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# Spatially resolved determination of dark saturation current and series resistance of silicon solar cells

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Luminescence images of silicon solar cells contain information about local recombination properties and local series resistance. It is difficult to separate the information and interpret single images correctly and quantitatively though, which greatly limits the use of single luminescence images, in particular for the application as an in-production characterization tool. We therefore developed a fast method based on photoluminescence imaging for a spatially resolved coupled determination of the dark saturation current and series resistance (C-DCR).



**1 Introduction** Electro and photoluminescence (EL/PL) imaging are fast methods for spatially resolved characterization of the electrical parameters of silicon solar cells [1–3]. Data acquisition times on the order of 1 s are suitable for inline quality control. In this case a large amount of image data has to be evaluated automatically, which will fail if the images contain ambiguous contrast of different physical origin, as is the case for single luminescence images. The local intensity in a luminescence image of a solar cell is influenced by three parameter classes: optical parameters, recombination parameters and the series resistance. Several methods have been proposed to separate these parameters by using a combination of luminescence images taken at different excitation or detection conditions [4–9]. Unfortunately, some of the methods require longer acquisition times or are restricted to only certain types of samples. All these methods only separate one parameter, so several methods have to be combined for a full characterization of the cell.

In this publication we will demonstrate a method to separate the information of PL images into a dark saturation current image, comprising the recombination parameters, and a series resistance image.

**2 Theory** Basis of our new method is that PL images can be calibrated to local junction voltage [4]. This has the advantage that the optical properties of the sample are eliminated in a voltage calibrated image. It is therefore assumed that the injection dependence of the charge carrier lifetime can be neglected and that at a pixel $i$ the intensity $I_i$ after subtraction of a short circuit image scales exponentially with the local junction voltage $V_i$

$$I_i = C_i \exp\left(\frac{V_i}{V_\mathrm{T}}\right), \qquad (1)$$

with the scaling factor $C_i$ and the thermal voltage $V_T$. $C_i$ can be determined from an image taken at low irradiation intensity at open circuit, where $V_i$ is assumed to be equal to the measured open circuit voltage. To evaluate a voltage image with respect to recombination properties and series resistance losses, we have to apply a specific model: We regard each pixel $i$ on the solar cell to be connected to the external contacts via a series resistance $R_{\mathrm{s},i}$. The local current–voltage characteristics are approximated by a one-diode model with the dark saturation current $j_{0,i}$, which includes all recombination channels. The diode ideality factor is assumed to be equal to 1. Ohmic shunts are ignored.

This results in the following equation:

$$R_{s,i} = \frac{V_{appl} - V_i}{j_{0,i} \exp(V_i / V_T) - j_p}, \tag{2}$$

with the externally applied voltage $V_{appl}$ and the photocurrent $j_p$. Based on Eq. (2), several methods were developed. Trupke et al. [4] determined the local series resistance assuming that $j_{0,i}$ is spatially constant and equal to the value calculated from open circuit voltage $V_{oc}$ and short circuit current density $j_{sc}$ of the cell:

$$j_0 = j_{sc} / \exp(V_{oc} / V_T). \tag{3}$$

Kampwerth et al. [7] elaborated this method by evaluating a series of photoluminescence images taken at different operating conditions in such a manner that the influence of $j_{0,i}$ is eliminated and an explicit voltage calibration is unnecessary. An EL based approach was recently published by our group [9]. According to Fuyuki et al. [1] we assumed $j_{0,i}$ to be inversely proportional to the calibration factor $C_i$, determined from an image taken at low applied voltage. Additionally, we used the finding of Michl et al. [10], that the average local series resistance $\langle R_{s,i} \rangle$ should approximately equal to the global series resistance. From this requirement we determined a factor which connects $C_i$ with $j_{0,i}$. With this method we are able to calculate a quantitative $R_s$ and a $j_0$ image. However, Fuyuki's approach to determine $j_0$ can be highly inaccurate for state-of-the-art silicon solar cells, where the bulk diffusion length is in the same range as the cell thickness [5].

We therefore propose a different method, in which two voltage calibrated PL images are used. This allows a **c**oupled determination of the **d**ark saturation **c**urrent and the series **r**esistance (C-DCR): The two images are taken at different operating conditions, e.g. at different applied voltages.

We obtain from Eq. (2) two coupled equations for each pixel for the two unknown parameters $R_{s,i}$ and $j_{0,i}$. We assume $j_p$ to be laterally constant and equal to the short circuit current density of the cell. Usually this is a good approximation as the effective diffusion length of the charge carriers (>50 µm) is large compared to the penetration depth of the laser light for illumination (<10 µm) and therefore the internal quantum efficiency is close to 1. At areas with lower internal quantum efficiency the overestimation of $j_p$ leads to an overestimation of $j_0$ and an underestimation of $R_s$, as can be seen by explicit solution of the equation system.

**3 Results and discussion** We demonstrate this method on a screen-printed multicrystalline solar cell. At standard test conditions the open circuit voltage was $612 \pm 5$ mV, the short circuit current density was $33.0 \pm 1$ mA/cm$^2$. Applying Eq. (3) we obtain a dark saturation current density of $1.6 \pm 0.3$ pA/cm$^2$ for the cell. The series resistance was $1.0 \pm 0.2\ \Omega$ cm$^2$ determined from illuminated and dark $I-V$ curve comparison [11]. The photoluminescence images are taken using expanded and homogenized laser light with a wavelength of 790 nm. A silicon deep depletion charge coupled device cooled to −50 °C is used to capture the images. The laser light is blocked by a stack of interference and absorption filters in front of the camera lens. The sample is kept at 25 °C on a temperature stabilized chuck.

A PL image for the voltage calibration was taken at open circuit at an illumination equivalent of 0.2 suns with respect to the short circuit current. The two images to be calibrated to voltage were taken such that at 1.2 suns approx. 25% and 75% of the short circuit current was extracted. This resulted in applied voltages of 570 mV and 600 mV. From all images a short circuit image at the respective illumination intensity was subtracted.

We compare the resulting $R_s$ image (Fig. 1a) with an image obtained using the method of Kampwerth et al. [7] (Fig. 1b), which is presumed to give the most reliable results. For Kampwerth's method an open circuit image at 0.2 suns and a series of 5 images with applied voltages between 530 mV and 570 mV at 1.2 suns were taken. Again, from all images a short circuit image at the respective illumination intensity was subtracted. C-DCR essentially results in the same $R_s$ image as Kampwerth's method. There are only small quantitative differences close to the busbar where the current is extracted. Both images clearly bring out series resistance related defects such as the two broken fingers of the front side metallization and eliminate lifetime related information, but for the C-DCR image less data acquisition time and computational resources were required compared to Kampwerth's method.

The $j_0$ image gained by C-DCR we compare with our formerly published EL method [8]. Our former method is based on a more realistic model of a solar cell, but requires the calculation of the Laplacian of the voltage image, making the method very sensitive to noise, so that data acquisition times on the order of 10 min are necessary. For our former method we took an EL image for the voltage calibration at 570 mV and an image to be calibrated to voltage at 630 mV.

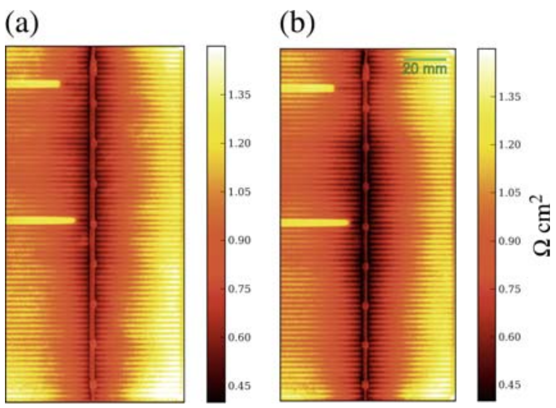


**Figure 1** (online colour at: www.pss-rapid.com) Detail of the series resistance images obtained using a) C-DCR and b) Kampwerth's method [7].

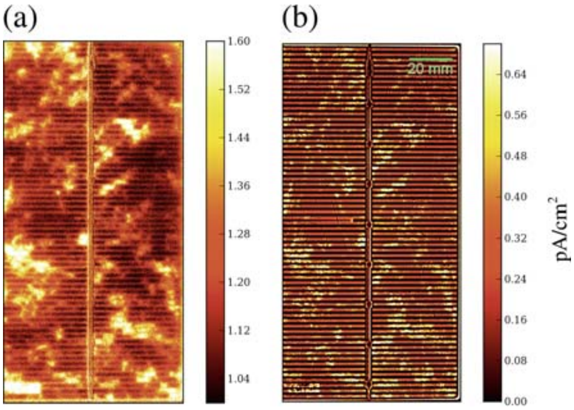


**Figure 2** (online colour at: www.pss-rapid.com) Detail of the dark saturation current images obtained using a) C-DCR and b) our former method [8].

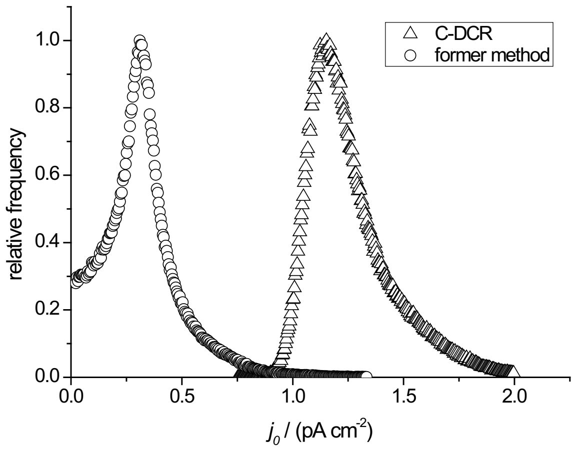


**Figure 3** Histograms of saturation current images gained using different methods.

The $j_0$ images from both methods show similar structures (Fig. 2a, b). Also, the series resistance related information is successfully eliminated, e.g. the broken fingers of the front side metallization no longer occur in the $j_0$ images. However, the two methods result in different quantitative values, as can be seen in the respective histograms in Fig. 3. The histograms relate to the full device area, and not only to the details shown in Fig. 2. We broadly masked out the metal grid, where no reliable information is gained, and our former method artificially results in negative values. Our former method results in an average value of 0.32 pA/cm$^2$, which seems very low with respect to the expected value of 1.6 pA/cm$^2$. In comparison with spectrally resolved light beam induced current [12] (SR-LBIC) measured on an adequate sample with low diffusion length, the values had also been too low [8]. A possible reason for this lies in that the voltage image gained from luminescence is blurred, especially since at a textured wafer surface the luminescence photons can leave the surface at a different point than where they have been generated. In a blurred image the local Laplace values are reduced and hence a $j_0$ will be calculated that is too low. Conversely, for our new method the blurring of the PL images only leads to a slightly blurred $j_0$ image. The average value of the C-DCR image is 1.26 pA/cm$^2$. This is still lower than the expected value. The difference can be explained e.g. by a typically increased $j_0$ under the front side metallization, that cannot be detected by C-DCR.

**4 Conclusions** We conclude that with C-DCR lifetime and series resistance related information of photoluminescence images can successfully be separated into a quantitative dark saturation current image and a quantitative series resistance image. For C-DCR, less data acquisition time and computational power is required than for the methods used as references in this paper. For the dark saturation current image, the quantitative results of C-DCR also seem more realistic with respect to the global cell parameters than for the reference method.

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