus bars. For $n_1=1$ this value becomes negative, but for $n_1=1.13$ not. The reason for the strong dependence of R_s on n_1 is the following. Any series resistance tends to linearize the I – V characteristic of a diode. If the diode current is approximated by an exponential, a series resistance increases the ideality factor. If the measurements point to a weaker than the expected exponential bias-dependence of the local voltage, the fitting procedure interprets this as a series resistance. Note that for $n_1 > 1$ the lifetime and thus also C_i increases with voltage, see (4) and (8). Therefore, if R_s is negligible, the luminescence increases steeper than $\exp(V_i/V_T)$ with V , which appears like an ideality factor smaller than unity. If $n_1=1$ is assumed, only a negative R_s allows to fit these luminescence data. Here we propose that the appearance of any negative R_s data in luminescence image evaluation is an indication of a carrier- resp. voltage-dependent lifetime. These results show that even a small increase of n_1 leads to substantial variations of the series resistance values resulting from luminescence image evaluation.

In this contribution we have generally described how an injection-intensity dependent lifetime has to be regarded in the quantitative evaluation of PL and EL images of solar cells. This procedure was implemented in the iterative EL image evaluation procedure described in [4], which delivers images of $R_{s,i}$, $J_{01,i}$ (resp. $J_{01,i}^{\#}$ for $n_1 > 1$), and the two local voltages $V_{1,i}$ and $V_{2,i}$ for the two applied voltages V_1 and V_2 . Note that these local voltages do not depend on the chosen value of the generally unknown factor f . From one of these local voltages and a dark lock-in thermography (DLIT) image taken at the same terminal voltage, an absolutely scaled series resistance image may be calculated according to the RESI method [13,10], which does not depend on the factor f .

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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