Effective Diffusion Length and Bulk Saturation Current Density Imaging in Solar Cells by Spectrally Filtered Luminescence Imaging

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Abstract—Most methods for interpreting electroluminescence (EL) or photoluminescence (PL) images of solar cells evaluate the local diode voltages but not the local luminescence intensity itself. One exception is the Fuyuki approximation, which assumes that the local value of the luminescence signal is proportional to the local effective diffusion length. This dependence has been derived for infinitely thick solar cells and neglects self-absorption of the luminescence photons. However, for real solar cells and imaging conditions, with increasing diffusion length, the luminescence signal approaches a limiting value; hence, the Fuyuki approximation no longer holds. In this paper, we compare EL and PL images of multicrystalline solar cells using different kinds of light filtering and find that gentle shortpass filtering is useful for avoiding optical artifacts. Based on earlier calculations, a physically founded formula for the dependence of the gently shortpass-filtered luminescence signal on the bulk diffusion length, for a given rear surface recombination velocity, is presented. Since this formula only barely allows us to calculate the diffusion length from the luminescence signal, a simplified approximate formula is proposed, and its accuracy is checked. This method is tested on EL and \( V_{ac} \) images of solar cells. For a typical industrial multicrystalline Al-backside solar cell, the obtained effective diffusion length images correlate well with such images obtained by spectral LBIC image evaluation. In addition, the saturation current density images correlate well with such images obtained by dark lock-in thermography, which show a much lower spatial resolution. The main limitation of the proposed method is that it is basically approximate and needs some fitting parameters.

Index Terms—Effective diffusion length, electroluminescence imaging, Fuyuki approximation, luminescence scaling factor, saturation current density.

I. INTRODUCTION

ELECTROLUMINESCENCE (EL) imaging is a standard method to characterize defects in solar cells [1]–[3], as well as in modules [4]. In addition, camera-based photoluminescence (PL) imaging, which originally was used for characterizing solar wafers [5], is now widely used for characterizing solar cells [6]–[8]. For interpreting luminescence images of silicon solar cells, the contribution of the emitter can safely be ignored, which was shown, e.g., in [9]. Both the local EL and the net PL signal (this is the PL signal minus the short-circuit PL signal [6]; see below) can be described by

\[
\Phi_i = C_i \exp \left( \frac{V_{di,i}}{V_T} \right),
\]

Here, \( i \) is a position index, \( C_i \) is the local luminescence scaling constant, \( V_{di,i} \) is the local diode voltage in position \( i \), and \( V_T \) is the thermal voltage. While PL imaging under current extraction allows one to image the local effective series resistance \( R_s \) in a solar cell directly [6] and independently also delivers information of the local saturation current density \( J_{01} \) [7], [8], the evaluation of EL allows one to image only the local product of \( R_s \) and \( J_{01} \). Therefore, Haunschild et al. [10] have proposed to apply the theory of Fuyuki et al. [2] for estimating the local value of \( J_{01} \) and thus allowing to image \( R_s \) by EL. This theory is based on the fact that, under forward bias in the dark, for a given local diode bias, the excess carrier concentration directly at the p-n junction is independent of the local diffusion length, but, for an infinitely thick solar cell, drops into the depth exponentially with the bulk diffusion length \( L_d \). Thus, the depth integral of the excess carrier concentration up to infinite, which should be proportional to the EL signal \( \Phi_i \) (under low injection condition and if photon absorption is neglected) and thus, for a given local diode bias, should be proportional to \( C_i \); at position \( i \), is expected to be proportional to \( L_d \). Therefore, EL was claimed in [1]–[3] to image the effective bulk diffusion length. For an infinitely thick solar cell, the bulk contribution to \( J_{01} \) (in the following called \( J_{01}^b \)) is proportional to \( 1/L_d \) [11]. Therefore, Haunschild et al. [10] have postulated as the “Fuyuki approximation” relation

\[
J_{01} = f \frac{J_{01}^b}{C_i}.
\]

Haunschild et al. [10] have made this postulation for the whole \( J_{01} \), thereby assuming that it is dominated by its bulk contribution \( J_{01}^b \). The parameter \( f \) in (2) is a scaling factor, which depends, e.g., on the camera parameters, the optics, and the surface condition of the cell. For an optically homogeneous cell, \( f \) should be constant. Then, this scaling factor holds for the whole cell, but it is hard to impossible to predict. Varying this factor varies \( R_s \) proportional to \( 1/J_{01} \), since only the product of both is measured in EL. As a rule, \( f \) is chosen, e.g., to fit the global mean value of \( R_s \) or of \( J_{01} \) of the cell [10], [12]. This...
way, effective $R_s$ and $J_{01}$ images can be obtained by EL imaging, but the question is how reliable are they? It has been shown experimentally that the $J_{01}$ distribution obtained this way by EL as well as that measured by PL, does not agree with that obtained by dark lock-in thermography (DLIT) (see [13] and [14]). The average values of $J_{01}$ of all methods agreed, but the $J_{01}$ difference between “good” and “poor” regions was much larger for DLIT than for luminescence investigations. Most previous EL and PL evaluation methods (except [15], more examples will be given in Section II) are based on the model of independent diodes. It has recently been shown that this model leads for PL to meaningful local $R_s$ data but in inhomogeneous cells to erroneous results for $J_{01}$ [16]. In [17], the “Fuyuki approximation” (2) was used to calculate the $J_{01}$ distribution from the $C_i$ distribution. Again, the question arises about the accuracy of this procedure.

There are serious doubts about the general applicability of the approximations that lead to the linear Fuyuki approximation (2). If a silicon detector is used for EL imaging, which is the usual case, only the short-wavelength fraction of the luminescence light can be detected. For this light, self-absorption cannot be neglected completely. The most critical approximation is the assumption of a cell thickness being much larger than the diffusion length $L_d$. This condition holds only in recombination-active defect regions of multicrystalline silicon cells, but not in “good” regions or in monocrystalline cells. It is obvious, and has been found already by Würfel et al. [18], that if $L_d$ comes into the order of or exceeds the cell thickness $W$, $C_i$ must run into a saturation value, although $J_{01}$ may further decrease with decreasing recombination probability. This saturation behavior was mentioned already in the original Fuyuki’s publication [1], where the case of small diffusion lengths leading to the linear behavior was given as a limiting case for small diffusion lengths. Hence, for large diffusion lengths, (2) is certainly no more valid. Based on [19], Bothe and Hinken [20] have realistically simulated the luminescence signal as a function of the effective diffusion length under various limiting conditions. As expected, in these simulations, the simulated luminescence signal saturates for increasing effective bulk diffusion length, respectively, decreasing $J_{01}$, in contrast with the linear Fuyuki approximation (2).

In this paper, after critically reviewing previous approaches for evaluating luminescence images, an expression derived in [19] for short wavelengths will be used for linking the luminescence scaling factor $C_i$ to $L_d$ and thus to $J_{01}$, alternatively to the linear Fuyuki approximation (2). Unfortunately, this expression describes only $C_i(L_d)$ explicitly but not $L_d(C_i)$, and it shows spurious poles, as will be shown in Section IV. However, it can be further simplified by assuming $L_{eff} = L_d$. The validity conditions of this assumption will be discussed. Moreover, we have checked the applicability of the saturation-type dependency proposed by Fuyuki et al. [1], which we call here “extended Fuyuki approximation.” In Section IV, some simulations are introduced, which support the applicability of our analytic approximate $C_i(L_{eff})$ expression for interpreting PL images and illustrate the statements made in Sections I and II.

These simulations show that our simplified short-wavelength approximate expression performs better than the extended Fuyuki approximation. Finally, in Section V, our approximate expression is applied to measured $V_{oc}$-PL and EL images of a typical multicrystalline silicon solar cell, and the results are compared to light-beam-induced current (LBIC)-measured $L_{eff}$ results and DLIT-measured $J_{01}$ results of the same cell.

II. PREVIOUS EVALUATION OF LUMINESCENCE IMAGES OF SOLAR CELLS

Most established methods for quantitatively evaluating EL and PL images are based on the model of independent diodes [6]–[10], [12]. Hence, it is assumed that each imaged pixel of a solar cell is connected to the terminals by an independent resistor. Then, the voltage drop between the terminal and the local diode is the product of the local current density $J_i$ and a local resistance $R_{s,i}$, which is given here in units of $\Omega \cdot \text{cm}^2$. In these methods, for measuring the local currents and, thus, $J_{01,i}$, only the local diode voltages $V_{d,i}$ measured after (1) are evaluated, but not the $C_i$ data. This has the advantage that vignetting, which is the inevitable signal drop toward the corners of the image, or inhomogeneities of the optical properties do not influence the results. Moreover, the $V_{d,i}$ results remain meaningful even in regions shadowed by gridlines and busbars, since in these regions, scattered light from the surrounding is detected by the camera, and only $C_i$ drops, which is not evaluated. However, it has been shown recently for inhomogeneous cells that this concept leads to significant errors for imaging the saturation current density $J_{01}$ [16], which is closely related via $J_{01}^p$ to the effective diffusion length $L_{eff}$ [21]; see below. The reason for this difficulty is the distributed nature of the series resistances in solar cells. In inhomogeneous cells, this leads to horizontal balancing currents in the emitter and the metallization, in particular under $V_{oc}$ condition, as will be explained in detail below. The independent diode model may also describe such balancing currents. However, this model assumes that they flow across the terminals and are limited by the effective series resistances of this simple model, as implicitly assumed, e.g., in [22]. This does not reflect reality, since it underestimated the resistive cross-coupling of neighboring regions by the emitter and the grid [16].

Note that if an inhomogeneous cell is under its $V_{oc}$, the local diodes are not all under their individual $V_{diode}$ condition. Instead, the voltages of diodes in “good” regions (low values of $J_{01}$, high $J_{sc}$, high $V_{diode}$) are below and that of diodes in “poor” regions (high values of $J_{01}$, low $J_{sc}$, low $V_{diode}$) are above their individual $V_{diode}$ values. This leads to the lateral balancing currents between these regions. The “good” regions supply current into the emitter, which flows back to the bulk of the “poor” regions, taking the shortest way. Hence, in “good” regions, the p-n junction acts as a sink for excess carriers, behaving like a plane of high recombination velocity, and in “poor” regions, it acts as an additional source of excess carriers, thereby increasing the injected current and thus the local voltage there. This process, which does not happen in wafers,
equalizes the luminescence contrast in solar cells compared with wafers showing the same lifetime distribution. In Section IV, we have simulated this situation. These balancing currents are strongest and dominant under $V_{oc}$ condition, but also at the maximum power point or any other loading condition, the current can be assumed to be composed from an extraction current and a balancing current component [17], [23]–[25]. In the “Suns—PL” method [26] an “effective lifetime” was introduced for the bulk of solar cells, which also includes these lateral balancing mechanisms. This lifetime, however, is then no longer a measure for the local bulk and backside recombination properties since, in inhomogeneous cells, it also depends on the recombination properties of the surroundings.

There are some estimates to evaluate luminescence images without assuming the independent diode model. The work of Fuyuki et al. [1]–[4] was already mentioned. Hinken et al. [27] have proposed to evaluate the ratio of PL images obtained under $V_{oc}$ and under $J_{sc}$ condition. They used a formula to consider the recombination activity of the emitter for the effective bulk diffusion length under $V_{oc}$ by describing the p-n junction by an effective recombination velocity $S_{eff}$, depending on the emitter part of $J_{01}$ ($J_{01}^e = $ emitter saturation current density, $N_A = $ net acceptor (hole) concentration in the bulk, $e = $ electron charge, $n_i = $ intrinsic carrier concentration)

$$S_{eff} = \frac{J_{01}^e N_A}{e n_i^2}.$$  

Note that this relation, if applied to the high injection case by replacing $N_A$ by $N_A + n$, is the base for measuring $J_{01}^e$ by the method of Kane and Swanson [28]. However, in the derivation of their formulas for the carrier profile, Hinken et al. [27] have generally assumed zero current extraction in the $V_{oc}$ case. This is not correct due to the balancing currents, as explained above. Therefore, the accuracy of this method, at least in the “good” crystal regions, may be questionable. Moreover, this method [27] has to neglect self-absorption of the detected radiation and, therefore, only works by using an InGaAs camera and longpass light filtering.

Another example of EL evaluation, which is not based on the independent diode model, is the spectrally filtered method of Würfel et al. [18]. This method uses the ratio of two images under the same biasing condition for different shortpass filter parameters instead of the luminescence intensity itself. Therefore, the result becomes independent of the local diode voltages and should be reliable. However, the relatively strong shortpass filtering necessary for this method (minimum 900 nm) leads to a strongly reduced sensitivity for this measurement and to long necessary image integration times.

A third example of EL and PL evaluation without the assumption of the independent diode model is the Laplacian-based method introduced by Glatthaar et al. [15], [29]. Here, the diode current density is obtained from the second derivative of the emitter potential, assuming a certain emitter sheet resistance. It has been shown recently that this method only leads to reliable results if the image blurring caused by light scattering in the detector is corrected [30]. This method is challenged by noise, which is strongly increased here by evaluating the second derivative of the luminescence signal.

In addition, the PL evaluation method of Carstensen et al. [17], [23] and Wagner et al. [24], [25] considers the existence of balancing currents (without calculating them explicitly) and does not use the independent diode model. Instead, it is assumed that the voltage drop between the terminal and the local diode corresponds to the product of the total cell current $I$ and a local series resistance $R_{s,i}$, which has the unit $\Omega$ here. This method does not lead to a $J_{01}$ distribution but rather uses the Fuyuki approximation (2) to calculate it [17]. Moreover, until now it cannot be applied to the EL case in the dark, since it always assumes illumination.

Many authors have not considered the balancing currents (which are generally unknown) for evaluating PL data of solar cells, or they have applied formulas valid for evaluating PL images on wafers to evaluate $V_{oc}$–PL images on solar cells [26], [31]–[33]. All this is only correct for a homogeneous cell but not for an inhomogeneous one. The difference between luminescence imaging on wafers and cells may be highlighted by considering the different local implied voltages $V_{impl}$. In an illuminated wafer, the implied voltage basically reflects the local p-n product under this illumination condition (low injection condition in p-type material assumed, $G = $ generation rate, $\tau_{eff} = $ effective lifetime)

$$p n = N_A G \tau_{eff} = n_i^2 \exp \left( \frac{V_{impl}}{V_T} \right).$$  

Note also that (4) only holds exactly for homogeneous lifetime, negligible surface recombination, and homogeneous generation, where the excess carrier concentration $n$ is homogeneous. If there is, for example, a sharp lateral step in the bulk lifetime, lateral carrier diffusion smears the carrier concentration and thus also $V_{impl}$ across this step. A characteristic length of this smearing is the diffusion length $L_d$. This effect was described in [34], where a simple method for desmearing the PL images of well-passivated wafers is proposed. Unfortunately, this method does not work on cells. In spite of this smearing effect, (4) is the base of PL-based lifetime imaging on wafers; see, e.g., [5]. Fortunately, in the most interesting low-lifetime defect regions, $L_d$ is low, and thus, the smearing effect is weak in PL imaging of wafers. Therefore, the use of (4) for interpreting PL images of wafers is usually justified and is the base for lifetime imaging on wafers.

The luminescence signals of illuminated solar cells and for EL imaging, on the other hand, can only be interpreted by considering the depth profile of excess carriers. Close to the p-n junction, $V_{impl}$ equals the local diode voltage $V_d$, independent of the local lifetime. This is a striking difference to the wafer case, where the implied voltage is generally proportional to $\tau_{eff}$ via (4). If all series resistance effects in a cell can be neglected, which is indeed the case in a well-processed cell for very low current densities, $V_d$ is homogeneous over the area and equal to the bias $V$ measured at the cell terminals. Under this condition, the lateral EL and PL contrast for different bulk lifetimes is caused only by different depth profiles of the excess carrier concentration, leading to different luminescence calibration constants $C_i$. In
low-lifetime regions, this carrier profile drops steeply, leading to a lower luminescence signal, and in high-lifetime regions, this profile is shallow, leading to a higher luminescence signal, as has been modeled, e.g., in [18] and [20]. If the current densities are so high that voltage drops at the series resistances cannot be neglected anymore, which is the usual case for EL and PL imaging under current extraction, the local luminescence signal is additionally strongly influenced by the voltage drops at the internal series resistances. This leads, in (1), to local diode voltages $V_d$ different from the applied voltage $V$, which is the base of all PL- and EL-based local series resistance measurement methods based on the independent diode model [6]–[10], [12]. With increasing current density, or under $V_{oc}$ condition with $d_i$ of all PL- and EL-based local series resistance measurement methods based on the independent diode model [6]–[10], [12].

In the EL case for an injection-independent lifetime, in any depth, the excess carrier concentration is proportional to $\exp(V_d/V_T)$. Therefore, (1) holds generally for any depth profile of the excess carriers, even if self-absorption is regarded. In the PL case, the influence of diffusion-limited carriers has to be regarded by subtracting the $J_{oc}$-PL image and thus evaluating the “net PL” or “EL equivalent” image [6], [20], [29]. In any case, (4) is no longer applicable to evaluate PL experiments on inhomogeneous solar cells. If this is formally done by calculating the local diode voltages based only on the optical generation rate $G$, assuming electrically isolated pixels, or by assuming that the lifetime is proportional to the luminescence signal at $V_{oc}$ of the cell, as, e.g., in [26] and [31]–[33], the obtained lifetime no more reflects the local bulk and backside properties, as mentioned above. This case will be simulated in Section IV.

However, for an optically homogeneous solar cell, the local luminescence calibration constant $C_i$ contains the information of the local bulk lifetime. $C_i$ is usually measured in a calibration measurement by PL at $V_{oc}$ under low illumination intensity or in a low-current EL measurement. Then, the local diode voltage $V_{d,i}$ is assumed to be everywhere sufficiently close to the measured cell bias $V$, and thus, $C_i$ can be measured after (1). The accuracy of this assumption will be checked in Section VI. Since we will show there that shortpass filtering is essential for avoiding optical artifacts, but for PL also the excitation light has to be filtered out, in this study, we use bandpass filtering from 950 to 1000 nm by an interference filter (Edmund part #86-972) for the luminescence signal. A residual influence of a locally varying cell bias, which is more disturbing in EL than in $V_{oc}$-PL imaging, can be corrected by using the linear response method described in [36], as will be demonstrated in Section VI. Note that here we have to correct the luminescence images for vignetting, which is done here by applying a correction formula.

III. ALTERNATIVE $C_i(L_{eff})$ DEPENDENCIES

A. $C_i(L_{eff})$ Dependence in Short-Wavelength Approximation

In [2] and [3], an infinitely thick solar cell was assumed, whose bulk was described only by the bulk diffusion length $L_d$. In [19] and [20] and in the following, a finite cell thickness $W$ and a rear surface recombination velocity $S_{rear}$ will be regarded. Then, the “effective diffusion length” $L_{eff}$ will be used for describing the bulk, which calculates as [21]

$$L_{eff} = \frac{L_d S_{rear} \sinh \left( \frac{W}{L_d} \right)}{L_d S_{rear} \cosh \left( \frac{W}{L_d} \right) + D \sinh \left( \frac{W}{L_d} \right)}.$$  

Here, $D$ is the diffusion coefficient for excess carriers. For short bulk diffusion lengths ($L_d \ll W$), $L_d = L_{eff}$ holds. Note that $L_{eff}$ is a measure of the concentration gradient of excess carriers below the p-n junction in the dark under forward bias. This is the reason why it is uniquely connected with the bulk part of $J_{01}$ by [21]

$$J_{01} = \frac{e D n_i^2}{N_A L_{eff}}.$$  

Since the depth profile of the excess carrier concentration, for a given diode voltage, is physically related to the depth profile of the collection efficiency [37], $L_{eff}$ can be imaged by wavelength-dependent LBIC mapping [21]. Note also that $L_{eff}$ can be both smaller and larger than $L_d$, depending on the value of $S_{rear}$. For $S_{rear} > D/L_d$, $L_{eff} < L_d$ holds, but for $S_{rear} < D/L_d$, $L_{eff}$ becomes larger than $L_d$ [38]. This is the reason why well-passivated thin solar cells may show very low values of $J_{01}$ and, thus, very high values of $V_{oc}$.

It was already mentioned that a silicon detector only detects the shorter wavelength fraction of the emitted radiation, peaking shortly above 1000 nm [3]. At this wavelength, the mean absorption length in silicon is about 160 μm [39], which is neither short nor long compared with a typical cell thickness of 180 μm. Moreover, the detected spectrum also contains longer wavelengths up to 1150 nm [3], and in some cases, even longpass filters are used for PL imaging, if the excitation is performed by LED light [40], and [41]. For PL and EL imaging, the detected wavelengths are generally close to the long-wavelength detection limit of the silicon detector, which leads to remarkable lateral light scattering within the detector [42]. For compensating the blurring effect due to this light scattering, spatial deconvolution must be applied to the measured images for ensuring that they indeed reflect the local luminescence signal. There are various methods to obtain the point spread function used for this deconvolution [41], and [43]. The lower the error made by this light scattering effect, the shorter the detected wavelength. Therefore, for minimizing this light scattering effect, shortpass filtering of the luminescence signal at 1020 nm has been proposed in [44]. It will be shown in Section V that if EL or PL is imaged with no filtering or with longpass filtering, certain artifacts for measuring $C_i$ may appear, which are obviously due to some inhomogeneities of the optical properties of the backside of the cell. For excluding these artifacts, the information depth of luminescence imaging should be limited to the
uppermost 100 µm of the cell. We have compared the influence of different filter parameters in measured EL and PL images and have found that shortpass or bandpass filtering up to 1000 nm provides a good compromise between acceptable loss in sensitivity and suppression of optical artifacts from the backside of the cell; see Section V. Therefore, in the following, we will calculate $C_i$ for 950–1000 nm bandpass-filtered light detection in PL imaging. The results will also hold if $C_i$ is obtained by shortpass-filtered EL imaging at low current.

All calculations are based on that performed in [19], which are partly published in [20]. In these calculations, a realistic excess carrier depth profile is considered, all generated spectral components of the luminescence are regarded, self-absorption is considered, and a typical spectral sensitivity of the camera is assumed. The surface texturing is considered by assuming a fixed angle of light propagation $\Theta_1$ before light detection, which is assumed to appear perpendicular to the surface. For alkaline etched random pyramids $\Theta_1 = 41.98^\circ$ holds [21]. For isotextured surfaces, this angle is somewhat lower; we will assume here $\Theta_1 = 35^\circ$. It must be mentioned that this selection is somewhat arbitrary. While for alkaline texture this angle is well defined, isotexture leads to shell-shaped surface structures, where light propagation in a broad range of angles is possible. On the other hand, also the light is not monochromatic as suggested by the later choice of a single value of $L_\alpha$. Therefore, here, we consider both $\Theta_1$ and $L_\alpha$ as effective values, which may be fitted for obtaining a good correspondence to related methods. Generally, we assume homogeneous optical properties of the surface.

In [19] and [20], besides the full spectral simulation, which cannot be given as an analytic expression, also simplified formulas for the short- and long-wavelength limit of light detection were presented. For example, the following formula for short-wavelength detection was derived:

$$C_i \sim 1 - \frac{L_\alpha \cos(\Theta_1)}{L_{\text{eff}}}.$$  \hfill{(7)}

Here, $L_\alpha$ is the absorption depth of the dominant wavelength contributing to the detected radiation. For 950–1000 nm bandpass-filtered light, $L_\alpha \cos(\Theta_1) \approx 103$ µm holds. Unfortunately, this expression (7) does not become zero for $L_{\text{eff}} = 0$, as it should, since for deriving (7), $L_{\text{eff}} > L_\alpha$ had been assumed. If this assumption is not made, the following formula can be derived, which corresponds to [19, eq. (6.17)]:

$$C_i \sim \frac{L_\alpha}{L_{\text{eff}}} \left(1 - \frac{\cos(\Theta_1)}{L_{\text{eff}}} \right).$$  \hfill{(8)}

This expression, according to the knowledge of the authors has not yet been published for interpreting luminescence signals. However, it was (without the cos-factor) used, e.g., by Spiegel et al. [45] for interpreting spectral LBIC signals, which is a similar physical problem. This expression still contains $L_d$ and $L_{\text{eff}}$ separately. In the limit of $L_d \gg \infty$, $L_{\text{eff}} = W + D/S_{\text{rear}}$ holds, and the maximum possible value of (8) becomes

$$C_{\text{eff}} \sim L_\alpha - \frac{L_\alpha^2 \cos(\Theta_1)}{W + D/S_{\text{rear}}}.\hfill{(9)}$$

If (8) is divided by (9), the unknown proportionality factor cancels, leading together with (5) to the dependence of $C_i/C_{\text{eff}}$ on $L_d$:

$$\frac{C_i}{C_{\text{eff}}} = \frac{\cos(\Theta_1)}{L_\alpha - \frac{L_\alpha^2 \cos(\Theta_1)}{W + D/S_{\text{rear}}}} \left(1 - \frac{\cos(\Theta_1)}{L_{\text{eff}}} \right)^2.$$

Unfortunately, the inverse function of (10), which we would need for imaging $L_d$ from measured $C_i$ data, cannot be given explicitly. Therefore, for evaluating (10) for given values of $L_\alpha$, $W$, $S_{\text{rear}}$, and $\Theta_1$, a lookup table must be made, which allows us to calculate also $L_d$ from $C_i$. Moreover, as will be shown in the next section, (10) contains a spurious pole at $L_d = L_\alpha + \cos(\Theta_1)$, which has to be interpolated in the lookup table data.

Since the application of this procedure to measured values of $C_i$ is quite elaborate, we propose to use (8) with the approximation $L_d = L_{\text{eff}}$ as the base for calculating $L_{\text{eff}}$ from measured values of $C_i$ for spectrally shortpass-filtered radiation, leading to our approximate result

$$\frac{C_i}{C_{\text{eff}}} = 1 - \frac{L_\alpha \cos(\Theta_1)}{L_{\text{eff}} + L_\alpha \cos(\Theta_1)}.\hfill{(11)}$$

For low values of $L_d$ in defect regions, $L_d = L_{\text{eff}}$ is a very good approximation, but not for high values in “good” crystal regions, as will be shown in the next section. However, for calculating $L_{\text{eff}}$ from $C_i$ in this study, we anyway must use $C_{\text{eff}}$ as a fitting parameter as will be demonstrated in Section V. This parameter mostly influences the high values of the diffusion length, which become automatically more correct by this fitting procedure. Therefore, it can be hoped that, in spite of the relatively poor approximation $L_d = L_{\text{eff}}$ for large $L_d$, (11) leads to reasonable results. Note that (11) is equivalent to (7) up to an $L_{\text{eff}}$ offset of $L_{\alpha} \cos(\Theta_1)$. The inverse function of (11), which can be used directly for evaluating measured $C_i$ images, is

$$L_{\text{eff}} = \frac{L_\alpha \cos(\Theta_1)}{1 - \frac{C_i}{C_{\text{eff}}} - L_\alpha \cos(\Theta_1)}.\hfill{(12)}$$

B. $C_i(L_{\text{eff}})$ Dependence in Long-Wavelength Approximation

In [1], the case $L_{\text{eff}} < W$, on which (2) is based, was only mentioned as a limiting case. For medium and high values of $L_{\text{eff}}$, this work also contains the more general formula:

$$C_i \sim \frac{L_{\text{eff}}}{W} \left(1 - \exp \left(-\frac{W}{L_{\text{eff}}} \right) \right).\hfill{(13)}$$

This formula has been derived under the condition of negligible light absorption; hence, it may be taken as a long-wavelength approximation. In the limit of large $L_{\text{eff}}$, the exponential function in (13) may be developed, leading to a constant $C_{\text{eff}} \sim 1,$
which finally leads to the extended Fuyuki approximation:

\[ C_i = C_{i,\text{max}} \frac{L_{\text{eff}}}{W} \left( 1 - \exp \left( \frac{-W}{L_{\text{eff}}} \right) \right). \]  

(14)

In addition, this formula saturates for large \( L_{\text{eff}} \) to \( C_{i,\text{max}} \) and thus provides a significant improvement to the linear \( C_i \sim L_{\text{eff}} \) dependence. Unfortunately, (14) cannot be resolved analytically to \( L_{\text{eff}} (C_i) \).

IV. SIMULATIONS

Fig. 1 shows various simulated dependences of \( C_i (\text{W}) \) as a function of \( L_{\text{eff}} \), all assuming \( W = 200 \mu \text{m}, L_a = 126 \mu \text{m} \) (dominating wavelength \( \approx 990 \text{ nm}; \) see [46]), \( D = 28.6 \text{ cm}^2/\text{s} \) for \( N_A = 10^{16} \text{ cm}^{-3} \), and \( \Theta_3 = 35^\circ \). Fig. 1(a) shows results of our simplified short-wavelength approximation (11) and Fig. 1(b) shows results of the two Fuyuki approximations. Results of our simplified approximation are drawn in (a) in two different scales. The short-dash line shows the dependence (11) directly. Note, however, that in reality, \( C_{i,\text{max}} \) is not fitted to the maximum possible \( L_{\text{eff}} \) holding for \( L_{\text{eff}} = \infty \) but rather to the highest \( L_{\text{eff}} \) appearing in a given cell. The straight line in Fig. 1(a) shows the result of (11) for \( C_{i,\text{max}} \) fitted to the exact point of the full spectral analysis at \( L_{\text{eff}} = 500 \mu \text{m} \) for \( S_{\text{rear}} = 30 \text{ cm}/\text{s} \). This curve fits the whole exact dependency very well. Besides our simplified short-wavelength approximation (11), the more accurate dependence (10) is displayed for \( S_{\text{rear}} = 30 \text{ cm}/\text{s} \) and \( 600 \text{ cm}/\text{s} \), which is typical for passivated emitter and rear cell (PERC) and Al-backside cells, respectively. Both curves after (10) show a pole at \( L_0 = L_a \cos(\Theta_3) \), which was mentioned already in [45]. Thus, if (10) should be applied to \( L_0 \) imaging, in the lookup table, the data in this pole region have to be interpolated. Moreover, some points of the exact full spectral analysis regarding our bandpass filter between 950 and 1000 nm are displayed for the same values of \( S_{\text{rear}} \).

Fig. 1(b) shows several variants of the Fuyuki approximation, together with results of the exact full spectral analysis. As expected, the linear Fuyuki approximation only holds in the limit of very low \( L_{\text{eff}} \). The extended Fuyuki approximation after (14) if fitted to \( C_{i,\text{max}} \) for \( L_{\text{eff}} = \infty \) is generally lying below the exact results, as the approximate solution after (11) did. In addition, this curve may be rescaled to fit the exact point of the full spectral analysis at \( L_{\text{eff}} = 500 \mu \text{m} \) for \( S_{\text{rear}} = 30 \text{ cm}/\text{s} \). This curve fits the exact values already better than before but worse than the correctly scaled short-wavelength approximation (11). Therefore, and since we need short-wavelength filtering for avoiding optical artifacts, in the following, we will use only this approximation.

The second simulation illustrates the difference between the luminescence signal in an inhomogeneous solar cell under \( V_{\text{oc}} \) condition, compared with that of an equivalent wafer. First, we simulate the conditions in an inhomogeneous cell. By using PC1D [47], we have modeled a PERC cell, which consists of five separate regions of different areas \( A_i \) with different bulk lifetimes \( \tau_{b,i} \). For simplicity, we have applied the model of independent diodes for this model cell; hence, we have assumed that each of these regions is connected with the terminals by a resistance of \( 0.6 \Omega \cdot \text{cm}^2 \). The most important parameters and the results of the simulations are summarized in Table I. The parameters are chosen in such a way that the individual \( V_{\text{oc}} \) of region #3, which is characterized by a bulk lifetime of 20 \( \mu \)s, coincides with \( V_{\text{oc}} \) of the whole cell. Hence, region #3 represents the average of the cell. The net current densities \( J(V_{\text{oc}}) \) of the different regions flowing at \( V_{\text{oc}} \) of the cell, which are the sources of the balancing currents explained in Section II, are also given in Table I. Here, negative values indicate dominating photocurrent and positive values dominating dark current. The voltage drop of these current densities at the \( R_s \) of 0.6 \( \Omega \cdot \text{cm}^2 \) just explains the differences between \( V_{\text{oc}} \) of the cell (which is that of diode #3, here 631.8 mV) and the local diode voltages \( V_{\text{oc}}(V_{\text{oc}}) \) of regions.
TABLE I
MODEL CELL SIMULATION RESULTS (SEE TEXT)

<table>
<thead>
<tr>
<th>diode #</th>
<th>$\tau_0$ [µs]</th>
<th>$A_i / A^{v_{cell}}$ [%]</th>
<th>$J_{sc}$ [mA/cm²]</th>
<th>$V_{diode}^{oc}$ [mV]</th>
<th>$V_D(V_{oc})$ [mV]</th>
<th>$J(V_{oc})$ [mA/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>26.4</td>
<td>35.3</td>
<td>1.68 $\times$ 10^{-13}</td>
<td>669.8</td>
<td>644.7</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>18.4</td>
<td>35.1</td>
<td>2.71 $\times$ 10^{-13}</td>
<td>657.4</td>
<td>641.3</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>18.4</td>
<td>34.3</td>
<td>7.16 $\times$ 10^{-13}</td>
<td>631.8</td>
<td>631.8</td>
</tr>
<tr>
<td>(average)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>18.4</td>
<td>33.2</td>
<td>1.35 $\times$ 10^{-12}</td>
<td>614.7</td>
<td>623.7</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>18.4</td>
<td>31.1</td>
<td>2.99 $\times$ 10^{-12}</td>
<td>592.5</td>
<td>611.9</td>
</tr>
</tbody>
</table>

The other parameters used for the simulations are cell thickness 200 µm, $N_A = 1.5 \times 10^{15}$ cm⁻³, $S_{int} = 30$ cm/s, $R_e = 0.66$ cm⁻², $J_{sc} = 90$ fA/cm⁻², and illumination at AM 1.5.

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Fig. 2. Simulated luminescence signal of regions with various lifetimes in a solar cell under $V_{oc}$ (full line) and in an equivalent wafer (dashed line).

#1, #2, #4, and #5. We see in Table I that, for these regions, the local diode voltages $V_D(V_{oc})$ significantly deviate from their individual $V_{diode}^{oc}$ values.

By using the bulk lifetimes and the local diode voltages in Table I, the luminescence signals of the different cell regions under illumination $\Phi_{cell}$ were calculated by using the full spectral analysis of [19] and [20], regarding bandpass filtering between 950 and 1000 nm. On the other hand, by using the same calculation method, the expected luminescence signals of wafers $\Phi_{wafer}$, assuming the same bulk lifetime and similar $S_{int}$, were simulated. Fig. 2 shows $\Phi_{cell}$ and $\Phi_{wafer}$ as a function of the bulk lifetime $\tau_0$. It is clearly visible that the luminescence signal in a solar cell varies much weaker with varying $\tau_0$ than the luminescence signal of a wafer. Under nonfiltered condition, this difference becomes even larger.

In the third simulation, we demonstrate by PC1D [47] simulations that a varying backside recombination velocity influences the excess carrier concentration not only in the depth of the cell but also close to the p-n junction. It will be shown in the following section that there are certain grains in the investigated cell, which appear dark in unfiltered or 1000-nm longpass-filtered luminescence. In 1000-nm shortpass-filtered luminescence, this dark contrast considerable reduces, and at 975-nm shortpass filtering, it nearly vanishes. Obviously, the longer wavelengths, which come from the depth of the bulk, carry the information of this “dark grain” contrast. There are two possible explanations for this contrast. It may be due to an increased backside recombination velocity, which would preferentially reduce the excess carrier concentration in the depth of the bulk. Alternatively, it may be due to a decreased backside reflectivity, which would also decrease the detected luminescence signal for long wavelengths. Fig. 3 shows two depth profiles of excess carriers in a typical standard solar cell under illumination at 850 nm equivalent to 0.1 suns with a bulk lifetime of 20 µs simulated by PC1D [47]. The full line shows the profile of a cell with a backside recombination velocity of 600 cm/s under its $V_{roc}$, as in our experiments. The dashed line shows the profile of a grain with a backside recombination velocity of 1200 cm/s at the same illumination and the same local bias. This curve simulates a “dark grain” caused by an increased backside recombination velocity. We see that the dashed curve of this grain is lying below that of the rest of the cell not only in the depth of the bulk but also already in the upper part. As discussed in the previous section, only at the p-n junction both concentrations agree, since the local diode voltages are the same. Hence, this “dark grain,” if it should be caused by an increased backside recombination velocity, should become visible also in short-wavelength luminescence, which characterizes only the upper half of the cell. Since this is not the case (see next section), this proves that the “dark grain” contrast is caused here by a locally decreased backside reflectivity. For avoiding this optical artifact, or generally for excluding the influence of reflected light from the backside, shortpass filtering should be used for quantitative evaluation of luminescence images according to our method.

V. EXPERIMENTAL SETUP

All results are obtained on a typical commercial multicrystalline silicon solar cell with full-area Al back contact of standard size (156 × 156 mm²). The EL and PL investigations were performed using an ANDOR iKon-M PV-Inspector camera having a 1024 × 1024 pixels Si detector, which is
thermoelectrically cooled to -40 °C. The objective was a LINOS inspec.x M NIR 1.4/50 mm. The PL excitation was performed by 850-nm LED light, which was sent through a shortpass interference filter at 870 nm (Asahi Spectra ZIS0870). Various light filters were placed in front of the camera (see Section VI). The cell was sucked by vacuum to a massive temperature-controlled (25 °C) copper base. From all EL images, the zero current image was subtracted, and from all PL images, the $J_{sc}$-PL image for obtaining the net PL or “equivalent EL” image, as described in Section I. The current to and from the cell was lead by low-ohmic current rails comprising 12 spring-loaded contact pins plus one sense contact per busbar. The spectral LBIC results have been obtained by using a LOANA system (see [48]). The DLIT results have been obtained by using the PV-LIT system of InfraTec [49].

VI. EXPERIMENTAL RESULTS

Fig. 4(a) shows an EL image taken at a current of 0.1 $I_{sc}$; the integration time was 4 min and the background image was subtracted. All images were separately scaled for displaying the recombination-active lattice defects with a similar contrast. At the upper left edge, there are two neighboring broken gridlines (positions indicated by arrows), which are visible in EL even at this low current. Below this site, two “dark grains” (marked by a white rectangle) as discussed in the previous section are visible; some more are visible in the right part of the cell. These “dark grains” were visible with the same contrast in a 1000-nm longpass-filtered (Edmund #84-766) $V_{oc}$ PL image, which is not shown here. This PL image looked very similar to the unfiltered EL image in Fig. 4(a), except that the high-$R_s$ regions were visible. Finally, Fig. 4(c) shows a background-corrected EL image taken at 0.1 $I_{sc}$ using a shortpass filter of 975 nm (Edmund #86-116). Here, the integration time needed was already 30 min. In this image, the high-$R_s$ regions are strongly visible again (note that the general image contrast is reduced for this low wavelength), but the “dark grains” are nearly invisible. Regarding the simulations made in the last section, we believe that this is a proof that the “dark grain” contrast is, at least in this case, basically an optical artifact caused by a different (reduced) backside reflectivity in these regions. The fact that the backside reflectivity does not influence the internal quantum efficiency, and thus also luminescence signal, only for absorption lengths smaller than the wafer thickness was nicely demonstrated by the simulations performed in [50].

Before calculating $C_i$ from the bandpass-filtered images, we have to correct them for systematic measurement errors. First, we have corrected the images for light scattering in the detector. Here, we have used the method described in [41] to measure the point spread function of our system including the bandpass filter and have corrected all measured EL and PL images by image deconvolution. This deconvolution leads to a weak but notable increase of the image contrast and to a sharpening of the structures. Then, we have corrected vignetting, which is done here by regarding the $\cos(\alpha)^4$ law described, e.g., in [51].
Since bandpass filtering between 950 and 1000 nm provides a good compromise between acceptable image integration time and good suppression of the “dark grain” artifact, we have further evaluated only $C_i$ data of the bandpass-filtered PL and EL images.

For these images, we have checked whether any residual series resistance effects play a role. For $V_{oc}$ PL imaging, only lateral balancing currents may lead to series resistance effects. In this respect, EL imaging is expected to be more critical than PL imaging, as we will see below. Here, we have applied the extrapolation method described in [36] to correct $C_i$ for residual $R_s$ effects. The basic idea of this method is to measure PL or EL images at two intensities, respectively, currents and to correct the image of the lower intensity by the ratio of the images at the two intensities, regarding the different biases. For example, two $V_{oc}$-PL images $PL^1$ and $PL^2$ are taken at two illumination intensities $I^1$ and $I^2$ leading to two open circuit voltages $V_{oc}^1$ and $V_{oc}^2$. The intensities $I_1$ and $I_2$, measured by their respective short circuit currents, have to differ here exactly by a factor of 2, which makes the procedure most easy to evaluate. In our experiments, the PL images were taken at intensities of 0.1 and 0.2 sun. Then, in any position, the local diode voltages $V_d^1$ and $V_d^2$ differ from the measured voltages $V_{oc}^1$ and $V_{oc}^2$, respectively, by the local voltage differences $\Delta V^1$ and $\Delta V^2$, which are unknown and depend on the unknown local horizontal currents and resistances. However, if we assume that all these local voltages drop scale proportional to the illumination intensity, in any position (for our illumination conditions) $\Delta V^2 = 2 \times \Delta V^1$ would hold. This linear response model was used already by Carstensen et al. [17], [23] and Wagner et al. [24], [25] for interpreting PL images. However, it has been found in [36] that $\Delta V$ does not increase linearly but rather sublinearly with increasing $I$. The reason is the distributed character of the series resistance. It has been shown there that the assumption

$$\Delta V^2 = (1 + X) \Delta V^1$$

is a good approximation, with $X$ being a nonlinearity parameter lying between 0 and 1. It was shown in [36] that the value of $X$ depends, among others, on the value of the illumination intensity $I$. For very low intensities, it approaches $X = 1$, which corresponds to linear response, and for higher currents, it decreases. With (13), the net PL signals at $V_{oc}^1$ and $V_{oc}^2$ become

$$PL^1 = C_i \exp \left( \frac{V_{oc}^1 \Delta V^1}{V_T} \right) = C_i \left( \exp \left( \frac{V_{oc}^1}{V_T} \right) \ast \exp \left( \frac{\Delta V^1}{V_T} \right) \right)$$

$$PL^2 = C_i \exp \left( \frac{V_{oc}^2 \Delta V^2}{V_T} \right) = C_i \left( \exp \left( \frac{V_{oc}^2}{V_T} \right) \ast \exp \left( \frac{(1 + X) \Delta V^1}{V_T} \right) \right).$$

Dividing (17) by (16) leads to

$$\frac{PL^2}{PL^1} = \exp \left( \frac{V_{oc}^2 - V_{oc}^1}{V_T} \right) \ast \exp \left( \frac{X \Delta V^1}{V_T} \right).$$

If this is inserted into (16), the following formula for $C_i$ appears, which no more contains the unknown $\Delta V_i$:

$$C_i = \frac{PL^1 \exp \left( \frac{-V_{oc}^1}{V_T} \right)}{\left( \frac{PL^2}{PL^1} \exp \left( \frac{V_{oc}^2 - V_{oc}^1}{V_T} \right) \right)^{\frac{1}{X}}}.$$ (19)

With no series resistance effects, $PL \sim \exp(V_{oc}/V_T)$ would hold everywhere, the denominator in (19) would be unity for any value of $X$, and (19) would reduce to (1). For EL evaluation, the same formulas hold, only $V_{oc}$ is replaced by the applied bias $V_s$ and the second current has to be twice the first current used for EL imaging.

Based on 2-D simulations of a typical solar cell region, it was estimated in [36] that, if $V_{oc}$ PL images at 0.1 and 0.2 suns are used, an optimum value for $X$ is 0.86. It is not useful to work here with higher intensities, since then we may approach the high-current regime where the value of $X$ deviates more strongly and in a generally unknown manner from unity [36]. This value was used here for correcting the $V_{oc}$ PL images. For the EL images taken at 0.1 and 0.2 $L_{oc}$, we have optimized the value of $X$ until the high-$R_s$ regions became invisible. This was the case here for $X = 0.55$. Fig. 4(d) and (e) shows the resulting $C_i$ images based on the EL and the $V_{oc}$ PL images, respectively. These $C_i$ images look very similar, which shows that both $V_{oc}$ PL and EL imaging can be used for $C_i$ imaging. Interestingly, while the EL-based $C_i$ (d) was corrected for not showing the high-$R_s$ regions, the PL-based image (e), which was corrected with another value of $X$, these regions weakly appear. The reason for this is not clear yet, but this is a very small effect.

Finally, the quantitative influence of the $R_s$ correction was checked for the $V_{oc}$ PL and the EL case. Fig. 4(f) shows an image of the $R_s$ correction factor for $V_{oc}$ PL $C_i$. This correction factor is the ratio of the corrected $C_i$ of Fig. 4(e) and $C_i$ calculated from the 0.1-sun $V_{oc}$ PL image without the $R_s$ correction, but including image deconvolution and vignetting correction. This correction factor image is scaled between 0.9 and 1.2 and shows that the correction amounts here between -10% and +20%, which is quite a weak correction. According to (1), +20% correction corresponds to a maximum local diode voltage correction of 4.7 mV in the defect regions. For the EL case, this factor was between 1 and 1.6, which corresponds to a maximum correction of +60% (this correction goes only in one direction), corresponding to an estimated voltage correction of 12 mV maximum. If also for EL evaluation $X = 0.86$ is used, the maximum correction is +33%, corresponding to 7.3 mV correction, which is still larger than that for $V_{oc}$ PL. Then, however, the high-$R_s$ regions would become visible in the $C_i$ image. Note that this correction is generally not exact, but the error made by this correction is certainly well below the correction itself. Therefore, these results indicate that the $C_i$ measurement performed by $V_{oc}$ PL should be more reliable than that performed by EL.

The $C_i$ data of Fig. 4(d) and (e) are used now for calculating $L_{eff}$ after (12) with the results shown in Fig. 5(a) and (b). Here, the unknown parameter $C_{max}^{max}$ has been estimated by fitting the maximum $L_{eff}$ values to the image of $L_{eff}$ obtained from
spectral LBIC investigations, which is also shown in Fig. 5(c). From the $L_{\text{eff}}$ data, $J_{01}$ data were calculated by applying (6) and adding $J_{e01}$ assumed to be 200 fA/cm$^2$ here. The parameter $N_A$ in (6) has been estimated by fitting the $J_{01}$ maxima to DLIT-$J_{01}$ maxima shown in Fig. 5(f) to be 6.5 $\times$ 10$^{15}$ cm$^{-3}$. We see that both the $L_{\text{eff}}$ and the $J_{01}$ images obtained agree very well between PL and EL evaluation. This proves again that, in spite of the larger $R_s$ correction made for the EL results, both imaging methods can be used for quantitative luminescence image evaluation.

**VII. DISCUSSION AND CONCLUSION**

The luminescence-measured $L_{\text{eff}}$ images in Fig. 5(a) and (b) agree very well with the spectral LBIC-measured $L_{\text{eff}}$ image (c). It must be mentioned that the data acquisition time of spectral LBIC has been 6.5 h in this case, whereas the PL measurements took altogether only 40 min. Note that the “dark grain” regions are still slightly visible in all these images. For the luminescence-based images, this is a result of the compromise done here to choose 1000 nm as the shortpass filter limit. When we calculate $L_{\text{eff}}$ from the 975-nm shortpass-filtered EL image, the “dark grains” remain nearly invisible. We believe that also for the LBIC-measured $L_{\text{eff}}$ image in Fig. 5(c), the visibility of the “dark grains” may be an optical artifact. This $L_{\text{eff}}$ is calculated based on LBIC images up to 980 nm, where reflection at the backside may already influence the result. Note also that the luminescence-measured $L_{\text{eff}}$ images (a) and (b) contain some defects, which are not visible in the LBIC-based image (c). Some of these defects are indicated by dashed white circles in Fig. 5(a). From bias-dependent DLIT investigations of this cell, we know that in these positions, a significant recombination current flows. In these positions, there are cracks or surface scratches. Since these defects do not influence the bulk lifetime, we do not expect that they influence $C_i$ and appear in $L_{\text{eff}}$ and $J_{01}$ images. Indeed, in the DLIT-based $J_{01}$ image [see Fig. 5(f)], they are not visible. However, these defects generate an additional depletion region recombination current, which also produces local voltage drops. This recombination current shows a much weaker voltage dependence than the $J_{01}$ current, which dominates everywhere else. Therefore, the $R_s$ correction procedure described in Section V does not work correctly in these regions. Hence, we believe that, in these defect regions, the local voltage drop due to this current component is not sufficiently corrected by our $R_s$ correction procedure, leading to the observed contrast. Indeed, when we further reduced the nonlinearity factor $X$ in this correction procedure, we could remove these contrasts in the $C_i$ image. Then, however, the broken gridline regions would become visible again.

The PL- and EL-based $J_{01}$ images in Fig. 5(d) and (e) correspond also quantitatively well to the DLIT-based $J_{01}$ image (f), but they show a much better spatial resolution. One difference is that the minimum values of $J_{01}$ in the “good” regions of the cell are lower in the DLIT-based than in the luminescence-based images. We believe that this disagreement comes here from the fact that we have fitted $C_{\text{max}}$ for fitting the maximum values of luminescence $L_{\text{eff}}$ to the LBIC-measured ones. It is possible that the procedure in the LOANA system for evaluating the LBIC data is also not perfect and leads to too low maximum $L_{\text{eff}}$ data. If a slightly lower value for $C_{\text{max}}$ would have been used here, $C_i/C_{\text{max}}$ and, thus, $L_{\text{eff}}$ would have become larger in these regions and the minimum values of $J_{01}$ would have become smaller. The average value of $J_{01}$ in the region between the middle and the right busbar obtained by PL was 1.72 pA/cm$^2$, for EL it was 1.63 pA/cm$^2$, and for DLIT it was 1.04 pA/cm$^2$. For the PL and EL values, the data in the gridline regions, which are...
too high due to the shadowing effect, are excluded in the calculation. One reason for the too high luminescence-based average $J_{01}$ values is the too high $J_{01}$ value in the “good” cell regions discussed above, which may be reduced by choosing a lower value of $C_{\text{max}}$. Regarding all this, the quantitative agreement between DLIT and luminescence imaging is good. It should be noted that our luminescence-based $J_{01}$ image nicely correspond to results of the Laplacian-based PL image evaluation method employing image deconvolution described recently by Frühauf and Breitenstein [30], where the same cell was investigated.

While in the past, $J_{01}$ imaging by DLIT and luminescence methods regularly lead to different results for $J_{01}$ [13], [14], with the advent of new luminescence evaluation methods in [30] and in this work, this discrepancy seems to be resolved now. The method introduced here is basically an extension of the Fuyuki method [1]–[4], which takes into account the saturation of the luminescence for high bulk lifetimes under short-wavelength filtering condition. In Section III-B, also, an improved formula for interpreting long-wavelength filtered luminescence images is given, which should be applicable, e.g., for PERC cells, where an inhomogeneous backside reflectivity is not expected. Still remaining differences to other methods and limitations of this method can easily be explained. Only now luminescence imaging may play off its main advantage to DLIT to have a significantly better spatial resolution. Note, however, that DLIT-based $J_{01}$ imaging is self-scaling and does not need any fitting parameters, whereas the luminescence evaluation method described here needs some fitting parameters, which are $C_{\text{max}}$ in (11), $N_A$ in (6) (which also could be measured) for converting $L_{\text{eff}}$ into $J_{01}$, and the nonlinearity parameter $X$ in (17).

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Authors’ photographs and biographies not available at the time of publication.