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Laplacian photoluminescence image evaluation employing image deconvolution

F. Frühauf*, O. Breitenstein

Max Planck Institute of Microstructure Physics, Halle, Germany

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ABSTRACT

The conventional evaluation of photoluminescence (PL) images of inhomogeneous solar cells, which is based on the model of independent diodes, leads to systematic errors in the estimation of the local saturation current density J_{01}. The Laplacian-based image evaluation, which was proposed already in 2009, does not rely on this model and has the potential to image J_{01} correctly. However, first applications of this method to PL images also have failed. In this work it is shown that this failing was due to the blurring effect occurring in the luminescence detector. If PL images are deconvoluted with the correct point spread function, the resulting images lead to the correct J_{01} distribution if evaluated by the Laplacian method.

1. Introduction

Photoluminescence (PL) imaging is an established characterization method for investigating locally inhomogeneous solar cells. Previous contributions proposed different evaluation methods for imaging the local series resistance $R_{s,i}$ (i=position index) and the local saturation current density $J_{01,i}$ of solar cells [1–4]. Dark lock-in thermography (DLIT) is less suitable for R_s evaluation but allows reliable quantitative imaging of J_{01} [5]. PL-J_{01} imaging shows a better spatial resolution than DLIT-J_{01} imaging due to the fact that DLIT images suffer from inevitable thermal blurring. Several publications show a qualitative agreement between obtained PL- and DLIT-J_{01}-images, but not a quantitative agreement. Local J_{01}-maxima appeared generally stronger in DLIT than in PL [6,7]. Two-dimensional device simulations have shown that this is a result of the assumed model of independent diodes, which leads for luminescence image evaluation to much stronger errors than for DLIT evaluation [8]. Moreover, if this model is applied to PL evaluation, the resistive interconnection of neighboring regions by the emitter leads to a resistive blurring effect. The Laplacian-based photoluminescence evaluation method shows the best spatial resolution of J_{01} images compared to all previously published PL-based J_{01} images, since it is not disturbed by the resistive blurring effect [9]. However, until now maxima of the Laplacian-based PL-J_{01} images did not agree quantitatively with DLIT results. It was already suspected in [9] that the reason for this disagreement might be an optical blurring effect in the light detector used for PL imaging.

Light scattering in the detectors of Si-CCD cameras, which are normally used for PL imaging, tends to smooth out local minima and maxima of the PL signal and leads to blurred PL images, which was reported first in 2012 by Walter et al. [10]. If a cooled silicon detector is used for PL/EL imaging, the maximum of detected radiation is at about 1000 nm [11]. The mean travelling path of light with the wavelength 1000 nm in silicon at room temperature is about 160 μm [12], but for a cooled detector it is even larger due to the increased gap energy. This is large compared to the pixel size of a Si detector, which is typically 13 μmx13 μm [13]. Hence, only a minor part of the light coming from one pixel area of a solar cell, which is about 150 μmx150 μm when using a 156 mmx156 mm sized solar cell imaged with a 1024×1024 pixel sensor, is detected in one pixel of the Si-CCD sensor. This results in a blurred image. To overcome this blurring we deconvoluted PL images according to Walter [10] with a point spread function (PSF) calculated from the edge spread function (ESF) by using an alternative method [14] to the method of Walter. All deconvolutions were made with the available software DECONV [15]. Then the improved Laplacian-based photoluminescence evaluation method after [9] was performed. As a result we show a PL-based J_{01} image

* Corresponding author.
E-mail address: fruehauf@mpi-halle.mpg.de (F. Frühauf).

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with high resolution, which is quantitatively comparable with a J_{01} image obtained by DLIT.

2. Experimental

The PL images were measured using an Andor “iKon-M” thermoelectrically cooled Si CCD-detector (-42 °C) camera with a resolution of 1024×1024 pixels [13] and 900 nm short-pass-filtered LED illumination at 850 nm. The objective used was a LINOS inspec.x M NIR 1.4/50 mm. The incoming light was filtered by a long-pass filter with a cut-off wavelength of 1000 nm. For our investigation we used a 156 mmx156 mm sized industrial standard multicrystalline solar cell (full-area back contact, V_{oc}=619 mV, J_{sc}=34 mA/cm^2). PL images under open circuit (V_{oc}) and short circuit (J_{sc}) were obtained at illumination intensities equivalent to 0.1 and 1 sun (I_{sc}=824 and 8279 mA, respectively). The integration time was 40 s for 1 sun measurements and 400 s for 0.1 sun. Each PL image is an average of 3 measurements to increase the signal-to-noise ratio.

3. Laplacian PL evaluation method

The dependence of the local luminescence intensity Φ_i from the local diode voltage $V_{d,i}$ is described by the well-known and established equation [3,8,16]:

$$\Phi_{PL,i} = C_i \exp\frac{V_{d,i}}{V_T} + \Phi_{PL,sc,i} \tag{1}$$

Here C_i is the calibration constant, which depends on the local lifetime and the optical properties of the used sample, $\Phi_{PL,i}$ is the local PL-signal, $\Phi_{PL,sc,i}$ is the local PL-signal under short circuit condition of the solar cell, which is due to diffusion-limited carriers, and V_T the thermal voltage. The “net PL” or “equivalent electroluminescence (EL)” image used for the following PL evaluation is obtained by subtracting the luminescence under short circuit $\Phi_{PL,sc,i}$ from the PL image under investigation [3]. Due to light blurring local minima in the PL images appear stronger than expected and local maxima are attenuated. Therefore all net PL images were deconvoluted by a PSF, which was determined from the edge spread function after the method recently presented in [14]. This deconvolution corrects the PL-signal $\Phi_{PL,i}$ for light blurring in the detector. The calibration constant C_i is obtained using the deconvoluted net PL image of the scaling measurement at V_{oc}-condition and 0.1 sun after Eq. (1), assuming $V_{d,i}=V_{oc}$. At this low intensity series resistance effects are expected to be negligible small. In a one-diode model, as it is typically used for PL evaluation, the local vertical current density of an illuminated diode can be described by the dark current density J_{01}, here defined to be positive, and the photocurrent density J_p, which is defined as negative:

$$J_i = J_{01,i} \exp\frac{V_{d,i}}{V_T} - J_{p,i} \tag{2}$$

In most previous PL evaluation methods it was assumed that each displayed pixel is connected to the terminal by an independent resistor, which corresponds to the model of independent diodes [1,3,4,17]. Then the local series resistance R_s is described by an area-related series resistance in units of Ω cm^2. In contrast, the Laplacian-based PL evaluation method, which was proposed by Glatthaar et al. [2,18], regards the distributed character of the series resistance. In fact, this method relies on the evaluation of horizontal balancing currents in the emitter. In this method the local vertical current density is calculated as the difference of all balancing currents flowing into and out of a pixel. Each pixel (i,j) has exactly 4 neighbors, which are connected by the homogeneously assumed emitter sheet resistance ϱ (in Ω/sq). The finite differences method after Glatthaar et al. [2,18] calculates the local diode current density as:

$$J_{i,j} = [(V_{em,i-1,j} - V_{em,i,j}) + (V_{em,i+1,j} - V_{em,i,j}) + (V_{em,i,j+1} - V_{em,i,j}) + (V_{em,i,j-1} - V_{em,i,j})]/(\varrho A) \tag{3}$$

The differential formulation of (3) for a continuous area is [2,18]:

$$J_i = \frac{\Delta V_{em,i}}{\varrho} \tag{4}$$

Here $\Delta = \nabla^2 = \mathrm{div(grad)}$ is the Laplacian operator, which leads to the second derivative of the emitter voltage in the directions x and y. The main practical problem of the Laplacian evaluation method is noise, since the Laplacian operator strongly increases any noise. Therefore Glatthaar et al. [2,18] have not used the finite difference method after (3) but have applied a quadratic fit over 11×11 pixels to the image data and then have applied (4). We have found that, for our detector and imaging conditions, 2×2 pixels binning of the resulting V_d images from 1024×1024 to 512×512 pixels was sufficient to allow application of the finite difference method after (3). As proposed in [9] we use the V_{oc} PL image for evaluation. However, in contrast to the proposal made in [9], we have found that the conventional scaling measurement performed at 0.1 suns with an increased image integration time leads to a better signal-to-noise ratio then use of two high intensity images for calculating C_i. For the Laplacian-based method we use the local diode voltage $V_{d,i}$ instead of the emitter voltage. This simplification may lead to certain errors as will be further discussed in Section 5.

4. Results

In the following we show results of our previous Laplacian-based PL evaluation [9] without applying deconvolution and results obtained after deconvoluting the PL images. In Fig. 1 the net PL signal at V_{oc} and 1 sun is shown before (a) and after deconvolution (d). Local minima in the PL signal are significantly decreased after deconvolution and maxima are increased. The spatial resolution is increased by removing the light blurring, as expected. The scaling measurement at V_{oc} and 0.1 sun yield the calibration constant C_i without and after deconvoluting the PL-images (not shown). The V_{oc}-PL images at 1 sun and the C_i lead with (1) to the diode voltage image shown in Fig. 1(b) without and (e) after deconvolution. As expected also the V_d image shows after deconvolution a higher resolution and stronger contrast than before.

The diode voltage images of Fig. 1(b) and (e) were used to calculate the local current density images after (3) after down-sampling them to 512×512 pixels, assuming an emitter sheet resistance of 50 Ω/sq. With the current density image and the local diode voltage the local dark current density J_{01} was calculated after (2). In the previous contribution [9] a homogeneous photocurrent density J_p was assumed. Here we used a J_p image obtained by light beam-induced current (LBIC) mapping equivalent to AM 1.5 G spectrum [19], see Fig. 1(g). However, we have found that this measure does not change the J_{01} results significantly, the biggest improvement is due to the deconvolution procedure. The reason is that, under V_{oc} condition, in the low lifetime regions the local dark current considerably exceeds the average photocurrent. The resulting J_{01} images are shown in Fig. 1(c) without and in (f) after deconvolution. We see that the deconvolution procedure decisively increases the obtained values of J_{01} in the low lifetime regions. Now they are also