ANALYSIS OF SERIAL RESISTANCE LOSSES ON SOLAR CELLS USING THE CELLO - TECHNIQUE

S.Mathijssen, J. Carstensen and H. Föll
Chair for General Materials Science, Faculty of Engineering, Christian-Albrechts-University of Kiel, Kaiserstr. 2, D-24143 Kiel, Germany, email: sm@tf.uni-kiel.de, phone +49 431 880–6181 FAX -6178

ABSTRACT: The CELLO (Solar CELl LOcal Characterization) technique is used to analyze the local distribution of the serial resistance of solar cells. The measurement principle and the data analysis method to calculate the local serial resistance will be presented. The influence of the local diode quality on the measurement results will be discussed, and a way to avoid misinterpretations due to local diode quality changes will be shown. A comparison of CELLO to the established CORESCAN technique shows a very good agreement between the two techniques. In addition, CELLO measurement results of the local serial resistance on CIS ($Cu(In,Ga)Se_2$) thin film solar cells will be presented, showing the ability of CELLO to characterize thin film solar cells.
Keywords: Characterization, Multi-Crystalline, $Cu(InGa)Se_2$

1 MEASUREMENT TECHNIQUE CELLO

1.1 Introduction

The CELLO technique measures the response of a globally illuminated solar cell to local excitations with an intensity modulated 780 nm LASER (Fig. 1); it is described in detail in [1, 2]. The CELLO technique is contactless (it uses the cell terminals) and non-destructive. All solar cells with electrodes can be measured, including thick and thin film solar cells.

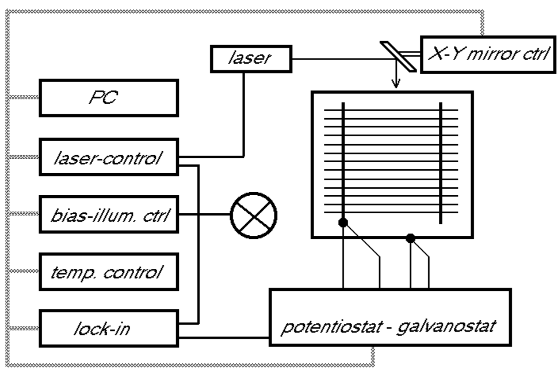

Figure 1: The CELLO system

During the measurement the cell is kept at a constant voltage V_{cell} or at a constant current I_{cell} by a high-precision custom-built potentiostat/galvanostat. The sinusoidally modulated LASER beam is scanned over the surface of the cell, and the amplitude (current response dI in the potentiostatic case or voltage response dU in the galvanostatic case) as well as the phase shift φ of the linear response are recorded by a lock-in amplifier.

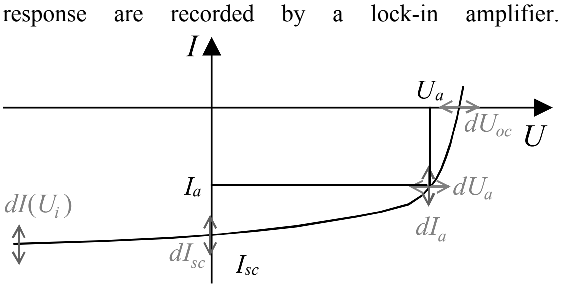

Figure 2: The five most common CELLO measurement modes along the IV curve of a solar cell. The suffix "a" refers to the optimal working point of the cell.

Several scans are taken on different points on the IV curve of the solar cell (Fig. 2). For a general quantitative characterization of the most important local solar cell parameters, scans on five points along the IV curve as shown in Fig. 2 (three potentiostatic and two galvanostatic) are advantageous.

To map the effective serial resistance distribution only, two scans are sufficient: potentiostatic dI_{sc} under short circuit conditions, and galvanostatic dU_{OC} under open circuit conditions. For a 100 x 100 mm^2 solar cell the resolution is typically 600 x 600 points or 360000 pixels (the laser points overlap partially, real resolution about 200 µm). The system can measure 100 points per second, leading to a measurement time of about 1 h per map. Ongoing work in noise reduction will increase the measurement speed with a concomitant reduction of the measurement time by a factor of about three.

1.2 Local analysis of serial resistances with CELLO

To obtain the local serial resistance with the CELLO system, the measured data are analyzed with respect to the (simplified) equivalent circuit shown in Fig. 3. In Fig. 3 the "two diode approach" to the real diode is omitted since this simplification does not significantly alter the series resistance results.

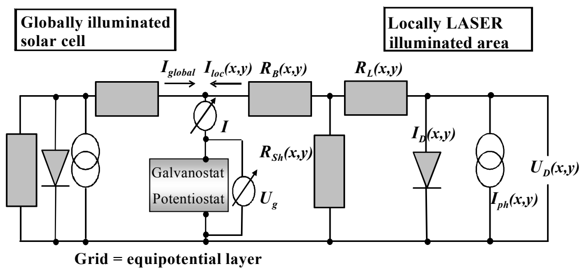

Figure 3: Simplified equivalent circuit of the CELLO system

The equivalent circuit analysis leads with some assumptions (neglecting R_{sh} and R_L, for details see [2]) to:

$$\frac{1}{R_{SC}(U_{OC})} \approx \frac{dI_{sc,n}}{dU_{OC,n}} - \frac{1 + R_{ser,n}\dfrac{dI_{sc,n}}{dU_{OC,n}}}{R_D + R_{ser,n}} \qquad (1)$$

with:

$R_{sc}(U_{OC})$:	Ohmic resistance of the global solar cell under open circuit conditions, known from the global IV curve.
$dI_{sc,n}$, $dU_{OC,n}$:	Current response dI under short circuit conditions or voltage response dU under open circuit conditions of pixel n, respectively, known from the corresponding CELLO maps.
$R_{ser,n}$:	Serial resistance of pixel n.
R_D:	Ohmic resistance of the local diode

Three of the five variables in equation (1) are known from the CELLO measurement and the global IV curve. In order to calculate $R_{ser,\,n}$ for every pixel or position n, R_D must be known. A sufficiently good value for R_D can be found by first assuming that R_D is constant over the whole solar cell. Since on the positions where the electrode contacts the solar cell, $R_{ser,n}$ is zero, R_D can then be obtained using (1). The position for the lowest value in the $\frac{dI_{sc,n}}{dU_{OC,n}}$ map is the contact point of the electrodes.
The algorithm to calculate $R_{ser,n}$ detects this point of the lowest value in the $\frac{dI_{sc,n}}{dU_{OC,n}}$ map, first calculates R_D there, then, using the obtained R_D value, calculates R_{ser} for all pixels or points n of the solar cell.
The map of $R_{ser,n}$ is called *effective* serial resistance map, because there can be two separate reasons for a high local value :

- a high serial resistance
- R_D variations due to an inhomogeneous emitter (i.e bad second diode).

Therefore a high effective serial resistance can also be caused by a locally bad diode. The results have to be examined with this background.

2 RESULTS AND DISCUSSION

2.1 CORESCAN and CELLO

The CORESCAN (COntact REsistance SCAN) method is a well-established method to measure the contact resistance. A light spot is scanned perpendicular to the grid over the short-circuited cell, and the potential induced by that light beam induced current is measured. The potential is recorded by pressing a small electrode in the center of the light spot onto the cell surface. The diameter of the light spot is larger than the distance between the grid fingers. Details about CORESCAN can be found in [3, 4].

There is a principle difference between the approach of CELLO and CORESCAN to series resistance mapping: CORESCAN measures the resistance of current flowing perpendicular into the grid and current is generated in every pixel between the grid fingers. CELLO measures the resistance of a current that is generated in one pixel and then spreads circularly into the emitter until it reaches the grid. The absolute values of the resistance obtained are thus not directly comparable. Relative values, however, are not effected and should show similar behavior. This is indeed the case as shown in Fig. 4a.

The grid on the multi-crystalline silicon solar cell in Figs. 4a and 4b has been intentionally fired inhomogeneously in order to obtain a broad distribution of the contact resistance. Figure 4a (top) shows the result of the CORESCAN measurement. High contact resistance can be found mainly in the lower and in the central part of the cell. Figure 4a (bottom) shows the corresponding results of the CELLO measurement based on the analysis described in subsection 1.2. In relative units, the CELLO measurement is in very good agreement with the CORESCAN method, even in small details.

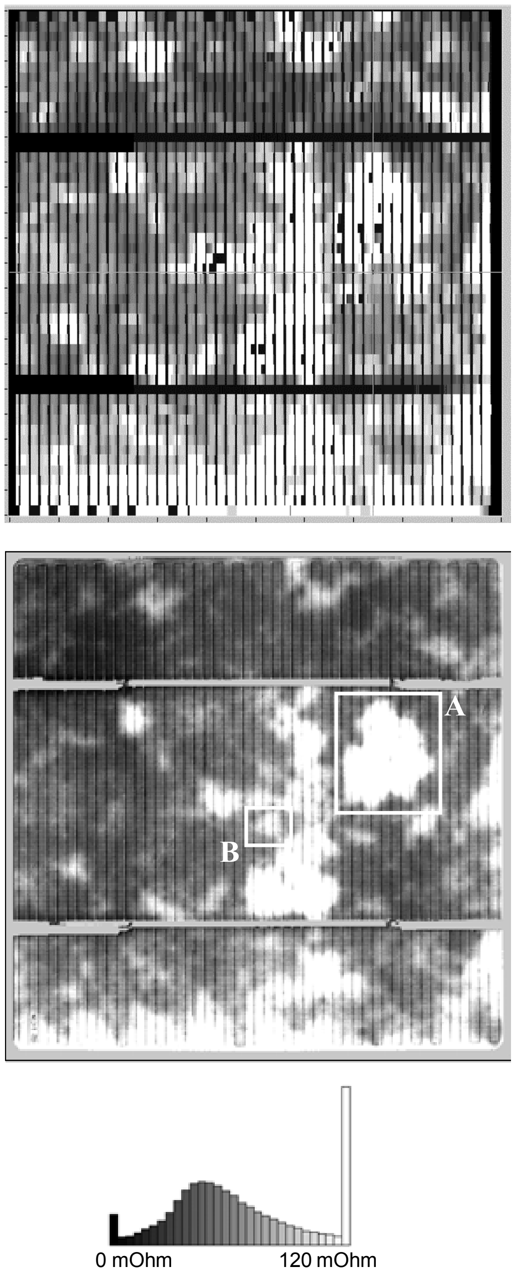

Figure 4a: CORESCAN map (top) and CELLO map (bottom) of the local series resistance of a 100 x 100 mm^2 silicon solar cell. Bright areas indicate high contact resistance; cf. the histogram. The histogram only holds for the CELLO map. Area A and B show a high resistance, but a different phase shift (Fig. 4b).

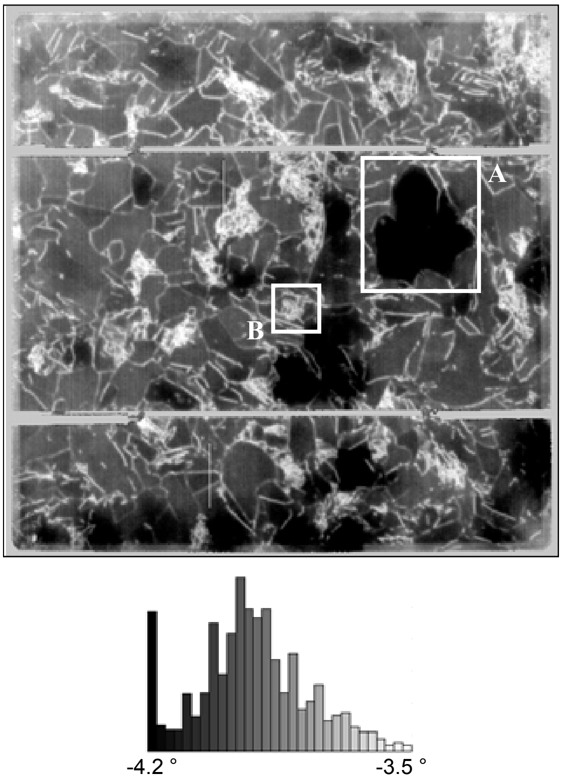

Figure 4b: Phase shift of the CELLO measurement under short circuit conditions (dI_{sc}) of the same cell. Large phase shifts correspond to dark, small phase shifts to bright colors. Note the different phase shifts in areas A and B. Explanation in the text.

The resolution of the CELLO map is around 200 µm, while the CORESCAN resolution is around 1 mm. Measurement time for the CORESCAN map is around 20 min, while it is 2 h for CELLO as mentioned earlier. With the same resolution as in CORESCAN, a CELLO measurement should take about 3.5 min; it is also strictly non-destructive unlike CORESCAN.

2.2 Influence of the local diode resistance R_D

The measured local serial resistance can be influenced by an inhomogeneous distribution of R_D, because for its calculation it is assumed that the value of R_D is constant. So not all high effective serial resistances values might reflect locally increased resistance, but also "bad" diodes; this is also true for the CORESCAN method. The areas marked "A" and "B" in Fig. 4a both indicate high series resistance, but, as will be shown in what follows, area A indeed has a locally increased serial resistance, while area B reflects a locally bad diode with a high R_D.

Fig. 4b shows the phase shift map for the current response of the cell under short circuit conditions. The phase shift reflects time constants of the system, it is determined by the sum of $\tau_n + R_n C_n$; with τ_n = local minority lifetime, R_n and C_n are the local serial resistance or the local capacity, respectively. In area A the phase shift is large. Since it is rather unlikely that this area would have far larger minority lifetimes or a larger capacity, this indicates that the serial resistance is locally increased, indeed. In area B the phase shift is low, indicating a small lifetime, hence a "bad" diode. Since the phase map also shows the grain boundary and areas of high dislocation densities quite clearly, it is obvious that the bad diode in area B corresponds to a high density of grain boundaries / dislocations. Why other areas with a large grain boundary density do not lead to bad diodes is unclear for this cell.

With the phase shift map always obtained for "free", i.e it is measured simultaneously with the amplitude without an increase of the measurement time, it is thus possible to distinguish between the two possibilities for a high effective serial resistance. CELLO thus will give far more information than CORESCAN in a shorter time or with better resolution without destroying the solar cell

2.2 CIS thin film solar cells

In contrast to CORESCAN, CELLO can also be used to characterize thin film solar cells due to its contactless measurement principle.

Here results for the measurement of the effective serial resistance of CIS ($Cu(InGa)Se_2$) thin film solar cells are shown, for a further discussion of CELLO measurements of thin film solar cells see [5].

Two CIS modules have been analyzed with CELLO. Each module consists of 15 cells, each cell 4 x 12 mm^2. All cells have been measured individually under the same conditions on each module. The module structure and the electrode positions are shown in Fig. 5.

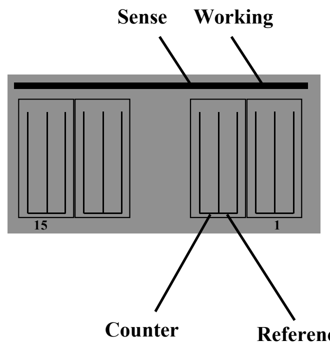

Figure 5: Module structure of the CIS modules. Electrode positions for the measurement of cell 2 are shown.

In Figs. 6 and 7 the effective serial resistance of the cells 2 to 4 of each module are shown. Only three cells are shown here due to the limited space for illustrations. Also the information in the maps is much clearer in the original color pictures.

Between the two modules big differences are visible. Module 1 (Fig. 6) shows a very inhomogeneous distribution of the effective serial resistance. An inhomogeneous photoactive layer is regarded as the reason. Module 2 (Fig. 7) shows a different structure. No patterns are visible in the effective serial resistance. The resistance increases from the position of the electrode on the bottom of the cell to the top. The mean resistance is reduced by a factor of 10 in comparison with module 1. The photoactive layer seems to be more homogeneous.

These results demonstrate the potential of the CELLO technique for thin film solar cells. Further examinations should find the reasons for the differences between the two modules.

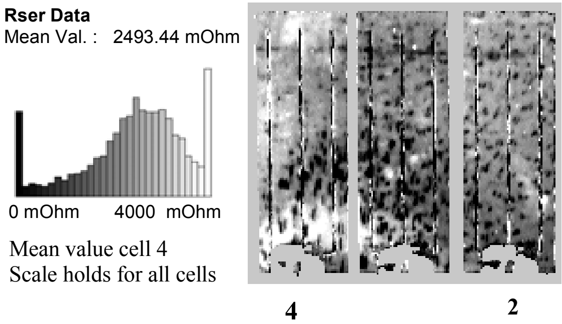

Figure 6: Effective serial resistance of cells 2 – 4 of CIS module 1. Note the inhomogeneous distribution of the resistance.

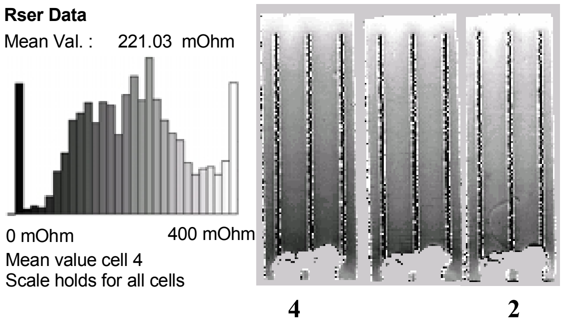

Figure 7: Effective serial resistance of cells 2 – 4 of CIS module 2. Resistance scaling is a factor 10 smaller than in module 1 (Fig. 6).

3 CONCLUSIONS

The CELLO technique is a valuable tool to determine the distribution of the local serial resistance on a solar cell. A comparison with the established CORESCAN technique shows a very good qualitative agreement. The differences in the absolute values are due to different measurement principles leading to different current flows. Further examination and analysis will lead to consistent quantitative results.

Using the phase shift information of the response it is possible to distinguish areas with a high local serial resistance from areas with a locally bad diode. Both areas show up as areas with an increased effective serial resistance in the CELLO and CORESCAN technique, but misinterpretations of the CELLO data can be avoided.

The CELLO technique is not limited to thick film solar cells, it can be applied to all types of solar cells which have externally contactable connections. First measurement on CIS thin film solar cells show the capabilities of CELLO.

Further improvement in the system will reduce the measurement time considerably, facilitating the broader use of CELLO.

4 REFERENCES

[1] J. Carstensen, G. Popkirov, J. Bahr, and H. Föll, in Proceedings of the 16th European Photovoltaic Solar Energy Conference, VD3.35, Glasgow (2000).

[2] J. Carstensen, G. Popkirov, J. Bahr, and H. Föll, Solar Energy Materials & Solar Cells 76, 599 (2003).

[3] A.S.H. van der Heide, A. Schönecker, G.P. Wyers and W.C. Sinke, in Proceedings 16th European Photovoltaic Solar Energy Conference, Glasgow (2000).

[4] A.S.H. van der Heide, J.H. Bultman, J. Hoornstra and A. Schönecker, in Proceedings of the 11th NREL workshop on crystalline silicon solar cell materials and processes, Estes Park (Colorado, USA) (2001).

[5] S. Mathijssen, J. Carstensen, H. Föll, G. Voorwinden, and H. Stiebig, in Proceedings 2005 MRS Spring Meeting, San Francisco (2005), in press.