# THE INFLUENCE OF THE ELECTRODE SHEET RESISTANCE ON LOCAL PHOTOCURRENT EXCITATIONS IN MICROCRYSTALLINE SILICON THIN FILM SOLAR CELLS

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ABSTRACT: CELLO (solar cell local characterization) measurements on a microcrystalline silicon ( $\mu$ c-Si) solar cell in the LBIC (laser beam induced current) mode under dark conditions are used to analyze the bias voltage dependence of the average current response and the lateral current distribution. The experimental results are compared to a SPICE simulation of a newly introduced three dimensional (3D) equivalent circuit model of a solar cell divided into subcells. Furthermore, the global current response due to local photoexcitation is described theoretically. The 3D simulation shows the necessity of taking subcell-subcell interactions into account in order to explain the lateral current response. The simulations are validated against our CELLO measurements of the average current response as well as the lateral current distribution and show excellent agreement.

Keywords: Characterisation, LBIC Laser Beam Induced Current, Modelling, Thin Film Solar Cell, TCO Transparent Conducting Oxides

### 1 INTRODUCTION

Thin film photovoltaic technologies, like CIGS, thinfilm silicon or organic photovoltaics (OPV) offer the potential of low-cost production at relatively high efficiency levels [1].

Scaling up from lab cell sizes to mass production relevant sizes requires production and quality control on the whole area of the solar cell taking into account coating induced defects, edge shunting effects etc. Therefore, imaging methods like electro- and photoluminescence [2], thermography [3, 4] or light beam induced current (LBIC) [5, 6] and its further development CELLO [7] (Solar Cell Local Characterization) become more and more important.

CELLO is used to characterize local effects in solar cells of all kinds of technologies, namely wafer-based crystalline silicon, thin-film silicon, OPV or CIGS [8] and allows the determination of local solar cell parameters like series resistance or charge carrier lifetime [9]. Beside imaging methods, three-dimensional (3d) simulations become also necessary to evaluate adequate solar cell geometries [10].

In the present work, CELLO is applied to microcrystalline thin film silicon ( $\mu$ c-Si) solar cells. The laser induced current responses at different constant bias voltages were measured at switched off illumination. The average values of the current response maps  $\langle dI \rangle (V)$  are shown in Fig. 1(a). At negative and small positive voltages  $\langle dI \rangle$  is approximately constant. With increasing bias voltage the absolute average current response decreases and finally tends to zero.

This trend of the mean value is surprisingly accompanied with a change of the lateral current distribution over the cell. In Fig. 1(b), examples of CELLO maps at different bias voltages are shown. Clearly, the structure of the current map changes. At negative bias voltages local solar cell inhomogeneities like point-defects or scratches in the substrate glass are visible. At voltages larger than the open-circuit voltage  $V_{oc}$  a systematic change of the current response structure



**Figure 1:** (a) Average current response  $\langle dI \rangle \langle V \rangle$  of CELLO maps at different bias voltages induced by red laser excitation ( $\lambda = 658$ nm) with a line as a guide to the eye (b) Measured *dI* CELLO maps at three different bias voltages

sets in. With increasing *V*, the current response increases from the solar cell center to the fringe whereas local inhomogeneities appear less and less pronounced.

This new current response structure at high bias voltages has the same four-fold symmetry as the contact of the transparent conductive oxide (TCO) which indicates a correlation of the TCO contact with the current pattern.

In order to understand the occurrence of this symmetric current pattern, we introduce a model of a solar cell divided into subcells and a TCO resistance network. We use this model to simulate the current response to local illumination by CELLO.

## 2 APPROACH

In the measurement setup CELLO the current and voltage responses of a globally illuminated solar cell to local intensity-modulated laser illumination is analyzed. A scheme of the setup is depicted in Fig. 2.



Figure 2: Schematic of the CELLO setup.

In our model the solar cell is described by an equivalent circuit which has already been used similarly [6, 11-13]. The TCO is modeled by a resistance network of equal resistances  $R_{\text{TCO}} = 20\Omega$ , the active layer by

 $N^2 = 441$  identical subcells connected in parallel. It is contacted at the circumference of the squared solar cell. The metal back contact is modeled by a perfect conductor. The subcells are described by the 2-diodemodel, where the corresponding parameters are derived from the measured *IV*-curve of the simulated cell (scaled regarding the number of subcells). The specific geometry is shown in Fig. 3.



**Figure 3:** Equivalent circuit model for the simulation: The TCO at the front contact is replaced by a resistance network build up of equal resistances  $R_{\text{TCO}}$ .

The CELLO measurement is modeled by the following procedure: For all subcell positions (i,j) the difference of the total current *I with* local photocurrent at (i,j) and total current *without* local photocurrent is calculated:

$$dI_{ij}(V) = I\left(V, \left\{I_{ph,kl}^{laserON}\right\}\right) - I\left(V, \left\{I_{ph,kl}^{laserOFF}\right\}\right)$$
(1)  
with  
$$I\left(V, \left\{I_{ph,kl}^{laserON}\right\}\right) = I_{ph,bias} + \delta_{ik}\delta_{jl}\Delta I_{ph}$$
$$I\left(V, \left\{I_{ph,kl}^{laserOFF}\right\}\right) = I_{ph,bias}$$

#### 3 THEORETICAL CONSIDERATIONS

In the following we first discuss the case of a single solar cell device which is fully illuminated by the laser beam. Then, the contributions of the non-illuminated subcell parts are taken into account.

#### 3.1 Single solar cell excitation

Assume in a general case that a voltage V is applied across the solar cell, a photocurrent  $I_{ph}$  is induced by the background illumination and the laser beam induces an additional photocurrent  $\Delta I_{ph}$ .

In general, the additional photocurrent induced by the laser is much smaller than the photocurrent originating from background illumination. Hence, the current response can be approximated linearly:

$$dI(V, I_{ph}) \approx \frac{dI}{dI_{ph}}(V, I_{ph}) \cdot \Delta I_{ph}$$
<sup>(2)</sup>

Therefore, dI is determined by the so-called transfer function  $f \equiv dI/dI_{ph}$  which can be obtained by using the 2-diode-model:

$$f = \frac{dI}{dI_{ph}} = \frac{-1}{1 + \frac{R_s}{R_p} + \beta eR_s \sum_{i=1,2} \frac{I_{0i}}{n_i} \exp\left(\frac{\beta e(V - R_s I)}{n_i}\right)}$$
(3)

A plot of this transfer function for a typical  $\mu$ c-Si cell is presented in Fig. 4.



Figure 4: Transfer function  $dI/dI_{ph}$  of a typical  $\mu$ c-Si cell.

3.2 Network-geometry excitation

In a next step, our model is extended to interactions between different solar cell parts caused by currents flowing laterally through the TCO. For this purpose the solar cell is conceptually divided into *i* small identical parts. Then, the total current *I* is the sum of the single currents  $I_i$ . Due to the finite TCO resistance the total applied voltage *V* is divided into  $R_{TCO}$  and the resistance of the subcells:  $V = V_{i,cell} + V_{i,TCO}$ . Depending on  $I_{ph}$ , the local voltage changes.

The total current I is a function of all local photocurrents and the local photovoltage. Therefore,  $I_{ph}$  must be replaced by all photocurrents  $\{I_{ph,i}\}$  in all subcells and  $\Delta I_{ph}$  by  $\Delta I_{ph,j}$ , the transfer function f of the whole 3d geometry has the following form:

$$f_{3d} = \left(\frac{dI}{dI_{ph,j}}\right)_{3d} = \frac{\partial I_j}{\partial I_{ph,j}} + \sum_{cell \ partsi} \frac{\partial I_i}{\partial V_i} \frac{dV_i}{dI_{ph,j}}$$
(4)

Here, the first term is exactly the same as in eq.(3) and the second term describes the contributions due to interactions between the subcells. Hence,  $f_{3d}$  is the sum of the single cell transfer function and an interaction term.

### 4 EXPERIMENTAL DETAILS

The calculations are carried out with  $LTspice^{\$}$  [14] whereas Matlab<sup>®</sup> [15] is used to create the input files and to evaluate the data.

The input parameters of our used model are the parameters of the 2-diode-model, the bias photocurrent  $I_{ph,bias}$ , the photocurrent  $\Delta I_{ph}$  due to the laser excitation, the TCO resistance  $R_{TCO}$  and the number of subcells  $N^2$ .

For our CELLO measurements we used a laser wavelength of 658nm without any further bias illumination.

## 5 RESULTS

In the following, the results of the simulation are compared with experimental data from CELLO measurements.

In Fig. 5 the average current response  $\langle dI \rangle \langle V \rangle$  is plotted. Both the simulation and measurement results show the same structural shape as the fully excited cell described by eq.(2) and reveal an excellent numerical agreement up to  $V_{oc} \approx 480$ mV. In the region from 480mV to around 1000mV, the network simulation is in much better agreement than the single cell simulation, indicating again the importance of the interaction effects at voltages V > V<sub>mpp</sub>.



**Figure 5:** Comparison of measurement and simulation results for the average current response  $\langle dI \rangle \langle V \rangle$ .

Next, a comparison of the CELLO map with the simulation of the  $\mu$ c-Si cell biased at 600mV is presented in Fig. 6(a) and (b). In excellent agreement to each other, the absolute value of the current response increases in both maps from the center to the fringe. As explained in the section of theoretical considerations, this trend is a result of the interaction term which cannot be neglected at this voltage.

In Fig. 6(c), a normalized line scan through the simulated map of Fig. 6(a) (dashed black line) is compared to a normalized line scan through the CELLO map of an identically constructed  $\mu$ c-Si solar cell (red solid line) as in Fig. 6(b). The two curves are in very good agreement. This demonstrates that the simulation correctly predicts the current response distribution up to a constant scaling factor and that the observed resistance effect is stable against small variations of the cell parameters.

## 6 CONCLUSION AND OUTLOOK

We developed a model to describe the average current response dependent on different bias voltages and to image the lateral current response obtained by CELLO measurements. The lateral current response is directly dependent on the TCO sheet resistance and can therefore be used to analyze the TCO influence in solar cells even after finalization. CELLO measurements are a sensitive method to obtain insights to crucial quantities like the TCO sheet resistance and lateral current distribution.



**Figure 6:** Current response *dI* across a  $\mu$ c-Si cell at 600mV (a) Simulation (b) CELLO measurement (c) Comparison of measurement and simulation results of the normalized current response along a cross section through an adjacent solar cell.

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