Fast series resistance imaging for silicon solar cells using electroluminescence

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We introduce a fast and easy to apply method for determining the local series resistance of standard silicon solar cells. For this method only two electroluminescence images taken at different voltages are needed. From these two images, the local voltage and the local current density through the device can be calculated. Knowing these parameters for each pixel yields the local series resistance. By calculating the cell's dark saturation current from the lower voltage image, the method also works with multicrystalline material. We show images, acquired in only 300 ms and compare them with other luminescence based series resistance images.

1 Introduction Electroluminescence imaging (EL) [1] is developing to an established tool for quality assurance in solar cell characterization. It is non-destructive and easy to apply, since only contacting and camera are needed.

One of the most important properties of a solar cell observable with luminescence imaging is the local series resistance (R_s). It has significant influence on the fillfactor and thus on the efficiency. The origin of high R_s values from $I–V$ characterization are in most cases not homogeneously distributed, but may vary laterally. Contact forming problems at the firing process, broken fingers, or bad properties of the screen printing paste cause locally increased R_s values. R_s imaging allows to identify such causes and to optimize these steps of production.

Apart from the luminescence imaging based methods [2–4], different techniques have been developed giving access to a spatially resolved characterization of R_s: Contact resistance scanning (Corescan) [5], solar cell local characterization (CELLO) [6], and recombination current and series resistance imaging (RESI) [7].

In this paper we present a new EL based method for a spatially determined R_s, requiring only two images taken at different voltages. We compare it with other EL and PL based methods and show that it is also working on multicrystalline silicon (mc-Si) cells.

2 Theory The electroluminescence intensity emitted by silicon solar cells is proportional to the excess carrier density within the sample. Assuming injection independence of charge carrier recombination properties, the EL intensity Φ_i at a pixel i scales exponentially with the local voltage U_i

$$\Phi_i = C_i \exp\left(U_i/U_t\right), \tag{1}$$

with U_t being the thermal voltage. The factor C_i is a calibration constant comprising recombination properties and optical factors of experimental setup and sample. The calibration constant C_i can be calculated through an image at low voltage, where the lateral currents on the cell are small enough to assume the local voltage U_i to be the same as the externally applied voltage U_{appl}. Now a second image taken at a higher voltage and calibrated with the C_i values of the first image yields the local voltage U_i.

Following Trupke et al. [2], we model the solar cell as a two dimensional network of parallel nodes consisting of a diode and a resistance. According to Ohm's law, the se-

ries resistance $R_{s,i}$ of each pixel i, is given by

$$R_{s,i} = (U_{appl} - U_i)/j_i \,, \tag{2}$$

where j_i is the local current density and $U_{appl} - U_i$ the voltage drop between the pixel i and the external contacts. We approximate the local current density j_i by a one diode model according to

$$j_i = j_{0,i} \exp{(U_i/U_t)} \,, \tag{3}$$

where $j_{0,i}$ is the local dark saturation current. For monocrystalline cells lateral $j_{0,i}$ variations are in most cases small and can be approximated by a constant value, extractable from global parameters [2]. But as soon as $j_{0,i}$ variations (e.g. material impurities, cracks, etc.) are present, they appear as increased R_s values, making this kind of analysis useless, especially for mc-Si cells. By determining $j_{0,i}$ as presented in Ref. [8], a correct mapping is achieved. However the long integration times to reduce signal noise needed for the $j_{0,i}$ mapping, excludes this approach for inline cell characterization.

Our new approach is to follow Fuyuki et al. [1], who assumed the pixel intensity of the calibration image C_i to be proportional to the effective diffusion length $L_{e,i}$ and hence proportional to $j_{0,i}^{-1}$. This result can be used for correcting the R_s images by setting

$$j_{0,i} = f/C_i \,. \tag{4}$$

The scaling factor f is chosen in a similar way as done in Ref. [9] such that the arithmetic mean value of $R_{s,i}$ equals the global R_s value $R_{s,gbl}$ obtained from illuminated and dark $I{-}V$ curve comparison [10]:

$$R_{s,gbl} = \frac{1}{N}\sum_{i=0}^{N} R_{s,i} = \frac{1}{N}\sum_{i=0}^{N} \frac{U_{appl} - U_i}{f\,C_i^{-1}\exp{(U_i/U_t)}}$$

$$\Rightarrow f = \frac{1}{R_{s,gbl}}\frac{1}{N}\sum_{i=0}^{N}\frac{U_{appl} - U_i}{C_i^{-1}\exp{(U_i/U_t)}} \,. \tag{5}$$

To use the arithmetic mean in order to scale $R_{s,i}$ to $R_{s,gbl}$ has proven to be a reasonable approximation [11].

3 Experimental results The measurements were performed on the electro- and photoluminescence measurement setup at Fraunhofer ISE. The images were acquired using a cooled one megapixel silicon charge coupled device (Si-CCD) camera. For all results presented in this paper, its resolution was reduced to 256×256 pixels through binning to reduce data acquisition time.

We compare our new method with three existing luminescence based methods for determining R_s: R_s-EL Hinken [4], R_s-PL Trupke [2] and R_s-PL Kampwerth [3]. We compare the methods on a monocrystalline Czochralsky grown silicon cell (Cz-Si) and a mc-Si cell. Both cells were taken out of the photovoltaic technology evaluation center (PV-Tec) production line at Fraunhofer ISE.

In Table 1 the circumstances achieving the R_s images are outlined. The number of images (# images) indicates how many images at different operating conditions are needed to be taken to calculate the R_s image. In the EL case, dark images were left out of the summation because they need to be taken only once to eliminate readout noise of the CCD. Images taken at short circuit conditions for the PL case also contain relevant information on the cell and need to be taken individually. The acquisition time (acc. time) contains the exposure time of the CCD and the camera readout of 30 ms per frame. The methods of Hinken and Kampwerth require a fitting procedure of every pixel to calculate R_s. Due to its derivation step, the method of Hinken is liable to signal noise. Therefore longer integration times are needed.

The excitation conditions of the compared methods were chosen to be as much as possible equal to those in the presenting papers: R_s-EL Hinken: Voltage series from 540 mV to 630 mV in 10 mV steps with voltage differ-

Table 1 Circumstances for achieving the R_s images.

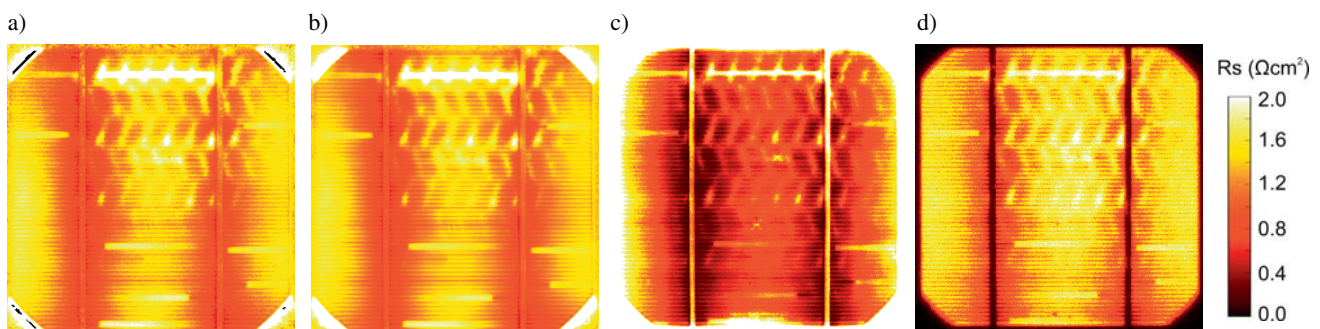| method	# images	acc. time (s)	fitting
R_s-EL Hinken	20	124	yes
R_s-EL ISE	2	0.3	no
R_s-PL Trupke	4	0.6	no
R_s-PL Kampwerth	8	4	yes

Figure 1 (online colour at: www.pss-rapid.com) Series resistance mappings on a Cz-Si solar cell. Several broken fingers and minor cracks and marks of the firing furnance belt are visible. Its global series resistance is $R_{s,gbl} = 1.09\ \Omega\,cm^2$. a) R_s-PL Trupke, b) R_s-PL Kampwerth, c) R_s-EL Hinken, d) R_s-EL ISE.
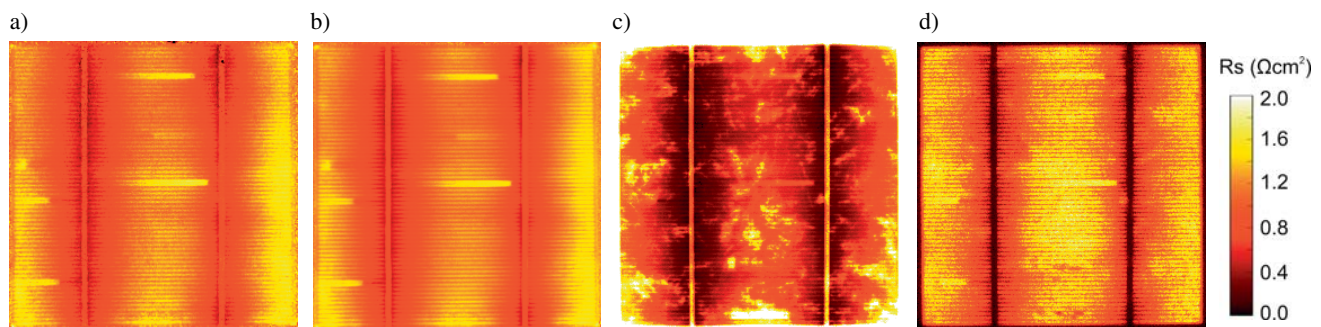
Figure 2 (online colour at: www.pss-rapid.com) Series resistance mappings on a mc-Si solar cell inhabiting several broken fingers and strong material defects. Its global series resistance is $R_{s,gbl} = 0.92\ \Omega\ cm^2$. a) R_s-PL Trupke, b) R_s-PL Kampwerth, c) R_s-EL Hinken, d) R_s-EL ISE.

ences of $\Delta U = 10$ mV for $U < 600$ mV and $\Delta U = 6$ mV for $U > 600$ mV. R_s-PL Trupke: Calibration images at 0.2 suns illumination equivalent; high illumination images at one sun and 80% current extraction. R_s-PL Kampwerth: Images A at 0.2 suns and six B series images at one sun from 560 mV in 10 mV steps downwards. R_s-EL ISE: High voltage image at 620 mV, calibration image at 570 mV.

In Fig. 1 the four methods are compared on a Cz-Si cell. In all of them the broken fingers and the structure of the firing furnace belt are clearly visible. This indicates problems on screenprinting and the firing process. Only in Fig. 1c the microcracks and the lasermarking at the bottom are visible, and thus misinterpreted as R_s contrasts. It also shows a lower mean R_s than for the other images. This phenomenon can partly be explained as in Refs. [10, 11]: Different current flow patterns in illuminated (PL) case than in dark (EL) case lead to increased R_s values due to homogeneous injection of charge carriers. Although the ISE method is also based on EL, it is calibrated with a global R_s value obtained from illuminated and dark $I-V$ comparison [10] and thus generates results comparable to the PL based methods.

One major difference is visible in the corners of the pseudo square cell format. The front side metallization did not completely fill the corners, leading to very high R_s values there. These increased values are not observable in the ISE method, indicating a calibration error: As pointed out above, the factor C_i not only contains information on the recombination parameters, but also on optical effects. Especially were there is no backside metallization, the light emission differs from the rest of the cell. These optical differences are treated as recombination effects in Eq. (4) and hence the reduced luminescence signal on the edges is contributed to high $j_{0,i}$ instead of high R_s. In Fig. 1a these regions appear as negative values, showing the limits of Trupke's method [2]. Only the method of Kampwerth yields reasonable values.

The edges of the images, the busbars and the fingers contain no information, since they hinder emission from beneath. Yet they still yield R_s values. These wrong values again result from stray luminescence light, illuminating neighboring pixels in the sensor. This problem is common for all luminescence based methods.

Figure 2 shows R_s measurements on a mc-cell. The method of Hinken (Fig. 2c) was not designed for this application, so it fails. Leaving the ISE method to be the only EL based method applicable in this case. In comparison to the PL based methods (Fig. 2a, b), the whole image is in good agreement, but still contains some minor $j_{0,i}$ contrasts. These contrasts result from the assumptions made for $j_{0,i}$ and the used theoretical model. Again the method of Kampwerth yields good results. Also the simplified method of Trupke produces good results, although it assumes $j_{0,i}$ to be constant. While for EL $j_{0,i}$ is proportional to j_i, in PL near short circuit conditions, $j_{0,i}$ has little impact on j_i. Therefore good results can already be produced without $j_{0,i}$ correction.

4 Conclusion In this paper we presented a new and easily applicable method based on electroluminescence. By taking the calibration image also for determining the local dark saturation current $j_{0,i}$, this method is also applicable on cells without a homogenous $j_{0,i}$ distribution, as it is the case with multicrystalline material. The presented method can be used to separate series resistance effects from other effects observed in EL images without the need of enhancing the experimental setup. Thus a more accurate inline analyses can be achieved.

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