Solar Energy Materials and Solar Cells 189 (2019) 133–137

Contents lists available at ScienceDirect

Solar Energy Materials and Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Luminescence based high resolution finite element simulation of inhomogeneous solar cells

F. Frühauf[a], J. Wong[b], O. Breitenstein[a,*]

[a] Max Planck Institute of Microstructure Physics, Halle, Germany
[b] Solar Energy Research Institute of Singapore, Singapore

ARTICLE INFO

Keywords:
Photoluminescence imaging
Quantitative evaluation
Solar cell modelling
Saturation current density imaging
Diode voltage imaging

ABSTRACT

The application of the model of independent diodes with an effective series resistance in units of Ωcm^2 leads to wrong predictions of the local diode voltages in solar cells, if their dark current is strongly inhomogeneous. Therefore, multicrystalline solar cells should be modelled by finite element methods such as that implemented in Griddler. Until now, the local parameters for this modelling were obtained for inhomogeneous solar cells by evaluating luminescence and dark lock-in thermography (DLIT) images. The inhomogeneous local diode parameters, in particular the saturation current density J_{01}, were obtained by the DLIT-based analysis (Local I-V), and the local emitter contact resistances were obtained by evaluating luminescence-based local diode voltages. This method, however, is experimentally demanding and shows a limited spatial resolution due to thermal blurring of the DLIT results. Previous luminescence-based methods for imaging J_{01}, based on the model of independent diodes, have been found to be erroneous. In this model it is assumed that each elementary cell region (image pixel) is connected to the terminals of the cell by an independent series resistance (Trupke et al., 2007) [1]. Meanwhile alternative luminescence evaluation methods are available for reliably imaging J_{01} with high spatial resolution. This opens the way for a purely luminescence-based finite element simulation of inhomogeneous solar cells. In this contribution this method is described and applied to a multicrystalline PERC cell made from high performance silicon material. The results are compared to that of a luminescence plus DLIT based evaluation.

1. Introduction

A solar cell with inhomogeneous recombination current density may be represented by an appropriate spatial distribution in the diode properties, but the determination of this distribution from spatially resolved data is often challenging because different parts of the solar cell are interconnected. This is true especially for solar cells made from multicrystalline (mc) silicon material, which shows strong lateral inhomogeneities of the bulk lifetime by more than an order of magnitude. The same contrast in lifetime holds also for cells made of modern high performance mc material, where only the areal content of these defect regions is lower than in conventional mc material [1]. Note that in 2016 still more than 69% of all worldwide produced solar cells were made from mc Si material, with monocrystalline only slowly catching up [2]. Therefore evaluating and understanding electronic inhomogeneities in mc solar cells is essential for further increasing the conversion efficiency of these cells.

The process of solar cell efficiency optimization usually occurs today by two- or even three-dimensional device simulations of symmetry elements of the projected cells. In these simulations the distributed character of the series resistance is correctly regarded. However, here usually homogeneous material parameters are assumed (monocrystalline Si material), hence this procedure cannot model inhomogeneous mc cells. For the purposes of extracting the spatial distributions of diode parameters in inhomogeneous cells, the dark lock-in thermography (DLIT) based 'Local I-V' method was developed [3,4]. In this method up to four DLIT images taken at various biases are evaluated and fitted to two-diode models of all image pixels, leading to images of the saturation current densities of the first and the second diode J_{01} and J_{02} (describing recombination in the bulk and the surfaces, and in the depletion region, respectively), the ideality factor n_2 of the second diode, and the ohmic parallel conductance G_p being the inverse of the parallel resistance R_p. Based on these local diode parameters and assuming certain values for the local short circuit current density J_{sc} and the local effective series resistance R_s, local expectation values of solar cell parameters like the open circuit voltage V_{oc}, the fill

---

[*] Corresponding author.
E-mail address: breiten@mpi-halle.mpg.de (O. Breitenstein).

https://doi.org/10.1016/j.solmat.2018.09.030
Received 1 June 2018; Received in revised form 24 September 2018; Accepted 25 September 2018

factor FF, and the local efficiency η can be simulated [4]. The basic limitation of this method is its millimeter-scale spatial resolution, caused by the inevitable thermal blur of the DLIT images. Moreover, it is still based on the model of independent diodes (Trupke et al., 2007) [5], hence it does not consider the distributed nature of the series resistance.

In the last years, large area two-dimensional finite element based solar cell modelling methods have become available to simulate solar cells, like the Griddler software [6], which also allows to model inhomogeneous solar cells. Electronic network simulations are usually performed by Spice software, see e.g. [7]. However, the time needed for analyzing a network increases dramatically with increasing complexity of the circuit, hence with increasing number of knots. By applying a proprietary strategy of meshing and data evaluation, the Griddler software allows to analyze whole solar cells with reasonable spatial resolution in short times, which is not possible by using Spice software. Therefore in this work Griddler has been used instead of Spice for modelling the solar cell. Only at the end of Sect. 3 Griddler-based results are compared to Spice-based results of a detailed region for comparison.

In a previous publication [8] we have simulated an inhomogeneous solar cell by Griddler, based on lock-in thermography and luminescence data. In that work the local diode parameters have been obtained by DLIT, local grid resistances have been measured by four-point probing, and the local emitter contact resistances have been obtained from evaluating luminescence-measured local diode voltages in the grid regions. In this paper, we will replace the DLIT measurements by PL-based J_{01} imaging using the Laplacian PL evaluation method [9]. Moreover, in contrast to [8], here the local grid resistances will also be obtained from evaluating luminescence data. In Sect. 2 the methodology used in this work will be described. Sect. 3 introduces results of the application of this method to a multicrystalline PERC cell.

2. Evaluation method

The Laplacian PL evaluation method was described e.g. in [9]. It is based on the evaluation of the local diode voltages in the non-shaded emitter areas, taking into account a certain given emitter sheet resistivity ρ. For obtaining correct results it is necessary to correctly regard image blurring by photon scattering in the detector [10], to measure the luminescence calibration factor C_i correctly by regarding voltage errors due to horizontal balancing currents in the emitter and the metallization caused e.g. by an inhomogeneous bulk lifetime [11], and to regard the so-called diode back voltage, which is the difference between the local diode and the local emitter voltages [12]. Then the local emitter voltage V_e can be measured sufficiently correct. The imaging of J_{01} is performed here by evaluating PL under V_{oc} condition, which is chosen since there the influence of J_{01} is largest. Note that, the J_{01} is much more inhomogeneous compared to J_{sc} [13,14]. As in [8] we simulate the local short circuit current density J_{sc} by evaluating the local J_{01} data after [13]. However, here this needs an iteration procedure since the calculation of J_{01} depends on J_{sc} by evaluating for each pixel the equation:

$$J_d = J_{sc} - J_{01}\exp\left(\frac{V_d}{V_T}\right) \tag{1}$$

Here J_d is the local diode current density measured by the Laplacian PL evaluation, V_d is the local diode voltage measured by PL evaluation, and V_T is the thermal voltage. The Laplacian evaluation itself is performed not with V_d but with the emitter voltage V_e, which calculates from the local V_d and the diode current distribution around as described in [12]. Also this process is included in the iterative procedure for self-consistently calculating J_{01} and J_{sc}. At the beginning J_{sc} is assumed to be homogeneously the known average value, then (1) is evaluated, in the Laplacian evaluation first assuming $V_e = V_d$, and with the obtained J_{01} the local J_{sc} is calculated after [13]. Then with these data the local diode back voltage V_b is calculated after [12], V_e is calculated as the sum of V_d and V_b, with this V_e the Laplacian evaluation for obtaining J_d is performed again, then Eq. (1) is evaluated again, leading to another J_{01} and so on. After 10–20 iterations the values of J_{01} and J_{sc} have stabilized. Note that the calculation of J_{sc} after [13] needs the fitting parameters A and B, which depend on the type of the investigated cell. For the PERC cell on HP mc Si material used in the following section optimum values of $A = 7 \times 10^9$ and $B = 0.013$ have been found by [14] and used in this work. Note also that the Laplacian evaluation only leads to data of J_{01}, but not of J_{02}, n_2, and G_p data, as the DLIT-based 'Local I-V' evaluation does. Hence, recombination in the depletion region and ohmic shunts are not considered here correctly. As a simplification homogeneous values of J_{02} (for $n_2 = 2$) and G_p are fitted from the I-V curve and used in the Griddler method. The significance of this limitation will be discussed in Sect. 4.

The local values of the grid resistance and the emitter contact resistance are obtained in this work, similar as in [8], by evaluating local diode voltage data obtained by EL evaluation (performed in the dark at a voltage, leading to a current slightly above 3 A) and by PL evaluation under illumination with current extraction (at maximum power point mpp). Also here the resistance of each gridline between two busbars (in units of Ω/cm) will be determined individually for each gridline, but will be assumed to be homogeneous within the gridline. In contrast to [8], where the grid resistances were measured by 4-point probing, here also the grid resistances are obtained by evaluating luminescence-obtained local diode voltage (V_d) data at the gridlines. Note that the original luminescence images have a resolution of 1024 × 1024 pixels. These images are downscaled to 742 × 742 pixels, which corresponds to 7 pixels between each of the 106 gridlines (including pixel at the gridline) and to a pixel size of 210 µm. The gridlines of the investigated cell have a width of 50 µm, hence a pixel located at a gridline receives enough light from both sides of the gridline for measuring V_d in gridline position. The measurement of the grid resistances is based on the assumption that the current flow to the gridlines is sufficiently homogeneous and that the emitter contact resistances, which are usually not homogeneous, see below, are sufficiently small. Note that the dark current density is certainly inhomogeneous in mc cells, but the diode current at mpp is much more homogeneous, and here the influence of J_{01} is inverted. Hence, in regions of high J_{01} the dark current is increased and the photo-generated current is decreased. The local grid resistances are measured by fitting the local diode voltage data below each gridline to a parabolic curve ($V_d(i) = a + b\,i + c\,i^2$, i = position index) and calculating the grid resistances R_{grid} for each pixel segment of 210 µm length from the quadratic coefficient c after ($<I_{cont}>$ = mean current entering each pixel through the emitter contact):

$$R_{grid} = \frac{2\ \ c}{<I_{cont}>} \tag{2}$$

Once the local values of J_{01} and J_{sc} are known and the local V_d data are known both in the dark and under illumination from EL and PL (mpp) evaluation, all local diode current data I_d can be simulated for these cases after (1) regarding the pixel size. The current I_{cont} entering a pixel at a gridline through the emitter contact below was calculated as I_d of the contact pixel plus the sum of I_d of the pixels in the pixel row on both sides of the contact pixel up to the minimum (for EL) or the maximum of V_d in this row (for PL). As a rule this is the current of altogether 7 pixels, that at the gridline plus 3 neighboring pixels on both sides. In this way two values for R_{grid} could be obtained, one for the EL and one for the PL case. The final value of R_{grid} is obtained from PL, regarding the fact that for mpp-PL the local diode currents are more homogeneous and the influence of an inhomogeneous J_{01} is inverted and weaker than in the EL case. It has been found that, the resulting parallel switching of all R_{grid} slightly deviates from measured busbar-to-busbar resistance values. Therefore, the R_{grid} map is scaled to the corresponding busbar-to-busbar resistance. Since this R_{grid} refers to one