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Description of the local series resistance of real solar cells by separate horizontal and vertical components

F. Frühauf [a,*], Y. Sayad [b], O. Breitenstein [a]

[a] Max Planck Institute of Microstructure Physics, Halle, Germany
[b] University of Mohamed Chérif Messaâdia, Souk-Ahras 41000, Algeria

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ABSTRACT

All previous concepts for describing the effective local series resistance of really existing solar cells, as it can be measured e.g. by luminescence imaging, try to describe it by a single local number. In solar cells showing an inhomogeneous saturation current density, this results in different series resistance images for the dark and illuminated case. The reason is the distributed character of the series resistance and the different diode current profiles under these different conditions. In this work the well-known finite element concept is used for describing a solar cell, which contains separate resistors carrying horizontal and vertical currents. A strategy is proposed how to fit these resistors to results of electroluminescence and lock-in thermography images of a real solar cell, leading to separate images of the local horizontal grid resistance, which may also show broken gridlines, and the local vertical'lumped emitter contact resistance'. The latter lumps all resistive inhomogeneities of the cell, caused by a possibly inhomogeneous contact-, emitter-, grid-, bulk-, and back contact resistance. It will be shown that this description of the local series resistance reasonably describes both the dark and illuminated case, even in inhomogeneous multicrystalline silicon solar cells.

1. Introduction

The series resistance is one of the basic solar cell parameters, which decisively influences its fill factor and thus its efficiency. In a solar cell different regions may contribute differently to the global series resistance of the cell. If the elementary local resistances in a solar cell are known, like the grid-, emitter-, bulk-, and contact resistances, finite element-based methods can be used to model their influence on the efficiency of the cell under operation conditions, see e.g. [1,2]. However, until now this method cannot be used for a given solar cell where the local resistance parameters are unknown and are possibly irregular. For visualizing the effective local series resistance in such devices and identifying local series resistance problems, like broken gridlines or regions with intolerable contact resistance, several series resistance imaging methods are used. The most direct method for imaging the local grid contact resistance is Corescan [3]. In this method a region of the short-circuited cell is illuminated and the local emitter voltage is measured in this region by scratching the surface with a metal wire. Unfortunately, this method is not strictly nondestructive, and it maps and displays only the local emitter voltage under this particular illumination and loading condition and not a local series resistance.

There are several possibilities to define a local series resistance $R_s(x,y)$. Most of the present R_s imaging methods define R_s as the local voltage drop between the bias V applied at the busbars (assumed to have zero resistance, like the back contact) and the local diode voltage $V_d(x,y)$, divided by the local diode current density $J_d(x,y)$:

$$R_s(x,y) = \frac{V - V_d(x,y)}{J_d(x,y)}. \quad (1)$$

In (1) and in the following the dark diode current is defined as positive and the photocurrent as negative. This 'area-related' R_s has the unit of $\Omega\,cm^2$. This definition was used right from the beginning of solar cell research for describing the global series resistances of cells of different size, thereby ensuring that the series resistance is independent of the area A of the cell. Implicitly it was assumed there that the influence of R_s is homogeneous across the cell, and that a large cell is the parallel circuit of smaller cells. Under this condition the'real' R_s given in the unit Ω can simply be obtained from the area-related R_s by dividing it through the cell area A. For an inhomogeneous solar cell, however, which contains e.g. regions of increased saturation current density J_{01} or regions of locally increased contact resistances, the definition in (1) is equivalent to the model of independent diodes, which is

* Corresponding author.
E-mail address: fruehauf@mpi-halle.mpg.de (F. Frühauf).

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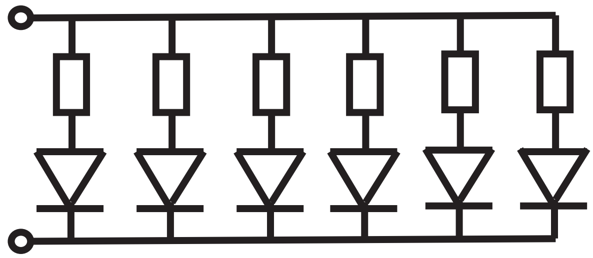

Fig. 1. Independent diode model of a solar cell.

sketched in Fig. 1. Here it is assumed that the cell consists of a parallel circuit of single diodes plus a series resistor, and that each resistor carries only the current of this connected diode. According to our knowledge, this independent diode model was used first by Mijnarends et al. [4] for considering extended macroscopic regions of different properties in a solar cell, which can indeed be assumed to be switched in parallel. Trupke et al. [5] have applied this model to each pixel of an image of a solar cell in photoluminescence (PL) imaging, and most other authors have followed this approach. It was used e.g. by Haunschild et al. [6] for interpreting electroluminescence (EL) images, by Glatthaar et al. [7,8], Kampwerth et al. [9] (in a somewhat modified form), and Shen et al. [10] for interpreting PL images, and by Ramspeck et al. [11] in their 'RESI' (REcombination current and Series resistance Imaging) method. The latter method measures the local current density by dark lock-in thermography (DLIT) and the local diode voltage by EL and leads to an R_s image after (1) for the dark case. Though PL-measured R_s and RESI-R_s are based on the same Eq. (1), both images for the same multicrystalline cell look differently [12,13]. In particular, the RESI-R_s image shows local minima in the positions of local J_{01} maxima, which are not visible in PL-R_s. The reason for this difference is meanwhile well understood [13]. It is due to the qualitatively different diode current profiles for both conditions (dark: very inhomogeneous in multicrystalline (mc) cells; illuminated under current extraction: nearly homogeneous) in combination with the too simple model of independent diodes (Fig. 1 and Eq. (1)) used for calculating R_s.

In reality we know that most part of the series resistance of a solar cell is given by the resistance of horizontal conductors, like the gridlines and the emitter layer, see e.g. [14,15]. In these conductors current contributions are flowing from many elementary diodes in different positions, not only from the position of the considered conductor. Hence these conductors represent a so-called distributed resistance. The properties of distributed resistances and in particular their influence on the global cell characteristic are well understood now [14,15]. Nevertheless, according to our knowledge there is until now only one attempt in literature by Carstensen et al. [16,17] and Wagner et al. [18] to consider the horizontal current flow in R_s imaging of a solar cell. In this approach the local series resistance is not related to the local current density but to the global cell current, therefore it is given in the unit Ω. Unfortunately, this linear response concept is made explicit only for the evaluation of measurements under illumination. Hence, at least until now, it cannot be applied in the dark case.

In this contribution we will fit the results of DLIT and EL imaging to the elements of a 2-dimensional equivalent circuit of a solar cell, which is a finite element model. The influence of photon scattering within the EL detector is corrected, which is a presupposition to measure the local diode voltages accurately [19]. Then, by assuming certain simplifications, EL and DLIT results are fitted to an equivalent model of the investigated cell. This fit leads to an image of the local saturation current density J_{01} (assuming a constant ideality factor n_1), an image of the local grid resistance, which is assumed to be essentially homogeneous, but shows local maxima in the positions of broken gridlines, and an image of the effective lumped grid contact resistance. By comparing the EL-measured with the simulated local diode voltages, the increased grid resistance at broken gridlines and the value of the emitter sheet resistance are obtained. We call the grid contact resistance 'lumped' here because it contains all resistive inhomogeneities of the cell, except the influence of a homogeneous emitter-, grid-, bulk-, and back contact-resistance. Therefore, in certain regions, this resistance may become considerably larger than a usual grid contact resistance.

Details of the local diode voltage measurement by EL imaging will be reported in Section 2. Then Section 3 describes the equivalent circuit for the cell used in this contribution. The fitting of resistive elements of this circuit to DLIT and EL results is described in Section 4. Section 5 describes how this circuit is evaluated self-consistently for arbitrary biasing and illumination conditions. Finally in Section 6 two different solar cells are evaluated by the method described here, and the results are compared to results of Local I-V evaluation [20,21], which is based on the model of independent diodes, and some of them to results of a Griddler simulation [2] using the same local resistance data, which provides a more realistic device simulation.

2. Mapping of local diode voltages by photon scatter-corrected EL and PL imaging

The local diode voltages are measured from luminescence images by using the well-known and generally accepted exponential dependence of the luminescence signal on the local diode voltage containing the calibration factor C_i (i=position index) [5], which can be measured by evaluating a low-current EL or a low-intensity V_{oc}-PL image. For measuring the local diode voltage at V_{mpp} under illumination by PL, the net PL image is evaluated, which is the PL image measured at V_{mpp} minus that measured under short circuit condition [5].

However, it has been found recently that, for obtaining sufficiently accurate results, it is necessary to correct the luminescence images for photon scattering in the light detector. The spectral maximum of the EL or PL signal of a silicon solar cell is at about 1150 nm [1]. This is already above the spectral detection limit of the cooled Si detector cameras used for EL and PL imaging. Hence these cameras only detect the short-wavelength fraction of the emitted radiation, peaking at about 1000 nm [22]. This wavelength belongs to a mean traveling path in silicon of still 160 μm [23], which is maybe not large compared to one imaged pixel size at the cell (152 μm for a 1024 × 1024 pixels image of a 156 × 156 mm^2 sized cell), but large compared to the pixel size in the detector, which is typically 13 × 13 μm^2 [24]. This means that light may scatter within the detector chip from pixel to pixel before it is finally absorbed. This light scattering effect was reported in 2012 by Walter et al. [19]. In their work the point spread function (PSF) describing the light scattering effect was directly measured by evaluating the image of a light spot. If a measured EL or PL image is spatially deconvoluted by this PSF, the 'real' EL or PL image is expected to appear. More recently Teal and Juhl [25] have pointed to the fact that a much easier measurement of the PSF over a dynamic range of many orders of magnitude is possible by evaluating a measured edge spread function (ESF), which is the image of a homogeneously radiating area with a sharp edge to a non-radiating area in the middle. In a recent work together with Teal [26] we have tested his PSF and found that it leads to slightly wrong results. Therefore we have proposed an alternative method for converting the EL-measured ESF into the PSF, which is based on an iterative deconvolution procedure [26]. This procedure includes