QUANTITATIVE ANALYIS OF LOCAL SERIAL RESISTANCE AND DIODE LOSSES USING THE CELLO TECHNIQUE

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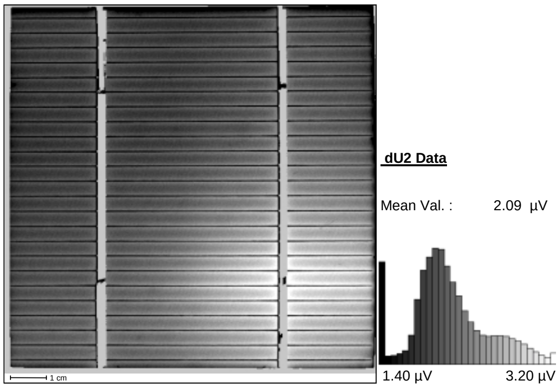
ABSTRACT: The CELLO (solar CELl LOcal characterization) technique is briefly described and demonstrated, in particular with respect to the voltage response map and their causal relation to series resistances. A suitable model for a solar cell allowing fully analytical calculations of the interrelation of local voltage response and series resistances is introduced and discussed. The analytical results are used to derive a simple algorithm that allows to extract local resistance data in a fully quantitative form from measured voltage response data. Using this technique in combination with present hard- and software CELLO implementations produces fully quantitative resistance maps with sufficient spatial resolution within a few seconds.
Keywords: Characterization, Modeling, Serial resistance

1 INTRODUCTION

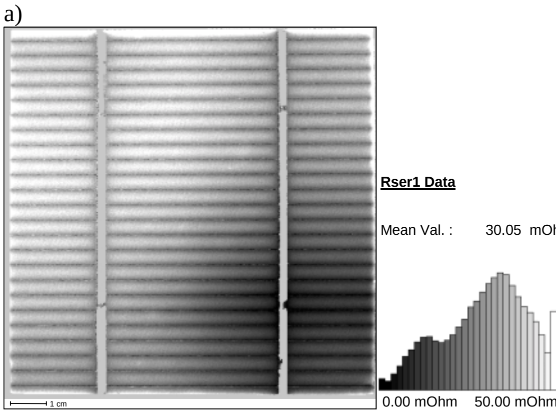
The CELLO (solar CELl LOcal characterization) technique allows to measure all parameters of the equivalent circuit of a solar cell *locally* and mostly quantitatively within a short time span (cf. Fig. 1) [1 - 3].

The technique analyses the current and voltage response of globally illuminated solar cell that is induced by local illumination with a modulated LASER beam. Using a very stable potentiostat/galvanostat, a four probe arrangement for the contact electrodes, and a Lock-in amplifier, the linear response is measured at several points along the IV-characteristics of the solar cell. The amplitude and phase shift of the linear response are measured with a typically high lateral resolution (~200 µm), i.e. ~500.000 pixel for a (100 x 100) mm^2 cell. In optimized versions of the technique, measuring speeds of up to 1.000 pixels/s have been realized [3].

For local current maps (e.g. LBIC maps) measured in the dark or under global illumination, the interpretation is quite clear since local currents (or current increments) add up to the full current of the global solar cell for the matching illumination. In other words, the globally measured current *I* or, for CELLO conditions, the current increment d*I*, always reflect the local properties of the area increment investigated. Therefore local currents as well as spatial averages of currents always represent contributions of certain areas to the total current obtained from the global IV-curve. For local voltage increments as measured by CELLO under constant current or galvanostatic conditions, this is not true. In the limit of extremely small grid and serial resistances, the voltage *U* would be the same everywhere on the solar cell (i.e. the Si surface would be an equipotential surface) and voltage increments d*U* as measured with CELLO would be extremely small. Turning the argument around leads to the conclusion that the “large” and measured voltage increment d*U* contains information about the resistance network of the solar cell. As will be shown, the local maps of serial and diode resistances, calculated from the voltage response distribution, can be handled like the current maps, e.g. averaging gives correct numbers, which can be compared to corresponding data extracted from the *IV*-curve. Using a somewhat simplified model of a solar cell, it will be shown in what follows that local resistance data can be extracted from voltage response data in a fully analytically way. From the results obtained a simple procedure can be defined that allows to calculate resistance maps from CELLO voltage maps in a fully quantitative way. The numbers obtained are, within certain uncritical limits, identical to numbers obtained by direct resistance measurements (e.g. with the “Corescan technique” [4]), but are obtained much faster, with far better spatial resolution, and without destroying the solar cell. As will be shown elsewhere [3], the method is principally capable of being used in-line in a production environment, satisfying the two basic condition of measurement time in the 1 s region and no destruction of the cell.



a)



b)

Fig. 1: CELLO maps of 100 x 100 mm² crystalline solar cell. The voltage response map (Fig. 1a) and the correlated serial resistance map (Fig. 1b) indicate a radial change around the reference electrode in the right lower corner.

2 SIMPLE MODEL FOR VOLTAGE RESPONSE ANALYSIS

2.1 The model

A typical CELLO voltage response map of a homogeneous mono-crystalline Silicon solar cell is shown in Fig. 1a). The corresponding (calculated) map of the local serial resistances $R_{ser}(x,y)$ is shown in Fig 1 b). In this experiment only one reference electrode (current free voltage probe) is used that is located in the lower right corner. In both maps a radial symmetry of the plotted properties around the reference electrode is obvious that cannot reflect non-uniformities of the solar cell. For points far away from the illuminated spot there is still a significant voltage response to the local illumination but it contains no local information about the grid since all areas far away from the spot show the same response. The maps shown in Fig. 1 have been measured under open circuit condition, i.e. no current is taken out of the solar cell. Thus the locally generated excess carriers are distributed (as a current) through the grid across the complete solar cell, causing an increase of the photo voltage, which gets smaller for points farther away from the illuminated spot due to ohmic losses induced by the current flow. Since a voltage response is found even far away from the illuminated spot, parts of the locally generated current must have reached these far-away areas. What we have just discussed for the open circuit condition is also true for CELLO voltage maps taken under global current flow conditions, since the current which is taken out of the solar cell is held constant, i.e. non of the additionally generated local photo current can leave the solar cell. The current distribution across a solar cell leading to local voltage changes will be investigated in a simple two-layer model. The upper layer 1, having a constant sheet resistance, represents the lateral resistance network of emitter + grid; layer 2 is the bulk of the solar cell. The interface between layer 1 and layer 2 is a pn-junction and will be described by a simple diode equation. For sake of simplicity the model solar cell is assumed to be a round disk with the illuminated spot in the center. The current flow through emitter, pn-junction and backside metallization is schematically illustrated in Fig. 2a). Changing the fixed global current for the CELLO voltage measurement, i.e. changing the working point for the measurement, does not change the sheet resistance ρ but changes the resistivity of the diode, represented by the inverse diode slope K in Eq. (2). We only need the diode equation in linear order because we will only calculate the linear voltage response to the locally generated photo current. The laterally distributed photo current leads to ohmic losses as described by Eq. (1).

$$dU(r) = -\frac{\rho}{2\pi r} I_{lat}(r)dr \qquad (1)$$

$$J_D(r) = J_0 \exp\left(\frac{eU(r)}{kT}\right) \approx KU(r) \qquad (2)$$

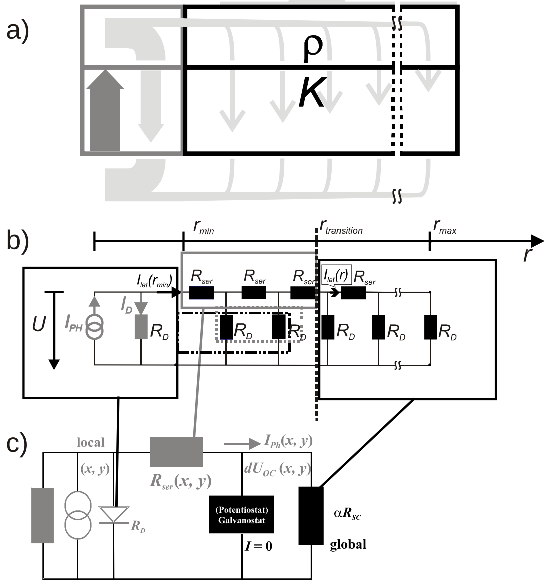


Fig. 2: Model for voltage response calculations. 2a) shows a cross section of the radial solar cell and the assumed current distribution for the case of local illumination, and 2b) shows the corresponding equivalent circuits for linear response. The network of small resistors can be simplified to Fig 2c).

Current losses through the pn-junction to the backside of the wafer (described by Eq. (2)) lead to a reduction of the lateral current. Combining Eq. (1) and Eq. (2) we end up with the differential equation (3), which is solved by Eq. (4).

$$\frac{dU}{dr} = -\frac{\rho}{2\pi r}\left(I_{lat}(r_{min}) - \int_{r_{min}}^{r} 2\pi r K U(r) dr \right) \qquad (3)$$

$$U(x) = AI_0(x) + BK_0(x) + \frac{\rho I_{lat}(x_{min})}{2\pi}\{I_0(x_{min})K_0(x) - K_0(x_{min})I_0(x)\}, \qquad (4)$$

with $x = \sqrt{\rho K}\, r$; I_0, I_1, K_0, and K_1 are modified Bessel functions with $dI_0/dx = I_1$ and $dK_0/dx = -K_1$.
The parameters A, B and $I_{lat}(x_{min})$ have to be calculated according to the boundary conditions.

For local illumination the spot size has to be specified by a radius r_{min}. Assuming the same diode properties as in the rest of the solar cell, the first boundary condition is $I_{lat}(r_{min}) = I_{Ph} - \pi r_{min}^2 K U(r_{min})$. Since no current can leave the solar cell, the second boundary condition is $I_{lat}(r_{max}) = 0$, and r_{max} is defined by the area of the solar cell. Using these boundary conditions, curve a) in Fig. 3 shows an example of the voltage distribution from the center of the illuminated spot to the boundary of the solar cell.

In addition, curve b) in Fig. 3 shows the voltage distribution for current flowing from the periphery into the solar cell. In this case the ratio between voltage and current is the slope of the global IV-curve. The boundary conditions are $I_{lat}(r_{max}) = -I_{Ph}$ and $B = 0$, i.e. $U(0)$ is not divergent. Consequently $I_{lat}(0) = 0$ which just reflects the symmetry of the problem and charge conservation.

The most important result of this model is illustrated by curve 3) in Fig. 3. Averaging the voltage distribution across the whole solar cell, both boundary conditions give the same result. This can be easily generalized by integrating Eq. (2) over the full solar cell:

$$I_{Ph} = \int_{r_{\min}}^{r_{\max}} 2\pi r J_D(r)dr = \int_{r_{\min}}^{r} 2\pi r K U(r) dr = K\langle U\rangle A_{SC} \quad (5a)$$

or $$R_{DSC} := \frac{1}{K A_{SC}} = \left\langle \frac{U}{I_{Ph}} \right\rangle \quad . \quad (5b)$$

The first equality in Eq. (5a) just means that all current is consumed in the solar cell. The definition of the diode resistance R_{DSC} in Eq. (5b) follows directly from Eq. (2). This result is independent of the sheet resistance ρ and the chosen boundary conditions as long as no current is flowing out of the solar cell.

As a last result, the lateral resistance $R(r) := U(r)/I_{lat}(r)$ is plotted in Fig. 4. It shows a broad minimum at $r_{transition}$, which is essential for the interpretation of voltage responses.

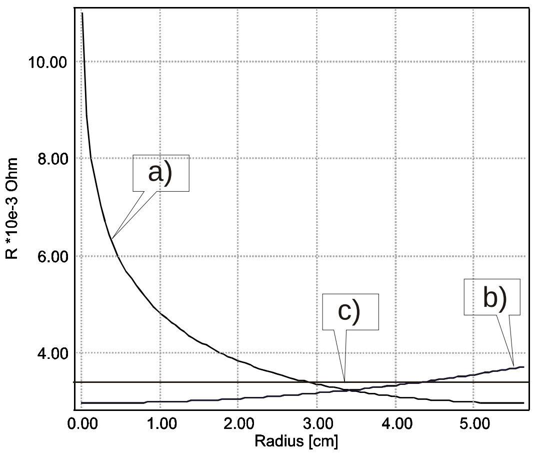


Fig. 3: Results of the simulation: $U(r)/I_{Ph}$ is shown for local illumination in 3a) and for the IV-curve measurement in 3b). Based on Eq. (3) and (10) the R_{DSC} is displayed for both cases in Fig. 3c).

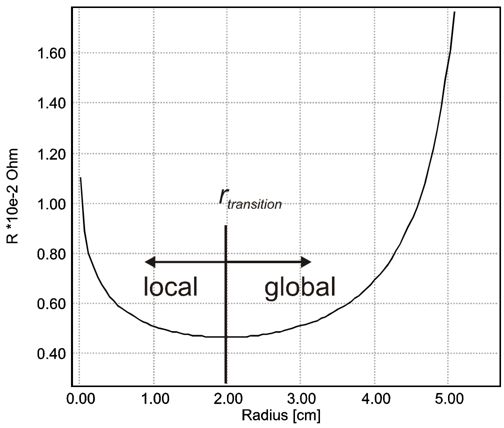


Fig. 4: The calculated local serial resistance $R(r) = U(r)/I_{lat}(r)$ for the case of local illumination is shown. There is a minimum at $r_{transition}$.

For small distances from the illuminated spot the ohmic losses lead to a strong decrease in the voltage response, while only a small fraction of the photocurrent is flowing through the pn-junction to the backside. For large distances from the illuminated spot the current density becomes very small, and ohmic losses are not relevant anymore. Due to the larger area, a high fraction of the photocurrent is flowing through the pn-junction, reducing strongly the lateral current flow. Thus there is a transition from a region of strong ohmic losses with well-defined direction of the current flow away from the illuminated spot to a large region where ohmic losses are nearly negligible. This describes qualitatively the experimental result presented in Fig. 1.

2.2 Using the model for a quantitative evaluation of CELLO maps

In order to calculate serial resistances, the continuous model of Fig. 2a) must be translated into a model of discrete resistances as shown in Fig. 2b). This resistance network, however, is too complicated to be useful for a simple (and fast) evaluation of the CELLO voltage response data. From the interpretation of Fig. 3a) we have learned that most current is consumed far away from the illuminated spot. This indicates that the resistances representing the diode in Fig. 2b) may be neglected without making large errors reaching to the equivalent circuit of Fig. 2c). The physical meaning of the local parameters $R_D(x,y)$ and $R_{ser}(x,y)$ is quite clear. Only the meaning of αR_{SC} has to be discussed in more detail. R_{SC} is the measured resistance of the global IV-curve. αR_{SC} is a somewhat larger resistance describing that part of the solar cell into which most of the photocurrent is flowing, i.e. it describes that part of the solar cell in Fig. 4 found between $r_{transition}$ and r_{max}. Thus α can be calculated by

$$\alpha = \frac{A_{SC}}{A_{SC} - \pi r_{transition}^2} \quad (6)$$

Although $r_{transition}$ is not known in advance, i.e. α is not known in advance, it can be calculated self consistently for the voltage data by applying the following procedure:

1) Calculate $\frac{1}{N}\sum \frac{U_{OC}(x,y)}{I_{Ph}(x,y)} = \frac{1}{KA_{SC}} = R_{DSC}$ (7)

2) Make an estimation for α

3) Short circuit current and voltage map now allow to calculate the local serial resistance and local diode resistance from Fig. 2c) by solving the following Eq.

$$\frac{1}{\alpha R_{SC}} \approx \frac{\Delta I_{Ph,0}}{\Delta U} - \frac{1 + R_{ser}(x,y)\dfrac{\Delta I_{Ph,0}}{\Delta U}}{R_D + R_{ser}(x,y)} \quad (8)$$

4) The average of all local serial resistances must fulfill the following equation

$$\frac{1}{N}\sum R_{ser}(x,y)(\alpha) = R_{SC} - R_{DSC} \quad , \quad (9)$$

which just means the global solar cell can be described by a diode in series with a resistance.

Step 2) to 4) must be repeated until Eq. (9) is met.

This is an easily established routine which gave reasonable results on a large number of solar cells.

3 SUMMARY AND OUTLOOK

A simple model for solar cells has been introduced, which can be solved fully analytically to describe the CELLO photo voltage response as a function of distance from the illuminated spot. Some general features could be extracted from this approach, e.g. that the average of all lateral voltage responses is independent of the serial resistances and just reflects the average resistance of the local diodes, which can be summed up to R_{DSC} , the diode resistance of the global solar cell. On the other hand, ohmic resistances are mainly responsible for the lateral distribution of the voltage response. A transition regime has been identified, which separates the local region around the illuminated spot with a well-defined current flow away from this spot from the "distant" areas containing the rest of the solar cell. The distant areas contain no information about (local) serial resistance losses since the local current densities are very small. This distant areas are described by αR_{SC}, and the local resistances can be calculated if α is known. It has been shown that α can be calculated self-consistently from the CELLO maps and R_{SC}. This procedure has been applied to a large number of solar cells, leading to excellent results matching direct measurements in nearly all cases.

4 REFERENCES

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