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# Finite element simulation of inhomogeneous solar cells based on lock-in thermography and luminescence imaging

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ABSTRACT

This work presents a method to extract the spatial distributions of local two-diode parameters, contact resistance, grid resistance, and emitter resistance of a solar cell, based on spatial data obtained by lock-in thermography, 4-point probing, electroluminescence, and photoluminescence imaging. The extracted parameters are input into Griddler, a finite-element simulator, to calculate the cell plane voltage distributions as a test of the goodness of fit. This Griddler model then can be used to predict the cell properties under conditions not measured before, e.g. at different temperatures, biasing, and illumination conditions, and it can be used to evaluate the influence of certain defects on the cell efficiency by excluding them in the simulation.

## 1. Introduction

Griddler [1,2] is a finite-element method (FEM) solar cell simulation tool which models the cell plane as a distributed network of resistors and diodes. It is written with a built-in H-pattern grid design interface, a metallization import function from AUTOCAD format, an efficient mesher that spaces out nodes further along the metal line direction than in the direction perpendicular to the lines, and a pre-solver for current crowding and contact resistance at the metal-semiconductor interface, making it an ideal software to describe and simulate solar cells with different metallization grids. Inhomogeneities of the cell may be introduced by inserting grid interruptions or ohmic shunts, and by defining spatial distributions of the resistance and diode parameters. Griddler's ease of use in defining the cell grid pattern and related device parameters down to great detail, enables highly realistic voltage and current distributions across the cell plane to be simulated with relatively little effort. In principle, it would also be plausible to take a suitable set of spatial data which represent the cell plane voltage and current densities, e.g. luminescence [3–5] or lock-in thermography images [6,7], and attempt to solve the inverse problem of finding a set of diode and resistance parameters that give rise to these measurements. Note that in this context, the resistance parameters would be resolved into components with traceable physical origins, namely the metal sheet resistance, contact resistance, and semiconductor sheet resistance. These resistance parameters are in contrast to the local series resistance $R_s$ defined in independent diodes model, which is an effective parameter given by the local voltage drop divided by the local diode current density. The latter definition of $R_s$ does not take into account the distributed character of the series resistance and leads to different results in the dark and under illumination [8].

The problem of finding a set of device model parameters to explain luminescence and lock-in thermography images has been tackled in an earlier paper [9]. This work aims to improve upon the earlier approach by removing a number of rather limiting simplifications. Namely, in [9], the grid and emitter resistances were considered to be homogeneous across the whole cell, with the exception of grid interruptions, and the grid contact resistance was the only spatially inhomogeneous variable. Therefore, this contact resistance was "lumped" in the sense that it also contained the influence of inhomogeneities in the grid line resistance. This homogeneously assumed grid resistance was adjusted in [9] to avoid the appearance of any negative values of the (lumped) contact resistance. Due to this ad hoc procedure, in regions of higher grid resistance, the contact resistance was overestimated. Moreover, in [9] only a one-diode model was used to describe the local diodes. Also, only the EL-based local diode voltage distribution in the dark was used for calculating the resistances, and this distribution was finally correctly modeled. Overall, the method of extracting the local resistances in the distributed model proved to be superior over methods that are based on the independent diode model, in terms of its ability to predict the cell voltage distribution under a wide range of illumination and biasing conditions. However, the prediction was not yet close to flawless because of the contact resistance error described above. This work aims to improve upon the local resistance extraction method by making the grid line resistance a spatially varying parameter. Though

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there are still remaining simplifications, the procedure introduced here is to a greater degree amenable to rigorous analysis than the previously presented one [9].

Section 2.1 briefly summarizes the applied method to evaluate DLIT images for obtaining images of the local diode parameters $J_{01}$, $J_{02}$ (the saturation current densities of the first and second diode), $n_2$ (the ideality factor of the second diode), and $G_p$=1/$R_p$ (the ohmic parallel conductance, being the inverse of the parallel resistance). The short circuit current density ($J_{sc}$) image is obtained from the $J_{01}$ image by applying the procedure introduced in [10], which was shown there to lead to sufficiently reliable results for the standard technology cells investigated here. Section 2.2 summarizes the method applied to measure the local diode voltages in the dark and under illumination and current extraction from EL and PL images. In this Section a modification of the formula for describing the luminescence signal is proposed, which was necessary for precisely fitting the EL-measured local diode voltages to simulated ones. The most important procedure to calculate the local values of the emitter resistance $R_{em}$, the grid resistance $R_{grid}$, and the grid contact resistance $R_{cont}$ independently are described in Section 3. In Section 4 this method is applied to obtain local cell parameters of a multicrystalline standard silicon solar cell containing grid interruptions and of another cell showing contact resistance problems. It was found there by comparing the self-consistently obtained grid resistances to directly measured ones that the first are coming out too large in most of the area. Therefore the contact resistances have been re-calculated based on the measured grid resistances. These local parameters are used for Griddler simulations of these cells, leading to simulated local diode voltage images. The comparison of these simulated $V_d$ images with the corresponding EL- and PL-measured images of these cells allows us to draw the conclusion on the accuracy of the cell evaluation method introduced in this work.

## 2. Obtaining the local cell parameters

### 2.1. Obtaining the local diode parameters from DLIT evaluation

All DLIT images used in this contribution were obtained by using the PV-LIT system by InfraTec, Dresden [11]. This system enables local emissivity correction to ensure that also the DLIT signal in gridline positions is correct. All measurements were made at a lock-in frequency of 50 Hz and a sample temperature of 25 °C (tested at the cell backside), −90° images were used for evaluation as suggested in [7]. At this lock-in frequency the thermal diffusion length, which governs the spatial resolution of the local current density images, is about 0.8 mm [6]. As the solar cells studied in this work have a metal grid finger pitch of 2.29 mm, the DLIT images cannot resolve the current density profile between two gridlines. The system uses a 4-quadrant power supply in 4-wire configuration (Höcherl & Hackl NL30V30C16), which senses the cell bias in the middle of the cell at the top and the bottom to an accuracy below 1 mV.

For obtaining images of $J_{01}$, $J_{02}$, $n_2$, $G_p$, and $J_{sc}$, the "Local I-V" procedure introduced in [7] and the method for calculating $J_{sc}$ from $J_{01}$ described in [10] were applied. Since all these images rely on DLIT images, their spatial resolution is only about 0.8 mm. The local diode currents and voltages below the gridlines will later be binned from originally 328 µm to 2.3 mm resolution. It can only be judged in the final stage, when the local diode voltage images derived from luminescence imaging are compared to those simulated by Griddler, whether these simplifications can be tolerated or not.

The "Local I-V" method [7], the software of which is available [12], is used to calculate the local 2-diode parameters $J_{01}$, $J_{02}$, $n_2$, and $G_p$ by fitting four DLIT images taken at typically 0.5, 0.55, 0.6, and −1V bias to a two-diode model. It is considered there that, due to the inevitable influence of the series resistance, the local diode voltages $V_d$ deviate from the applied bias $V$. This influence is considered in "Local I-V" based on the model of independent diodes, hence by considering a local effective series resistance of $R_s$=($V$-$V_d$)/$J_d$, with $J_d$ being the local diode current density. It was shown in [8] that, in spite of the inaccurate independent diode model used there, DLIT results of the local diode parameters are reliable. This is due to the fact that DLIT measures local current densities directly, in contrast to luminescence methods, which basically measure local voltages. The effective series resistance at the highest forward bias $V_3$ (here 0.6 V), where the influence of $R_s$ is expected to be strongest, is obtained here by applying the so-called RESI method [13]. This method measures the local current density by DLIT and the local voltage drop at this bias by EL imaging. It is implemented in the "Local I-V" software by the option to load a local diode voltage ($V_d$) image at the highest DLIT forward bias $V_3$.

Note that already for the application of the RESI method we have the conflict that the current density image has a lower spatial resolution than the diode voltage image. As it will be shown in Section 4, the $V_d$ image in the dark shows a clear profile between neighboring gridlines, in particular in low lifetime regions. However, the DLIT images do not, since DLIT averages the current in this region. If a saturation current density image $J_{01}$ would be calculated from the low-resolution current density image and the high-resolution diode voltage image, the resulting $J_{01}$ image would show local minima in gridline positions, since there $V_d$ shows maximum values but the apparent current density is the same. This $J_{01}$ profile would be a clear artifact of the evaluation. In order to prevent this artifact, we artificially blur the EL-measured $V_d$ image by using the thermal point spread function of the DLIT measurement. Only the blurred $V_d$ image is used in the RESI evaluation of the "Local I-V" software, leading to smooth effective $R_s$ and $J_{01}$ images.

For calculating the $J_{sc}$ image from the $J_{01}$ image we apply the method described in [10], which is also implemented in the "Local I-V" software [12]. This method assumes a relationship between $J_{sc}$ and $J_{O1}$, based on the assumption that both of these parameters are spatially varying due to variance in the bulk lifetime. The method in [10] uses an empirical but physically founded formula containing two parameters $A$ and $B$ for calculating the local $J_{sc}$ image, whereby the global value of $J_{sc}$ of the cell has to be known. Once these parameters $A$ and $B$ are estimated for a certain cell type, they may be applied to all cells of this type. Here we are using $A$=1*10$^9$ and $B$=0.01 A/cm$^2$, which was found to be optimum in [10] for standard (BSF-type) cells and leads there for the same cell to a good correspondence between simulated and blurred LBIC-measured $J_{sc}$ images.

### 2.2. Obtaining local diode voltage images from luminescence images

The EL and PL investigations were performed using an ANDOR iKon-M PV-Inspector camera having a 1024×1024 pixels Si detector, which is thermoelectrically cooled to −40 °C. The objective was a LINOS inspec.x M NIR 1.4/50 mm. The PL excitation was performed by 850 nm LED light, which was sent through a short-pass interference filter at 870 nm (Asahi Spectra ZIS0870). Two identical band-pass filters were placed in front of the camera (950–1000 nm, Edmund #86–972). If only one such filter would be used, the suppression of excitation light would be not sufficient. Also for the luminescence measurements the 4-quadrant power supply with cell voltage sensing in 4-wire mode was used, and the cell was kept at 25 °C by measuring its temperature from behind.

Care must be taken in ensuring equal bias voltage at each point of electrical contact to the cell grid. In order to minimize uneven bias voltages which would be a nuisance to the analysis, we have used for the luminescence measurements an extremely low-ohmic current distribution wiring scheme, massive copper current rails for the busbars, and no plugs to the current distribution knot. It shows from the distribution knot to the most distant point in any current rail a resistance below 380 µΩ. Each current rail is equipped with 12 low-ohmic spring-loaded contact pins.