FAST CELLO MEASUREMENTS FOR DEFECT IDENTIFICATION AND LOSS QUANTIFICATION OF SOLAR CELLS

J. Carstensen[1], A. Schütt, G. Popkirov[2], and H. Föll[1]
[1]Chair for General Materials Science, Faculty of Engineering, Christian-Albrechts-University of Kiel,
Kaiserstr. 2, 24143 Kiel, Germany, email: jc@tf.uni-kiel.de, Phone: (+49) 431 880 6181, Fax: (+49) 431 880 6178
[2]Bulgarian Academy of Sciences, Central Laboratory for Solar Energy and New Energy Sources, Sofia, Bulgaria

ABSTRACT: The speed of CELLO (solar CELl LOcal characterization) measurements has been increased drastically by a complete redesign of the hardware, allowing now for measuring 1000 points per second routinely. Examples of such fast measurements are presented and possibilities for identifying local defect types and quantifying their influence on the solar cell efficiency are discussed. Reducing the lateral resolution by defocusing the LASER beam still allows to correctly identify various defect structures and to obtain quantitative values for, e.g., resistances, within a few seconds. Strategies for reducing the measurement time to < 1 sec. are discussed, which would allow for using CELLO as an in-line control tool.
Keywords: Characterization, Multi-Crystalline, Solar Cell Efficiencies

1 CELLO MEASUREMENT TECHNIQUE

1.1 Introduction

The CELLO (solar CELl LOcal characterization) technique analyses the current and voltage response of a globally illuminated solar cell to local illumination with a modulated LASER beam [1, 2]. 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 lateral resolution of up to ~200 µm spot diameter. Typical local photocurrents are of the order of 100 µA to 1mA, while short circuit currents of the global solar cell are of the order of 1A. The measured local photo voltage response is in the order of some µV. Since all measured signals are very small, signal to noise ratio is a decisive issue of the CELLO setup. By averaging the response over several periods of the sinosodially modulated perturbation signal, the Lock-in technique allows to improve the signal to noise ratio drastically, but this leads to long measurement times. Improving the signal to noise ratio and increasing the Lock-in frequency are therefore essential for fast measurements. Since the allowed or reasonable Lock-in frequency depends on the time constants of the complete measurement setup, i.e. the time constants of the solar cell and the time constants of the CELLO setup, the measurement speed can be increased, by making the CELLO hardware "faster". A complete redesign of all CELLO hardware components with respect to good high frequency characteristics and good signal to noise ratio in the last year allowed for an increase of the measurement speed by about a factor of 30. Several examples of fast CELLO results measured with 1000 pixel per second will be discussed in what follows, focussing on the information which can be extracted from the phase shift and on serial resistance losses.

1.2 Interpretation of phase shift maps

The measured currents and voltages contain information on amplitude and phase shift Φ of the linear response to the modulated LASER light where $\Phi = -\omega\tau$, ω is the modulation frequency, and τ the effective time constant for the transition of the signal from the illuminated spot to the electrical contacts on the solar cell. Under short circuit condition the time constant for the locally generated photo current may be written in a very simplistic form as

$$\tau = \frac{1}{\frac{1}{\tau_{bsr}} + \frac{1}{\tau_{bulk}}} + RC \quad . \qquad (1)$$

τ_{bsr} characterizes the recombination processes at the backside of the wafer, τ_{bulk} is the bulk life time, and the product *RC* is the time constant for the current flow from the illuminated spot through the grid to the electrical contacts. *C* is the local capacitance at the illuminated spot (mainly of the pn-junction) and *R* is the serial resistance from the illuminated spot to the electrical contacts. Additional time constants of the CELLO setup for measuring currents and controlling the potential have been omitted since they are very small in the new CELLO setup. Due to the active compensation of resistance losses, the CELLO short circuit current measurement differs somewhat from LBIC [3] results. In LBIC the relevant *R* is principally larger since additional ohmic losses occur at the contact and in the contacting wires. CELLO thus principally allows for higher measurement speed for short circuit currents than LBIC.

2 RESULTS AND DISCUSSION

2.1 Defect identification on a typical mc-Si solar cell

Fig. 1 shows CELLO results on a 10 cm x 10 cm mc-Si solar cell measured with 610 x 610 pixel with the new, fast CELLO setup at 1000 pixel per second. Measuring the complete cell in one mode takes roughly 6.5 minutes, generating an amplitude and a phase shift map as shown for the short circuit current in Fig. 1a) and 1b). Combining the short circuit map (Fig. 1a) and the open circuit voltage map (not shown), the local serial resistance losses can be calculated; the result is shown in Fig. 1c) [4]. Since two maps are needed to get quantitative results, such a high-resolution serial-resistance map needs 13 minutes measurement time. Several defect types leading to larger serial resistances (regions with white color) can be identified (in particular on the original color images):

1. Straight lines, some of them parallel to each other, indicate scratches through the emitter, which are induced by the handling of the solar cell.
2. A number of broken grid fingers lead to higher ohmic losses starting at the position of the break to the pe-

riphery of the solar cell.

3. An area with higher ohmic losses, which cannot be related to broken grid fingers because it does not extend to the edge of the cell. Due to this geometrical feature such defects can be identified with high probability as regions of increased contact resistance between emitter and grid.
4. Everywhere around the edge of the solar cell the serial resistance is increased in areas perfectly matching the areas not covered with the Al metallization on the backside of the cell. The ohmic losses are larger on the left side of the cell, which corresponds to a misalignment of the backside metallization.

In addition to this defect identification, by plotting the resistance between two grid fingers as shown in Fig. 1d) allows to analyze the sheet resistance of the emitter.

Some of the serial resistance structures are visible in the phase shift map of the short circuit current in Fig. 1b) as well. Most prominent is a jump to smaller phase shifts in the region without Al backside metallization. The dominant effect here is the missing of the back surface field (BSF), leading to a smaller τ_{bsr} and a reduced effective recombination lifetime. Consequently, the short circuit current amplitude (Fig. 1a) is smaller in exactly that region around the edge of the solar cell. The same holds for the grain boundaries, which are visible as dark lines in Fig. 1a) and as bright lines with reduced phase shift in Fig. 1b). According to Eq. (1) the larger serial resistance in the edge area leads to an increase in the phase shift, but this is overcompensated by the missing BSF. All regions with broken grid fingers show indeed a larger phase shift, although this is not easy to see in the gray scale images presented here.

There is one feature visible in the phase shift map neither seen in the current amplitude nor in the serial resistance map: A roughly 2 cm broad area at the right side of the cell shows a smaller phase shift. This area most probably exhibits a smaller capacitance, indicating a change in the bulk doping.

Without going into details, the CELLO technique allows to calculate the losses in the solar cell efficiency induced by the individual defects [5, 6]. For the missing backside metallization, e.g., we find relative losses of 1 % in the photo current due to the missing BSF and 2% due to the increase of ohmic losses. In total, losses are only 3%, which is exactly the reason why such defects are accepted for commercially available solar cells. On the other hand this results demonstrates the sensitivity of the CELLO technique and its capability to quickly pinpoint any serious problem encountered in production.

2.2 Fast CELLO measurements for inline control

Most commercially available silicon solar cells are nowadays made from multcrystalline silicon wafers, which need a high spatial resolution to investigate, e.g., recombination features due to the high density of grain boundaries. For further increases of solar cell efficiencies even inline control will need tools that measure solar cell parameters with high spatial resolution.

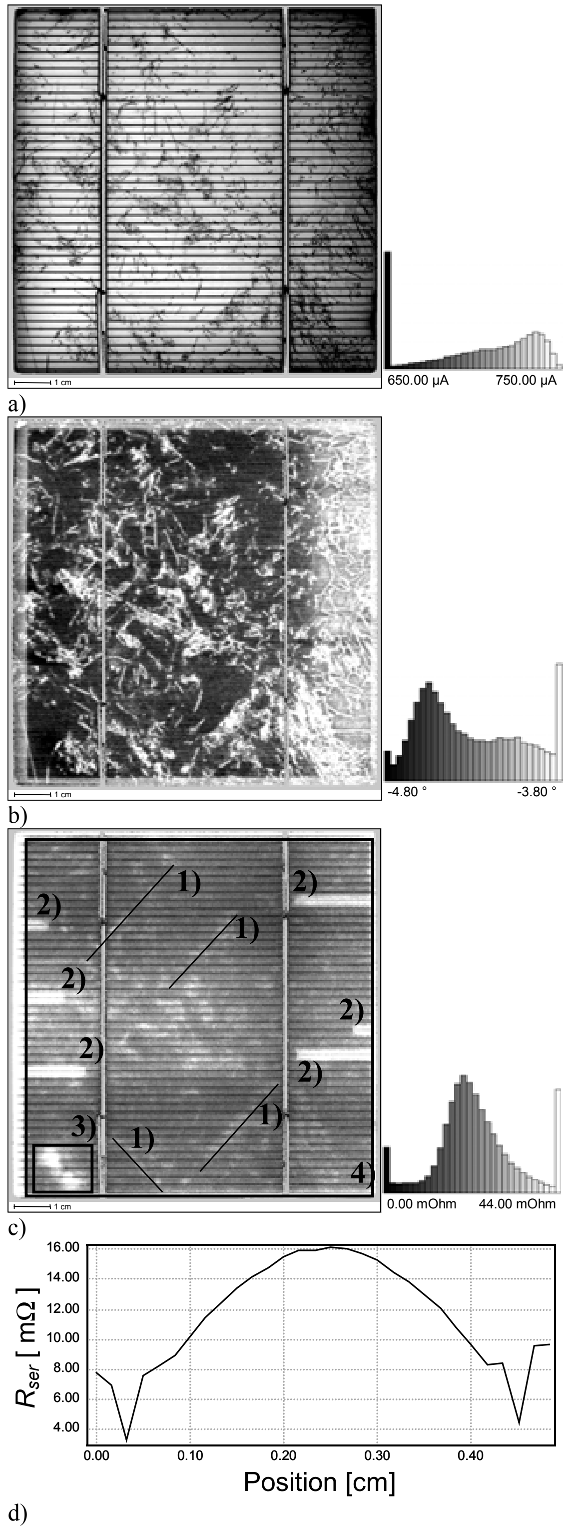
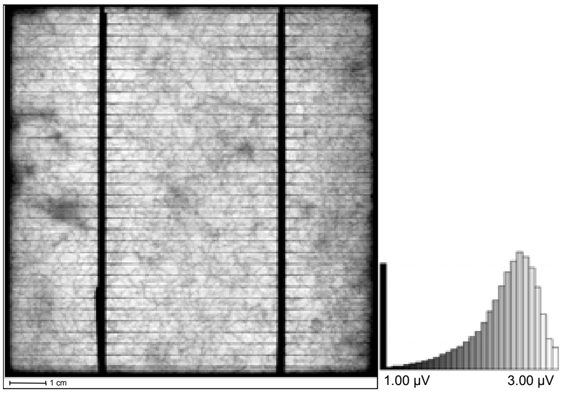
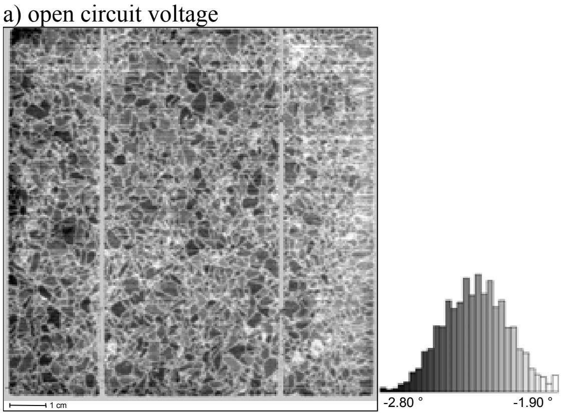


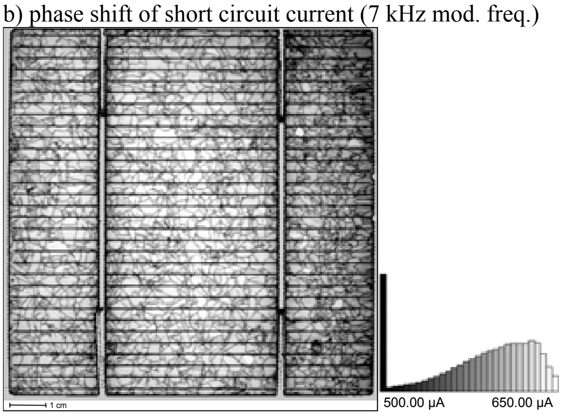
Fig. 1: CELLO maps of a typical 10 cm x 10 cm mc-Si solar cell measured with 1000 pixel per second. a) amplitude of short circuit current; b) phase shift of short circuit current (LASER modulation frequency: 7.5 kHz); c) calculated serial resistance with several defect types (1): scratches; 2): broken grid fingers; 3) high contact resistance between grid finger and emitter; 4): missing backside metallization); d) run of serial resistance between two grid fingers.



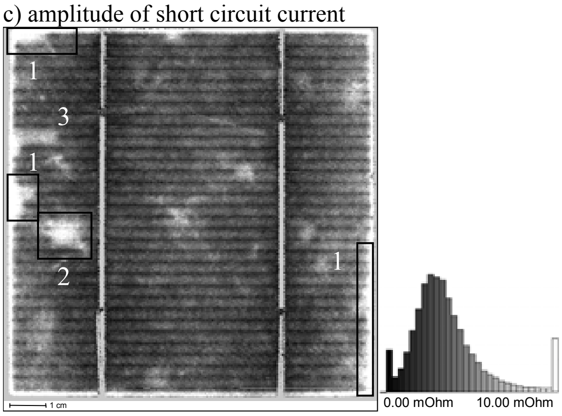
a) open circuit voltage



b) phase shift of short circuit current (7 kHz mod. freq.)

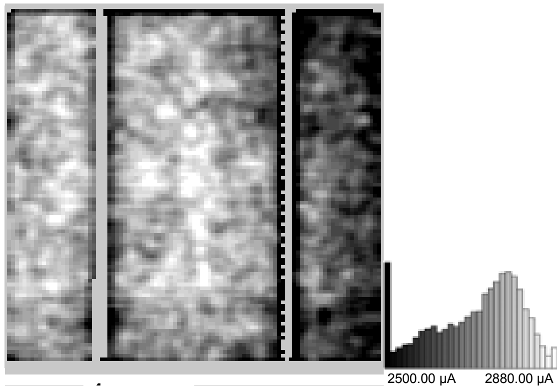


c) amplitude of short circuit current

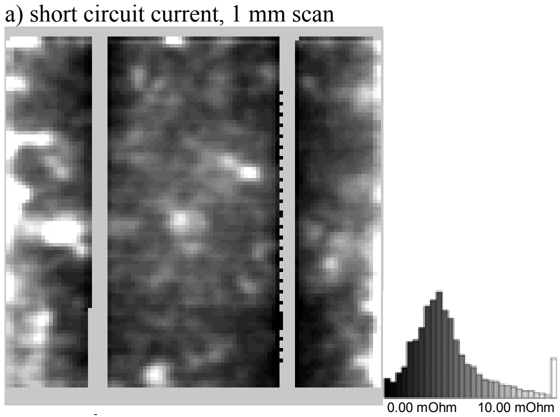


d) calculated serial resistance

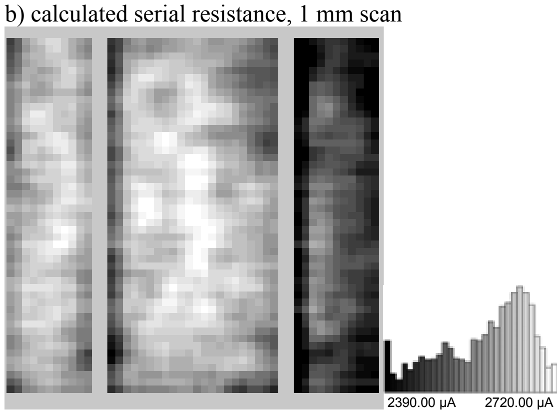
Fig. 2: CELLO maps of a 10 cm x 10 cm mc-Si solar cell. 610 x 610 pixel are measured with 1000 pixel per second. The voltage map a) plus current map c) were measured within 13 minutes. Combining these two, the serial resistance map d) is calculated.



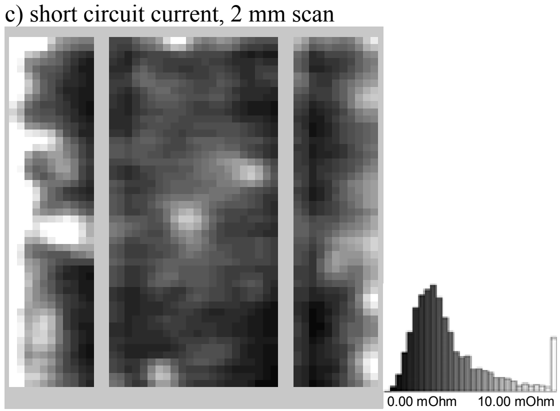
a) short circuit current, 1 mm scan



b) calculated serial resistance, 1 mm scan



c) short circuit current, 2 mm scan



d) calculated serial resistance, 2 mm scan

Fig 3: CELLO maps for the same solar cell as in Fig. 2 measured with reduced spatial resolution: a), b): 1 mm scan measured within approximately 30 seconds; c), d): 2 mm scan measured within less than 7 seconds.

Fig. 2 b) and c) show an example of amplitude and phase shift for short circuit current measurements where the high lateral resolution is essential for a detailed investigation of the local recombination activity. The only aspect of the phase shift map that we will discuss here is what can *not* be seen in comparison to the phase shift map in Fig. 2b: No BSF effect around the edge is visible and there is no large region with a smaller phase shift, which would be an indication of differences in the bulk doping across the wafer.

Fig. 2a) shows the open circuit voltage measurement, which in combination with Fig. 2c) allows to calculate the serial resistance map in Fig. 2d. It is evident that the serial resistance map does not show structures as small as the other maps; this is a general observation for resistance maps in strong forward direction. The reason is that lateral current flow through the grid compensates for local inhomogeneities and this "smears out" the local details. While this might occur to be a problem, it is rather advantageous because this effect allows to obtain quite reasonable results for the serial resistance from measurements with significantly smaller lateral resolution. Fig. 3 shows CELLO results for the same solar cell as in Fig. 2 with a lateral resolution reduced to 1 mm and 2 mm. Comparison of Fig. 2d) and 3d) show that even for the 2 mm scan the main features of the serial resistance are still visible, which is not true for the corresponding current maps in Fig. 2c) and 3c). For the 2 mm scan the LASER focus has been increased to 2 mm and the LASER intensity was increased by a factor of 5 (which still leads to a lower current illumination intensity than in the high resolution maps). Measuring 1000 points per second, the short circuit current as well as the open circuit voltage map took about 3 seconds, leading to an over-all measurement time of less than 7 seconds for the serial resistance map shown in Fig. 3d). For this map the Lock-in frequency as well as the local LASER intensity were in the same range as for Fig. 2d) allowing for a fully quantitative analysis of the data.

There are several ways to increase the measuring speed even more. Increasing the LASER intensity and the Lock-in frequency would allow for an increase in measurements speed by a factor of 4 to 8 while still giving reasonable, reproducible results. Measuring local photocurrent or lifetime maps is not a unique feature of CELLO. Such data could be extracted from other fast inline tools. In combination with only the CELLO voltage data resistance maps could then be calculated, allowing for a further increase of measurement speed by a factor of 2. For a known grid design the number of measured points could be further decreased, e.g. by measuring only several lines parallel to the main bus bars. This would still allow identifying broken grid fingers and defects around the edge of the solar cell, which occur quite often. In conclusion, measurement times of around 1 second are definitely possible, even on larger solar cells, which would allow for CELLO to be used as an inline tool.

3 SUMMARY AND CONCLUSIONS

By optimizing all CELLO hardware components with respect to the signal-to-noise ratio and good high frequency characteristics, CELLO measurements are now routinely performed with 1000 points per second. This allows to measure, quantitatively and reproducibly, high resolution maps in a very reasonable time (500000 points in 8 minutes), i.e. a full CELLO analysis (5 data sets at different points along the IV-curve of the solar cell) in less than one hour. Since amplitude and phase shift are measured simultaneously, these 10 maps allow to identify nearly all defect types in a solar cell. Several examples have been shown in this paper. In turn, detailed local knowledge of a solar cell allows to calculate the influence of defects on the global solar cell efficiency, giving clear guidelines for improving material and processes. As has been shown, for the quantitative characterization of the serial resistance a high-resolution analysis is not necessary for many types of solar cells. This allows a drastic reduction of the number of scanned points and enables measuring times of some seconds. Strategies for further increasing the measurement speed have been discussed, which show that meaningful CELLO maps can be measured within less than 1 second, enabling the CELLO technique to be used as a tool for inline control.

4 REFERENCES

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