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Improved Laplacian Photoluminescence image evaluation regarding the local diode back voltage distribution

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ABSTRACT

Laplacian photoluminescence-based local diode voltage evaluation was shown recently to lead to correct mean values of the local saturation current density in mm-sized regions, but local maxima in the positions of recombination-active grain boundaries appear overestimated. It is shown here by 2-D device simulations that this effect is at least partly due to the influence of the local diode back voltage, which is caused by the voltage drop at the bulk and back contact resistances. Visually the image of this back voltage appears like a blurred copy of the local diode current density. It is shown in this work that indeed the diode back voltage can be simulated in good approximation by blurring the diode current image, which comes out of the Laplacian evaluation, multiplied with an effective vertical bulk resistance. The corresponding point spread function can be obtained e.g. by device simulation. An iterative procedure is proposed leading to self-consistent results for the diode current density and the diode back voltage. If this method is applied to simulated local cell data, the assumed distribution of the saturation current density is retrieved accurately. Applying this method to measured photoluminescence images leads to a better correspondence to non-linear Fuyuki PL evaluation results than the previously performed direct evaluation of the local diode voltage data. Remaining differences will be discussed.

1. Introduction

The saturation current density J_{01} is one of the most important parameters of a silicon solar cell, if not the most important one. It is a measure of the recombination probability in the bulk and at the surface and thus governs both the short circuit current density J_{sc} [1] and the open circuit voltage V_{oc}. In multicrystalline (mc) solar cells J_{01} is distributed very inhomogeneously due to the presence of local defect regions, some mm or cm in size. These defect regions are often called "dislocation clusters" though they contain not only dislocations but also grain boundaries. In particular low angle grain boundaries, which may be considered as very dense rows of dislocations, may show the highest recombination activity [2,3]. In these defect regions J_{01} may show values as large as 8 pA/cm^2 [4], but in defect-free regions J_{01} is about 0.6 pA/cm^2 for standard technology cells [4] and below 0.2 pA/cm^2 for PERC cells [5]. For evaluating the influence of these defect regions on the efficiency of a cell, J_{01} imaging is necessary. Until recently dark lock-in thermography (DLIT [6]) was the only reliable method for J_{01} imaging. In particular the so-called "Local I-V" method for evaluating DLIT results leads, within its spatial resolution limit of a few mm, to reliable J_{01} distributions [7]. There have been several attempts for using also luminescence for imaging J_{01} [8,9], which shows a better spatial resolution and lower acquisition times and is very successful for imaging the effective series resistance R_s [10]. However, in all previous comparisons between DLIT-J_{01} and PL-J_{01} on mc-Si cells, PL-J_{01} distributions showed a significantly lower image contrast than for DLIT-J_{01} [11]. The evaluation of finite element simulated PL and DLIT signals on assumed J_{01} distributions in a realistic cell model has shown that this discrepancy is due to the assumption of the model of independent diodes, in particular for luminescence evaluation [12]. While this model is allowed to be used for DLIT evaluation, since in DLIT the local currents are measured very directly by monitoring their heating action, for luminescence imaging this model leads for inhomogeneous J_{01} distributions to erroneous results. The reason is that PL can only measure local diode voltages [13]. In these PL evaluation methods the current is measured from the voltage drop at a series resistor, which is assumed to carry only the current of this diode. Hence, in this model the local diode is assumed to be electrically isolated from its surrounding. In reality neighboring diodes are coupled to each other by the emitter and grid resistances, hence the series resistance is distributed, which is not considered in the model of independent diodes and leads to the described current errors.

Recently two alternative PL evaluation methods have been proposed for J_{01} imaging, which are Laplacian evaluation implying image

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deconvolution [14,15] and non-linear Fuyuki evaluation [16]. The latter method evaluates the local luminescence calibration constant C_i and needs two fitting parameters, which may be obtained e.g. by fitting an artificially blurred PL-J_{01} distribution to a DLIT-measured J_{01} distribution [5]. Laplacian PL evaluation, on the other hand, has as the only free parameter the emitter sheet resistance ρ, which is as a rule well-known. Unfortunately, this method has some other problems. For example, it reacts very sensitive to any image noise, since it evaluates the second spatial derivative of a voltage distribution as the local diode current density. Fortunately, modern PERC cells show little recombination and high V_{oc} values and therefore generate significantly higher luminescence signals than previous standard technology cells. Moreover, in these cells the emitter sheet resistance ρ is typically higher than in standard technology cells, which also leads to a higher Laplacian signal. In the original work on Laplacian luminescence evaluation [14] the results were wrong by a factor of two. It was suspected already there and also in [17] that the reason could be some blurring of the luminescence images. Indeed, it was found later that correcting lateral photon scattering in the detector by image deconvolution leads to a more realistic J_{01} distribution, though the J_{01} maxima were still not as high as expected [15]. After employing image deconvolution and approximately regarding the voltage drop at lateral emitter and grid resistances for calculating C_i, the J_{01} maxima in recombination-active grain boundaries became even stronger than expected [5]. The final problem, which will be treated in this contribution, is that actually this method has to evaluate the local emitter voltage V_{em}. Luminescence image evaluation, however, only reveals the local diode voltage V_d, which differs from V_{em} by the so-called diode back voltage V_b. This diode back voltage is due to the voltage drop of the vertical diode current J_d at the bulk and back contact resistance R_{c1} and is typically only in the order of some mV [17]. Therefore, and since the Laplacian method evaluates only the second derivative of the voltage, in regions of homogeneous J_{01} the use of V_d instead of V_{em} leads nearly to the same results [17]. However, if J_{01} varies strongly spatially, as e.g. at the sharp edge of an increased J_{01} region or at a recombination-active grain boundary (GB), using V_d instead of V_{em} leads in Laplacian evaluation to significant overshoots [17]. Due to these overshoots the local J_{01} in GB positions appears overestimated. The goal of this contribution is to find a method for avoiding these artifacts.

In Section 2 the problem to be solved is illustrated by showing results of finite element device simulations of a region in a solar cell showing a realistic J_{01} distribution. Section 3 introduces a method to calculate the diode back voltage (V_b) distribution from the diode current density (J_d) distribution. Note that the local diode current J_d, which determines J_{01} and thus also the photocurrent density J_p, is influenced by the diode back voltage V_b. The local photocurrent density J_p can be simulated from the local J_{01} data by applying a method proposed in [1]. It has been shown recently that this method works well also for high-resolution J_{01} distributions [18]. In this work an iterative method is proposed for obtaining a self-consistent solution for J_d, J_{01}, J_p, and V_b in an improved Laplacian image evaluation. This method is tested on the device simulation results from Section 2. Finally, in Section 4 the improved Laplacian PL evaluation method is applied to measured PL images, and the J_{01} results are compared to results of a nonlinear Fuyuki evaluation.

2. Device simulations

In [17] device simulation results of an artificial device have been shown being a symmetry element of a solar cell (a field between two busbars and two gridlines) containing three local regions with increased $J_{01} = 3\ \mathrm{pA/cm^2}$ and elsewhere homogeneously $1\ \mathrm{pA/cm^2}$. There the above mentioned over- and also undershoot was observed at the sharp edges of the high-J_{01} regions. Here we simulate a larger region of a cell by ngSPICE [19]. The cell model is the same as used in [12,17], which is a square net of nodes containing the local diode characterized by J_{01} and the photocurrent density J_p, a vertical resistor R_{c1} regarding the bulk and back contact resistance for vertical diode current flow and horizontal resistances to the neighboring nodes R_{bulk}, acting to horizontal currents in the bulk below the emitter, and R_{em} acting to horizontal emitter currents. One node corresponds to the pixel size of the PL evaluation, which is $153 \times 153\ \mu\mathrm{m}^2$ here. In all nodes containing gridlines, additionally a grid contact resistance R_{c2} and horizontal grid resistances R_{gr} to the neighboring nodes below the gridline are provided [12], here assumed to be $R_{c2} = 1.5\ \mathrm{m\Omega\,cm^2}$ and $R_{gr} = 0.4\ \Omega/\mathrm{cm}$ as reported in [12]. In this work a PERC cell, as it will be used also in Section 4, will be simulated. The backside of these cells shows point contacts embedded in a region with dielectric passivation. The method for regarding V_b to be introduced in Section 3 cannot regard explicitly an inhomogeneous back contact. Therefore in this work we apply the approach to describe the back contact as an effective homogeneous back contact. We assume that 12.5% of the area is covered by the Al back contacts showing a resistance of $8.5\ \mathrm{m\Omega\,cm^2}$, leading to an effective back contact resistance of $68\ \mathrm{m\Omega\,cm^2}$. The assumed bulk resistance (given by the producer) is $1.76\ \Omega\,\mathrm{cm}$, corresponding for a bulk thickness of 180 µm and a homogeneous back contact to a vertical bulk resistance of $31.7\ \mathrm{m\Omega\,cm^2}$. If point contacts are used, this bulk resistance increases due to current crowding effects. We have compared a SPICE simulation of a cell with a homogeneous back contact and with point contacts and have found that, for the cell data assumed here, an effective homogeneous vertical resistance of $R_{c1} = 320\ \mathrm{m\Omega\,cm^2}$ describing both the bulk and back contact resistance is most equivalent to the point contact geometry. The assumed J_{01} distribution was taken here from an earlier nonlinear Fuyuki PL evaluation result of this cell [18]. In contrast to [12] we assume in this work the photocurrent J_p not to be homogeneous. Instead, the J_p distribution is simulated here from the J_{01} distribution by applying the method described in [1] using the parameters $< J_{sc} > = 39.56\ \mathrm{mA/cm^2}$, $A = 7{*}10^{-9}$, $B = 0.013$, and $n = 1$, which have been found to be optimum for simulating high-resolution J_p data in PERC cells [18]. However, as reported already in [12], regarding an inhomogeneous J_p distribution does not significantly affect the resulting J_{01} distribution.

Fig. 1(a) shows the assumed J_{01} distribution in the simulated part of the cell. The distribution of V_d in the simulated region is shown in (b), assuming that this region is at its open circuit condition ($V_{oc} = 666.6$ mV). The emitter voltage distribution is visually hard to distinguish from that shown in b). It differs from b) by the back diode voltage (V_b) distribution shown in (c). Fig. 1(d) shows the distribution of the diode current density J_d under this V_{oc} condition. We see a clear similarity between Fig. 1(c) and (d), whereby (c) appears as a blurred copy of (d). It will be shown in Section 3 that this is indeed the case. If the emitter voltage distribution is evaluated by the Laplacian method, this leads to exactly the assumed J_{01} distribution shown in (a) (not shown here), as it was shown already in [17]. Fig. 1(e) shows the J_{01} distribution resulting from a Laplacian evaluation of the diode voltage (V_d) distribution in (b). In comparison with the assumed J_{01} distribution in (a), the maxima of J_{01} in the GB regions are slightly higher, e.g. visible in the lowermost defect group (see arrows in (a) and (e)). This overestimation is due to the influence of the diode back voltage. Finally, Fig. 1(f) shows J_{01} calculated by using the iterative method to be described in Section 3.

3. Improved Laplacian PL evaluation method

This method can work correctly only if the local diode voltage V_d is imaged as correct as possible. The first condition is that, if a Si detector is used for luminescence detection, photon scattering in the detector is corrected by performing appropriate image deconvolution [20,21]. For Laplacian evaluation this has to be done even if 950–1000 nm bandpass filtering is used [5,16]. The second condition for correctly imaging V_d is the correct measurement of the luminescence calibration constant C_i. As a rule C_i is imaged by performing EL at a current of 0.1 or 0.2 J_{sc} or V_{oc}-