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The reliability of thermography- and luminescence-based series resistance and saturation current density imaging

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ABSTRACT

The conventional quantitative evaluation of dark lock-in thermography (DLIT), electroluminescence (EL), and photoluminescence (PL) images of solar cells is based on the model of independent diodes, where each image pixel is assumed to be connected with the terminals by an independent series resistance. In reality, however, the solar cell represents a 2-dimensional resistance-diode network. In this work solar cells containing well-defined spatial distributions of the saturation current density J_{01} and also containing J_{02}-type and ohmic shunts are modeled for various externally applied biases and illumination conditions realistically as a 2-dimensional resistance-diode network. The resulting local diode voltage distributions are converted into DLIT, EL and PL images, which are further processed by conventional evaluation methods, which rely on the simple model of independent diodes. These are the so-called "Local-IV" method for the DLIT analysis, which may be supported by EL results to obtain series resistance images, and "C-DCR" for the PL analysis. This leads to calculated images of the local effective series resistance R_s and of J_{01}. Regarding the resulting R_s images, PL shows the expected series resistance distribution and is not affected by the shunt regions. The DLIT–EL R_s images instead yield expected values only in the homogeneous regions, which are not affected by the assumed shunts. DLIT–EL determines higher values of R_s in local shunt regions and lower values around these regions and in spatially extended shunt regions. Regarding the J_{01} images both methods again give the expected results if J_{01} is distributed homogeneously. However, in the shunted regions, PL suffers from balancing currents within the emitter and DLIT from optical blurring. By comparing local and extended regions of increased J_{01} we find that DLIT approximates the expected J_{01} value better than PL, which clearly underestimates even extended local maxima of J_{01}. For a local current analysis of silicon solar cells we recommend the use of DLIT for the determination of J_{01} images and PL for the determination of R_s images.

1. Introduction

Solar cells, in particular wafer-based multicrystalline silicon cells, are large-area devices and exhibit unavoidable inhomogeneities. For example the excess carrier lifetime is affected by grain boundaries, dislocations, metallization and edge effects. Also the local voltage is inhomogeneous since the current has to be transported from the local region to the contacts and suffers from the series resistance of the grid and the emitter series resistance. Such inhomogeneous cells can be understood in detail only by applying appropriate imaging methods, which allow extracting e.g. the local saturation current density J_{01} or the effective series resistance R_s [1,2]. J_{01} is a measure for the current loss within the device due to recombination within the emitter, the bulk and at both surfaces and R_s gives the resistance for the current transport from the local region to the contacts.

Until now two types of camera measurements, dark lock-in thermography (DLIT) and luminescence imaging using either electrical (EL) or optical (PL) charge carrier generation have been introduced leading to images of J_{01} and R_s when analysing solar cells at different operation conditions [3–8]. From these local diode parameter images, images of locally expected cell efficiency parameters like the open circuit voltage V_{oc}, the fill factor *FF*, or the locally expected efficiency η may be calculated [9,10]. While the PL analysis directly leads to images of J_{01} and R_s, the pure DLIT analysis has to be supported with series resistance information. For this purpose DLIT can be combined with EL imaging [3], called DLIT–EL analysis in the following. Alternatively, if no series resistance image is required, a homogeneous value for R_s can be assumed. Thus, the pure DLIT analysis provides only images of J_{01}.

All DLIT-, EL- and most of PL-based imaging methods are based on the "model of independent diodes", because a realistic analysis of measured data in a 2-dimensional device model and their

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conversion into local J_{01} and R_s data is really hard to accomplish. Hence, it is assumed that each pixel is connected to the terminals by an independent series resistance and is electrically isolated from the neighbouring pixel [11], which is most easy to evaluate. In reality, however, the solar cell represents a resistance-diode network where neighbouring pixels are electrically connected to each other by the emitter layer and the grid. Hence, the series resistance is distributed and the independent diode approach does not properly consider horizontal balancing currents, which exist in inhomogeneous solar cells due to a laterally varying local diode bias. When in the past the same solar cell was analysed both by DLIT–EL and PL, it was regularly found that the results agree only qualitatively, but quantitatively they are inconsistent to each other [12,13]. Only in one case, where at the PL analysis the ideality factor was used as an additional fitting parameter, the agreement was reasonable [14]. The question is which of the methods delivers the most correct results, in particular of the J_{01} distribution? In this work this question will be answered for DLIT, DLIT–EL, and PL.

It should be noted that there are two different definitions of the local series resistance R_s in the literature. The most common definition, which is also used by most previous DLIT, EL, and PL methods [1–14], is to define R_s in units of $\Omega\,\mathrm{cm}^2$ as the local voltage drop between the terminals and the local diode, divided by the local diode current density. This definition corresponds to the equivalent model of isolated diodes for each position, which neglects the distributed character of the resistive network of the device. There is another PL-based R_s evaluation method, which uses a linear response approach for the description of the solar cell [15,16]. This method is also used in the light-beam-induced current-based measurement technique CELLO (solar cell local characterization, [17]). Here R_s is defined as the local voltage drop divided by the *global* cell current, therefore it is given in units of Ω. This approach corresponds to a model of nearly perfectly interconnected local diodes. However, it does not allow to determine the local diode properties (J_{01}) in a straightforward way. The different definitions of R_s complicate a direct comparison of the results of DLIT–EL, PL, and CELLO. In the only attempt of such a direct comparison [18] it was found that the results of DLIT–EL and CELLO agree qualitatively, but not quantitatively, as for the comparison between DLIT–EL and PL [12,13].

In this work DLIT, EL, and PL images of solar cells with known parameter distributions are realistically simulated, and then these data are back-converted into R_s and J_{01} images by applying acknowledged methods for evaluating measured DLIT, EL, and PL images. We apply a dedicated 2-dimensional resistance-diode network simulation tool [19] to model a symmetry element (1/4 of the free area between two busbars and two gridlines) of a typical industrial solar cell. Two different geometries are investigated, both containing certain defects. The first has three different types of local shunts (J_{01}-type, J_{02}-type and ohmic-type) and the second has extended regions of increased J_{01} values, see Section 2 for more details. The results of the 2-dimensional simulations are images of the local diode voltages and local currents under various biasing and illumination conditions. From these images DLIT, EL, and PL signal images are calculated and then evaluated according to generally accepted quantitative DLIT, DLIT–EL and PL evaluation methods [4,5]. These evaluation methods, which are all based on the model of independent diodes, lead to predicted images of the effective series resistance R_s and of J_{01}, which are compared to each other and to the J_{01}-distribution which was entered into the simulation. The differences between the input J_{01} distribution and the calculated J_{01} images are discussed by regarding the independent diode model approximation, horizontal balancing currents and thermal blurring.

2. Simulation details

The used device simulation tool is based on ngSpice [20]. It enables the simulation of a resistance-diode network with a high number of elements (here 2000) with resistances, diodes, and current sources in each element. The simulations were performed on a symmetry element $1.3\times26\,\mathrm{mm}^2$ in size, which represents 1/4 of the area of one window between two grid lines and two busbars in a typical industrial $156\times156\,\mathrm{mm}^2$ sized silicon solar cell containing 3 busbars and 66 grid lines. In the resulting images the whole window between two gridlines and two busbars is displayed, which has an area of $2.6\times52\,\mathrm{mm}^2$ and is obtained by combining 4 correspondingly mirrored symmetry elements. The pixel size was chosen as 130 μm, hence one symmetry element contains 10×200 pixel and the whole window 20×400 pixel. The solar cell parameters, which are used for calculating the electronic component parameters of the network model, are given in Table 1, together with all variables used in this work and their units. In particular, a homogeneous value for J_{01} of 1 pA/cm^2 was chosen for most of the area, which is a typical value for an industrial solar cell of first generation (thickness 200 μm, p-base, 50 Ω/sqr emitter, full-area Al back contact).

Two geometries, A and B, are modelled in this work. Geometry A contains highly localized shunts. In the centre of the window region J_{01} is increased to 10 pA/cm^2 leading to a so-called "J_{01}-type shunt". In addition, two J_{02}-type and two ohmic-type shunts (described by a parallel conductance G_p [S/cm^2], being the inverse of the parallel resistance R_p [Ω cm^2]) are introduced in this geometry left and right

Table 1
Used variables and basic device parameters.

R_s	Area-related local series resistance [Ω cm^2]
J_{01}	1st Diode saturation current density, here 1 pA/cm^2; 10 resp. 3 pA/cm^2 in J_{01}-shunt regions
J_{02}	2nd Diode saturation current density, 0.867 μA/cm^2 in J_{02}-type shunt, zero otherwise
G_p	Parallel conductance, 0.132 S/cm^2 (7.58 Ω cm²) in ohmic shunt, zero otherwise
V	Applied bias
$V_{c1}=V_{12}$	Base potential below pn-junction (corresponds to voltage difference between point 1 and 2 as shown in Fig. 1)
$V_d=V_{23}$	Diode voltage
$V_e=V_{13}$	Emitter potential
J_p	Photocurrent density, here 38 mA/cm^2
R_{c1}	Back contact and base resistance for current flow into the depth, here 0.04 Ω cm^2
R_{bulk}	Bulk resistance, here 1.5 Ω cm
R_{em}	Emitter sheet resistance, here 50 Ω/sqr
R_{gr}	Grid resistance, here 0.4 Ω/cm
R_{c2}	Grid contact resistance, here 1.5 mΩ cm^2
V_T	Thermal voltage, here 0.0257 V at 25 °C
i	Position index
I	Total device current
C_i	PL/EL scaling factor