# CELLO FFT IMPEDANCE ANALYSIS OF SOLAR CELLS WITH A STRONG INJECTION LEVEL DEPENDENCE

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ABSTRACT: The CELLO impedance analysis uses frequency dependent amplitude and phase shift data measured for three LASERs with different penetration depths for fitting local solar cell parameters to a 1D model for generation, recombination, and transport in a solar cell. Solar cell parameters with a strong injection level dependency are quite common but always difficult to analyze. In this paper several approaches will be discussed for the identification of injection level dependent parameters including second harmonic analysis. So often measurement conditions can be found which allow to neglect injection level dependencies. Several examples for injection level dependent solar cell parameters will be discussed.

Keywords: characterization, defects, lifetime, injection level dependency

### 1 INTRODUCTION

On several types of solar cells the frequency dependent CELLO linear response analysis of the short circuit current allows to extract maps of a large number of solar cell efficiency determining parameters, just using one LASER wavelength and least square fitting the data to a complete 1D model wavelength dependent charge generation, diffusion and recombination in bulk and at back surface, charge separation in the space charge region (SCR), and current transport through emitter and grid [1]. But uncertainties in parameters like the thickness of the wafer can lead to large errors for the fitted parameters

- bulk life time  $\tau_{\text{life}}$
- back surface recombination velocity  $S_{\rm B}$
- time constant  $R_{ser}C_{SCR}$
- if necessary: diffusion constant D

and several solar cells could not be analyzed at all due to at that time unknown reasons. Using now three different LASERs (RED: 658 nm; IR: 830 nm; SIR: 934 nm) each at two different intensity modulation frequencies and fitting the amplitude and phase shift data (i.e. using 12 measured maps) the results now become much more robust. In addition the reasons, why on several types of solar cells the fitting still does not work could now be identified to be most often an injection level dependency of one or more solar cell parameters which is not taken into account in the fitting models up to now. Several approaches have been tested to analyze the injecting level dependency: adding global illumination, changing the focus size and/or intensity of the LASER, using several confocal LASER beams simultaneously. In addition the second harmonic generation which is a standard tool to analyze non linear phenomena showed up to be a very convenient and powerful tool to analyze several types of injection level dependent phenomena on solar cells. Examples for the fitting of solar cells as well as for the identification of injection level dependent parameters will be presented in this paper.

## 2 EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 1 shows some of the measured CELLO maps (LASER focus size of 400 µm) for a solar cell out of a series for optimization of the firing condition of the Al back contact. On this multicrystalline Si solar cell the back contact has been over fired. A selection of the fit results (using a diffusion coefficient  $D = 28 \text{ cm/s}^2$  and literature values for the penetration depths) is shown in Fig. 2. Most prominent are the strong differences in the phase shift maps for the very deep penetration SIR LASER in Fig. 1b) and the less deep penetration RED LASER in Fig. 1c). Most of the features visible in Fig. 1c) show up in the fitting results for the  $R_{ser}C_{SCR}$  time constant in Fig. 2d), i.e. as expected the RED LASER is not very sensitive to recombination processes in the solar cell bulk but mainly reflects the series resistance and the capacitance of the pn-junction. Fig. 1d) shows the serial resistance R<sub>ser</sub> map extracted from standard CELLO voltage maps. The comparison to the  $R_{ser}C_{SCR}$  map shows a good agreement for most parts of the solar cell, emphasizing ones more, that the fit nicely separates transport phenomena from recombination processes on solar cells. The features visible in Fig. 1b) are mainly visible in the fitting result for the back surface recombination velocity. The strong variation in the values of the phase shifts for certain grains is only slightly visible in the amplitude map in Fig. 1a) which demonstrates that the phase shift contains most of the relevant information for the solar cell parameters. Fig. 2c) shows the X<sup>2</sup> map. Here large numbers correspond to areas where the fit does not work perfectly. These areas correspond to regions with a high dislocation density or near grain boundaries (cf. dark areas in Fig. 1a)), i.e. regions with a strong lateral variation of the bulk recombination, for which the 1D fitting model as expected is not valid. Summarizing all fitting results, on this solar cell the over firing of the back contact mainly leads to an increase of the surface recombination of certain grains but does not show up as an increase of the serial resistance.



d)

**Figure 1:** Examples of the measured impedance data; SIR Laser modulated with 15977 Hz a) amplitude and b) phase shift; c) RED Laser modulated with 15977 Hz phase shift. d) Serial resistance map extracted from standard CELLO open circuit measurement [2].



d) **Figure 2:** Selected fit results showing a)  $S_b$ ; b)  $\tau_{eff}$ , c)  $X^2$ , and  $\tau_{RC}$ .



**Figure 3:** Current amplitude map of the RED LASER beam (details see text). In the lower half the second SIR LASER is switched on, in the upper part it is switched off.



**Figure 4:** Second harmonic (mixed frequency response of RED and SIR LASER).



**Figure 5:** a) Ratio of two photo current maps with two different LASER focus sizes (250  $\mu$ m and 500  $\mu$ m) for a p-type mc-Si solar cell produced from UMG-Si (from upper part of block near transition to n-Si). Clearly the concentric rings in the upper part of the cell with strong injection level dependency are visible.

b) The same area is visible in the second harmonic maps.

In the 1D fitting model no injection level dependencies are taken into account, e.g. bulk recombination is assumed to be independent of the minority carrier concentration. More precisely the bulk recombination should not vary as a function of depth, just reflecting the change of the carrier concentration as a function of the depth in the solar cell. In a Taylor series approximation this could be taken into account as

$$\frac{1}{\tau_{\rm eff}} = \frac{1}{\tau} + \frac{n}{T} \tag{1}$$

leading to a recombination term

$$\frac{\partial n}{\partial t} = -\left(\frac{n}{\tau} + \frac{n^2}{T}\right) \quad . \tag{2}$$

In consequence this would result in a non linear diffusion equation which can not be solved analytically.

Applying a LASER intensity perturbation with a frequency  $\omega$  in linear order the solution for the concentration profile would be

$$n(z,t) = \exp\left(\pm\frac{d}{L}\right)\exp(i\omega t) \quad (3)$$

The second term on the right side of Eq. (2) would generate a term

$$n^{2}(z,t) = \exp\left(\pm \frac{2d}{L}\right) \exp(i2\omega t) , \qquad (4)$$

i.e. twice the frequency  $2\omega$  of the applied frequency  $\omega$  would be generated as is true for any non linear process. Correspondingly applying several perturbation frequencies simultaneously, all mixed frequencies would be generated.

This second harmonic can be analyzed and mapped simultaneously with the linear response analysis and thus does not need any additional measurement time.

As a first example results for a mono-Si solar cell will be discussed. Two confocal LASER beams (RED and SIR) with different perturbation frequencies have been used for simultaneously scanning across that solar cell. Fig. 3 shows the amplitude map of the current response of the RED LASER. When reaching roughly the middle of the map, the SIR LASER was switched off, leading to a drastic change in the RED LASER response especially around the main bus bar. In the lower part of the map the amplitude is larger than far away from the main bus bars, in the upper part the amplitude of the RED LASER is smaller than far away from the main bus bars. Obviously a strong nonlinear mixing between the two LASERS exists for this measurement condition. The bulk concentration of charges generated by the deep penetrating SIR LASER is significantly smaller around the main bus bars due to the missing of the BSF at back side. This smaller bulk injection leads to larger bulk life times which are probed by the RED LASER beam. This strong bulk injection dependence can be directly monitored by analyzing the non linear mixed (sum) frequency of the two LASERs. Fig. 4 shows the amplitude at these frequency and is a second direct prove for the non linear-

ity induced by the injection level dependent bulk recombination. This non linear effect can be overcome by reducing the LASER intensities and/or defocusing the LA-SERs. Just to save measurement time often in the CELLO setup several confocal LASER beams are scanning simultaneously across the solar cell. Routinely, e.g. the second harmonic is monitored, to make sure, that the measured data can reliably be fitted by the standard 1D model. Luckily solar cells with such a strong injection level dependent bulk recombination are very rarely found. Choosing quite defocused LASER beams with a focus spot size of 400 µm not just reduces the danger of artificial injection level dependencies when applying several LASER beams simultaneously; it is nearly a must for roughly 200 µm thick solar cells to allow for 1D modeling. In addition using LASERS with penetration depths larger 50 µm it would be nonsense even trying to use a focus size of around 50 µm since the diffusion will spread the charge carriers to much larger spot sizes.

An example where the change of the focus size has directly been used to analyze the injection level dependence is shown in Fig. 5a). Here the ratio of two photo current maps with two different focus sizes (250  $\mu$ m and 500  $\mu$ m) is shown for a p-type mc-Si solar cell produced from UMG-Si (from upper part of block near the transition to n-Si). Clearly the concentric rings in the upper part of the cell with strong injection level dependency are visible, probably indicating the bad charge separation in the pn junction due to extremely low p-type bulk doping.

Similar maps are found for maps measured at different injection levels by applying additional homogeneous illumination. As shown in Fig. 5b) the concentric rings are visible in the second harmonics as well. While Fig. 5a) needed two scans across the solar cell at different bulk injections, the second harmonic map in Fig. 5b) has just been measured simultaneously with the linear response. In contrast to the cell discussed in Fig. 3 not LASER focus size or LASER intensity could be found for overcoming the injection level dependence on that cell in order to use the standard 1D model for fitting the data.

Many more examples could be presented for injection level dependent solar cell parameters; e.g. several solar cells only show injection level dependencies for the deep penetrating SIR LASER. It is a clear hint that (only) the surface recombination velocity at the back side is injection level dependent. Up to now no analytical models exist which can take these effects into account. The models have to be analytical because otherwise the fitting procedure would be too time consuming. At least for an injection level dependent back side surface recombination velocity ideas exist how to implement this into the existing 1D model and will be tested in the near future.

## 3 SUMMARY

Material and/or process induced injection level dependent solar cell parameters significantly increase the difficulty for a quantitative analysis of local solar cell defects (not only for CELLO but for all characterization tools). Before performing frequency dependent CELLO measurements using several LASERS with different penetration depths the injection level dependency is routinely checked, e.g. to choose a correct beam focus size or LASER intensity. Measuring the second harmonic generation is often a fast and reliable tool for analyzing the injection level dependence without applying subsequently several intensities. On solar cells without injection level dependencies a quantitative analysis of most local solar cell parameters is possible. Up to now at least qualitative information about local parameters showing a strong injection level dependency are measurable. Routines for a quantitative analysis of some injection level dependent solar cell parameters are currently developed.

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#### 5 REFERENCES

- J. Carstensen, A. Schütt, and H. Föll, in Proceedings of the 24th European Photovoltaic Solar Energy Conference, 1AO.4.5, Hamburg (2009).
- [2] J. Carstensen, A. Schütt, and H. Föll, in Proceedings of the 23rd European Photovoltaic Solar Energy Conference, 1CV.1.38, Valencia (2008).