Suns-ILIT: Accurate Method for Non-Contacted Local *IV* Measurements

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Abstract. We demonstrate a novel method to measure the lateral distribution of the recombination current without an external load, hence without the need to establish an electrical contact. In combination with photoluminescence imaging, which can be used to calculate the lateral implied open-circuit voltage iV_{OC} distribution, accurate local current-voltage *IV* characteristics similar to global Suns-V_{OC} curves are obtained based on measurements with varying illumination intensity. This method can also be used on unfinished, non-metallized cell precursors. In addition to its value for assessing limitations in standard solar cells, it has the potential to be very useful for the analysis of the *IV* characteristics of individual sub-cells in tandem devices by using different excitation wavelengths.

INTRODUCTION

Global *IV* characteristics measured under illumination are a central part of the solar cell production and cell technology development, as it yields the most important information: the power output under varying working conditions. Dark *IV* characteristics are usually used for process and quality control by analysing the global saturation currents j_{01} and j_{02} as well as the parallel resistance R_p and series resistance R_s. However, the latter requires a finished, metallized solar cell and a good contacting scheme in order to transport the current through the diode, and as such is always affected by the series resistance. The Suns-V_{OC} method [1] gives the opportunity to analyze also unfinished solar cells by plotting the illumination intensity – taken as a current equivalent – versus the V_{OC}, which can often be reliably measured even on cell precursors. Since no current is transported through an external load, the series resistance plays a different role in this case.

As the global solar cell parameters often are not sufficient to identify the reasons for non-optimal cell processing, a variety of imaging techniques has been developed which allow locating processing issues and thus give valuable additional information. Breitenstein et al. for example have used Dark Lock-In Thermography (DLIT) to establish a spatially resolved counterpart of global dark *IV* measurements [2,3]. It inherits the advantages and drawbacks of dark *IV*, namely the necessity to use finished solar cells with acceptable contact resistances. A Suns-V_{OC} counterpart was developed by Hameiri et al. [4] and Michl et al. [5] based on photoluminescence imaging (PLI) (thus called "Suns-PLI") that can be used on wafer, cell precursor and finished cell level. From the PL images, the distribution of the iV_{OC} can be calculated. By assuming a *laterally homogeneous* recombination current density distribution equal to the generation current density j_L, injection dependent measurements can be used to calculate local *IV* characteristics. However, the recombination current density j_{rec}, which is the relevant one, is strongly inhomogeneous due to strong lateral gradients in the electrostatic potential introduced by processing faults, shunts, highly recombination-active regions, edge recombination etc.

We therefore present an approach combining Illuminated Lock-In Thermography Measurements (ILIT) and PLI at varying illumination intensity allowing for an accurate determination of local *IV* characteristics under illumination

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and V_{OC} conditions. This approach does not need any electrical contact to the sample and is therefore easy to apply and especially useful for cell precursors. In addition, by employing different wavelengths, we expect this technique to be very useful for the characterization of individual sub-cells of tandem solar cells.

A more detailed description of Suns-ILIT and a discussion about all contributions to the measureable local power distribution can be found in Ref. [6]. In this work, we exemplarily apply it to analyze a multicrystalline silicon PERC solar cell with huge non-ideal recombination losses and compare the derived local pseudo fill factors with those of Suns-PLI.

MEASUREMENT OF THE RECOMBINATION CURRENT DISTRIBUTION

Lock-In Thermography measures local temperature variations resulting from local power dissipation. ILIT measurements can be calibrated to determine the power density distribution in a variety of ways, e.g. by equating the integrated ILIT signal to the power absorbed by the solar cell [7]. In Ref. [6], we show that from the power density image, the recombination current density distribution can be calculated via

$$j_{rec} = j_L - j_{pn,eff}, \tag{1}$$

where $j_{pn.eff}$ signifies the net current density which crosses the pn junction and

$$j_{pn,eff} = \begin{cases} \dfrac{p_{in} - p}{V_{OC} + \dfrac{\Delta E_{e/f}}{q} + \dfrac{\Delta E_{f/h}}{q}} \\ \dfrac{p_{in} - p}{V_{OC}} \end{cases}. \tag{2}$$

The upper equation applies to the case where all the lateral (majority) current transport happens exclusively in the emitter and base (e.g. in the absence of metallization), the lower equation describes the case where all current is transported through the metallization. p_{in} and p denote the (laterally homogeneous) power density due to absorption of a photon with energy E_{ph}

$$p_{in} = j_L \frac{E_{ph}}{q}, \tag{3}$$

and the measured local power density, respectively. $\Delta E_{e/f}$ and $\Delta E_{f/h}$ are the differences between electron energy and electron quasi-fermi energy level and between hole quasi-fermi energy level and hole energy, respectively.

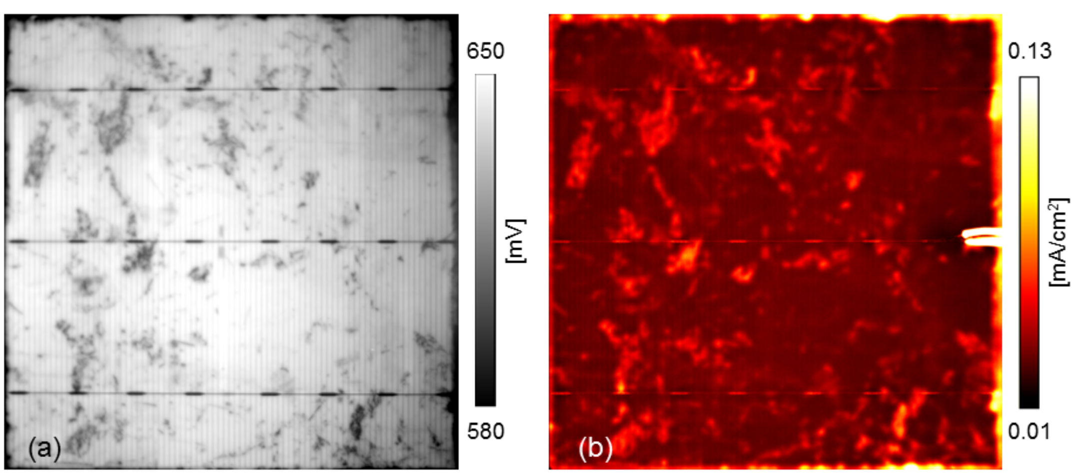

FIGURE 1. (a) PL image calibrated to the implied V_{OC} at 1 sun equivalent of a mc-Si PERC solar cell with processing faults. (b) Recombination current density at the same generation rate. The two bright lines to the right are caused by a contact pin used for cross-checking. Please note that they are not necessary.

For (2), we use the implied V_{OC} distribution as measured via PLI. For $\Delta E_{e/f}$ and $\Delta E_{f/h}$, we parameterized literature data of the Peltier coefficients [6]. Fig. 1 exemplarily demonstrates measurements of a faulty mc-

Si passivated emitter and rear solar cell (PERC): the emitter at the front edges suffered from a non-optimal rear side etch. The increased recombination current at the edges is clearly visible.

LOCAL I-V CHARACTERISTICS

A set of recombination current density and iV_{OC} images obtained at varying illumination intensities can now be used to generate images of the parameters j_{01}, j_{02}, the ideality factor n_2 etc., of the applied diode model. A fast and easy way for example is to use the algorithm developed by Breitenstein [2], which is based on the two-diode model. Of course, also a (computationally expensive) direct fit of every data point is possible and is applied in the following.

In Fig. 2, the saturation current densities j_{01} and j_{02} of the same solar cell as above are displayed. It is clearly seen that the processing fault leads to increased j_{02} values and the edge contribution can be well discriminated from other influences such as defect clusters. j_{01}, on the other hand, is dominated by bulk defects such as dislocation clusters.

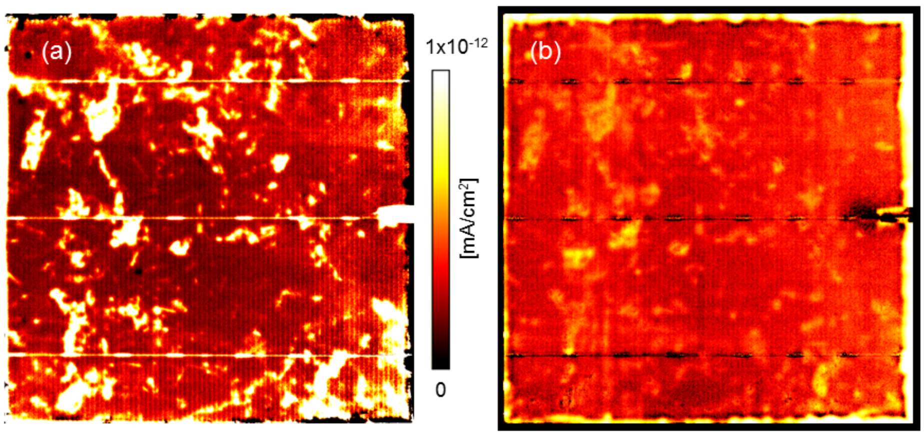

FIGURE 2. (a) Image of the saturation current j_{01} (linear scale). (b) Log(j_{02}) image. Note that here, a black background was chosen in order to highlight the high edge values. n_2 was kept fixed at 2.

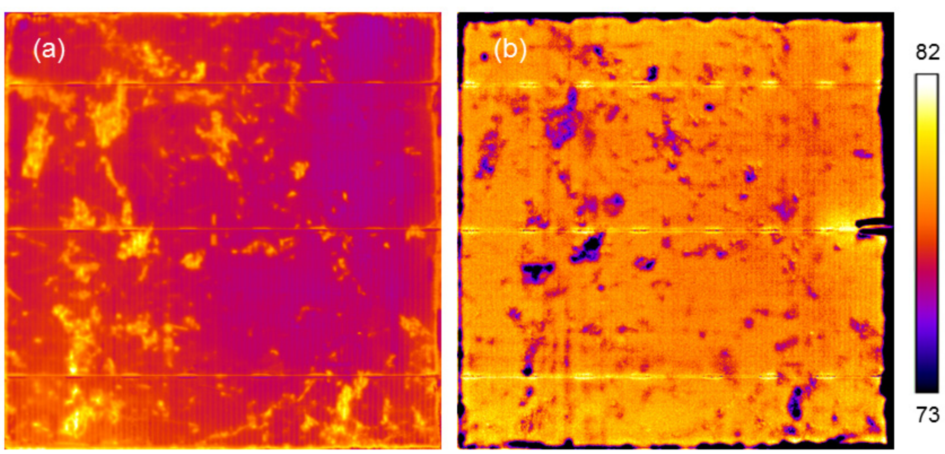

FIGURE 3. Pseudo fill factor (PFF) calculated from (a) Suns-PLI and (b) from Suns-ILIT. The image averages of both methods are close to the global Suns-V_{OC} value (~77% vs. 78%). The colorbar holds for both images.

Another example for an important solar cell parameter is the pseudo fill factor (PFF). If spatial resolution without applying any contacts is needed, the Suns-PLI method has been used in the past [4,5]. Since in this method the current distribution, as mentioned above, is assumed to be laterally homogeneous, the calculated images do not meet the expectations. In Fig. 3 (a), a typical result of Suns-PLI is shown: highest PFF values are found in defect clusters, whereas high-lifetime regions feature low PFF values. If the real distribution of the recombination currents is taken into account by means of Suns-ILIT measurements (cf. Fig. 3 (b)), the PFF image is in agreement with the expected distribution.

CONCLUSION

Suns-ILIT, a camera-based technique to image the lateral distribution of recombination currents at varying generation rates, is a highly valuable extension of global Suns-V_{OC} measurements, accurately quantifying the regions responsible for certain *IV* parameters detected in global measurements. The requirements for sample preparation are even lower than for Dark *IV* or Suns-V_{OC} measurements, because no electrical contact is needed. This feature can also be exploited for the local *IV* characterization of sub-cells of tandem devices.

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