CELLO: An advanced LBIC measurement for solar CELL LOcal characterization

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Poster VD3 / 35

PRINCIPLE OF MEASUREMENT

- Constant homogeneous illumination
- Additional local illumination with LASER beam
- Extremely stable voltage or current source
- Lock-in measurement of small currents **dI** or voltages **dU**
- Scan of solar cell with high spatial resolution
- Various working points (U,I) on IV-curve at each position

⇒ Complete local information of illuminated area

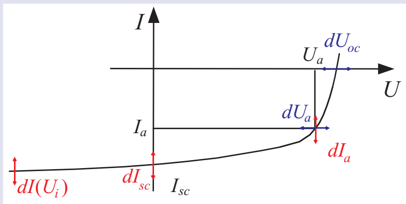

Fig. 1: CELLO measurements along IV-curve

INTERPRETATION OF LOCK-IN DATA

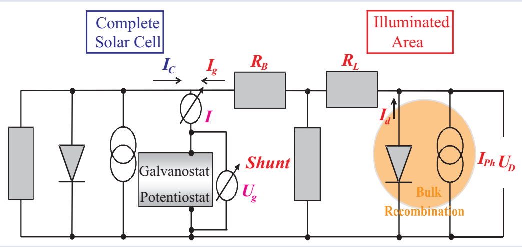

Fig. 2: Equivalent circuit for CELLO measurements

- Simple local interpretation of Fig. 2 only possible if GRID = EQUIPOTENTIAL LAYER
- Otherwise complete simulation of solar cell necessary
- **Basic Equations**:

$$I_g = I_D + I_{Sh} - I_{Ph} \quad (1) \qquad I_D = I_{D1}\left(e^{\frac{qU_D}{n_1 kT}}-1\right) + I_{D2}\left(e^{\frac{qU_D}{n_2 kT}}-1\right) \quad (2)$$

Grid and local Shunt serve as a (local) voltage divider

$$U_g = R_{Sh} I_{Sh} + R_B I_g \quad (3)$$

NEW: For inhomogeneous diffusion length distribution $L(x,y)$ additional recombination losses occur

Analysis to linear order allows to quantify Lock-in measurements according to the equivalent circuit of Fig. 2

$$I_{Ph} = I_{Ph,0} - C_{Rek}(I_D)^3 \quad (4)$$

serial resistance to loc. illum. point

slope of local IV-curve

local illumination intensity (L)

$$-\frac{\frac{\Delta I_{Ph,0}}{\Delta I_g(U)} - 1}{\frac{\partial I_C}{\partial U_C}(U)} = R_L\,\frac{\frac{\partial I_D}{\partial U_D}(U)}{\frac{\partial I_C}{\partial U_C}(U)}\left(1+3\frac{C_{Rek}}{R_L^3}U_{LD}^2\right) \approx R_L \quad (5)$$

slope of the global IV-curve

local current response

increased recombination due to locally inhomogeneous L-distribution

$$F(i,j) = \left(\frac{dI_i}{dI_j} - 1\right)*1000$$

"$L(x,y)$- free" information on local defects

ESSENTIALS FOR MEASUREMENT

- **S**pace **C**harge **R**egion (SCR) of solar cell has an extremely large **capacitance**
  - → Only low frequency regime of Lock-in signals can be interpreted using Fig. 2
  - → Strong restriction for the Lock-in frequency (cf. Fig. 3 a,b)
  - → Optimized integration time to reduce noise
- **Local illumination intensity** must be comparable with global illumination density
  - → Otherwise ohmic losses and recombination processes change (cf. Fig. 3 c)
  - → Local illumination about 100µA ⟷ Global illumination about 1A
  - → Decreases signal to noise ratio
- Scaling with **size of solar cells**:
  - → Capacitance increases → Lock-in frequency is further reduced
  - → Area increases → signal to noise ratio is further decreased

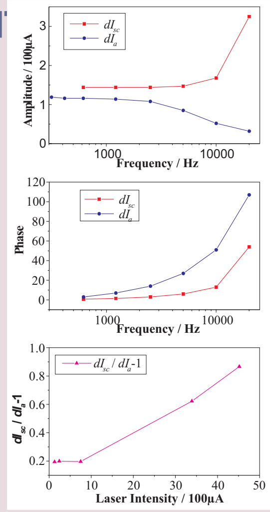

Fig. 3: Frequency and illumination intensity dependence

Requirements on Hardware:

- Extremely stable voltage/current source must be sensitive to relative changes of 1 : 10000
- Extremely stable (time and spatial) homogeneous illumination to minimize noise for Lock-in measurement
- Good reference electrodes to be sensitive to local ohmic losses on solar cell (various resistances)
- Good LASER focus to get high spatial resolution

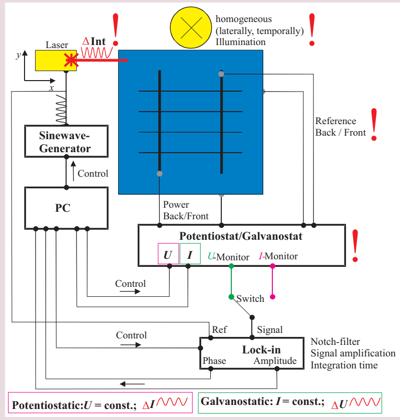

Fig. 4: The measurement system

High measurement speed is essential

- Several measurments are necessary to characterize individual defects
- High spatial resolution is necessary for inhomogeneous solar cells
- Many points must be measured several times

High reproducibility and long term stability

- Temperature stabilization
- Drift elimination for several parameters

EXAMPLES FOR PROCESS INDUCED DEFECTS

- 10cm x 10cm solar cell: Maps with a spatial resolution of 0.25 mm
- Two potentiostatic measurements: dI_{sc} at U=0V; dI_a at U= U_a (working point of solar cell)
- Two galvanostatic measurements: dU_{oc} at I=0A; dU_a at I= I_a (working point of solar cell)
- dI_{sc} -Map reflects diffusion length distribution $L(x,y)$ (equivalent to LBIC)
- Evaluation of data: F(sc, a) = (dI_{sc} / dI_a - 1) * 1000
  Current losses at working point due to imperfection of the diode and/or ohmic losses
- Many defects visible in the dU_{oc} -Map occur as well in the F(sc, a) - Map:
  → They refer mostly to an increased serial resistance
- Most of these defects are process induced (see examples 1-4)
- For all large solar cells an increased local serial resistance of the boundary is found by CELLO measurements

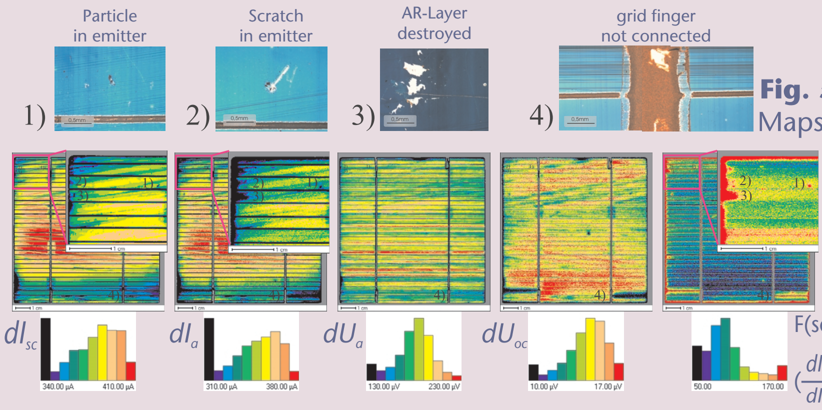

Fig. 5: CELLO-Maps and local defects

INCREASED LOCAL RECOMBINATION DUE TO INHOMOGENEOUS $L(x,y)$-DISTRIBUTION

- At several points (x,y) the Lock-in current signal $dI(U_n)$ is measurend for n = 50 different voltages along the IV-curve
- This measured data is fitted to the model refering to the equivalent circuit of Fig. 2.
- Independent of the number of fitting parameters no good results are obtained for the classical equivalent circuit (cf. Fig. 6)
- Taking into account an additional recombination according to Eq. (4) the fits become very good for all areas (cf. Fig. 6).

INTERPRETATION:

- The dI_{sc} current only measures diffusion and recombination properties for the boundary condition where all charges are collected at the pn-junction
- e.g. at the working point of the solar cell only a part ot the minority carriers is collected while another part builds up the photo potential
- Lateral diffusion is therefore enhanced:
  a) if the surrounding has a larger L then the illuminated point we find an decreased effective recombination
  b) if the surrounding has a smaller L than the illuminated point we find an increased effective recombination
- This information on the gradient of L is not included in dI_{sc} but described by the additional (necessary) parameter C_{Rek}
- **The mean diffusion length does not sufficiently characterize solar cells for which the lateral gradient in the diffusion length distribution $L(x,y)$ is important**

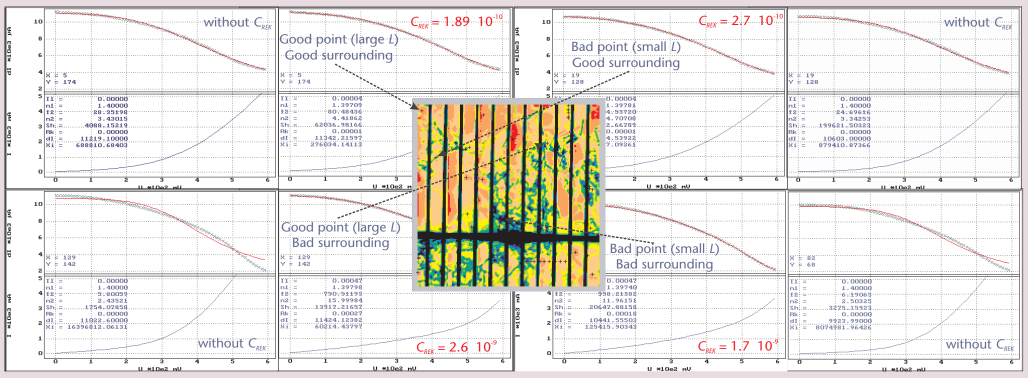

Fig. 6: Fitting of local IV-curves using CELLO $dI(U_n)$ - data

NON RECOMBINATION LOSSES IN A SOLAR CELL: SERIAL RESISTANCE VERSUS SHUNTS

- According to Eq. (3) local shunts and the serial resistance of the grid (which depends on the illuminated point) act as a local voltage divider
- For large forward bias the serial resistance is always dominant
- Under reversed bias we must distinguish between two cases:
  a) R_{ser} < R_{Sh}: By increasing the bias we increase the fraction of current which flows through the grid and thus dI reaches a saturation value
  b) R_{ser} > R_{Sh}: By increasing the bias we decrease the fraction of current which flows through the grid and thus dI decreases monotonically
- Since changes in the current are very small, we plot the function F(A,B)= (dI_A / dI_B - 1)*1000; A and B are indicees for measurements at different constant potentials along the IV-curve
- Defects related to such additional losses can be process and/or material induced
- Fig. 7 and Fig. 8 show two extremely different examples for such defects

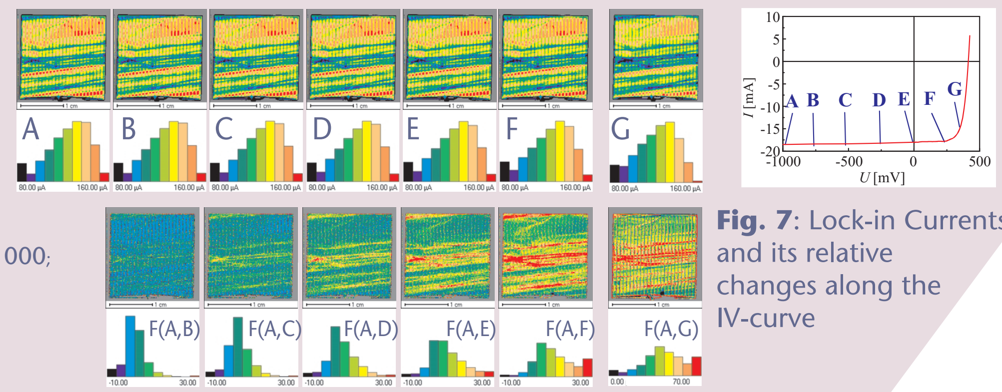

Fig. 7: Lock-in Currents and its relative changes along the IV-curve

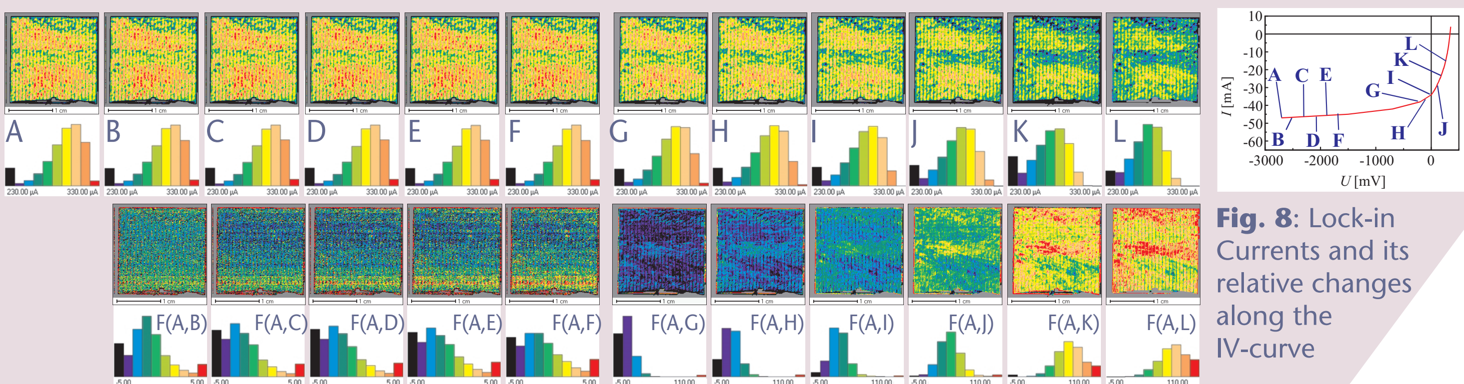

Fig. 8: Lock-in Currents and its relative changes along the IV-curve

DISCUSSION OF THE EXAMPLES

Solar Cell of Fig. 7

- dI_{sc} reaches a saturation current unter reversed bias
- Structures in the maps of relative changes correspond to the structure in the dI_{sc} maps
- For forward bias the regions of small diffusion length show strong additional losseses

Solar Cell of Fig. 8

- The lower part reaches a saturation current but not the upper part
- Structures in the maps of relative changes do not (!) correspond to e.g. grains, grain boundaries, but to the distance from the main grid finger at the lower side of the solar cell
- For forward bias the regions of small diffusion length show strong additional losseses

INTERPRETATION OF THE EXAMPLES

- Some structural defects show a strong recombination activity
- In addition the **same local defects** act as (probably recombining, not ohmic) shunts
- The serial resistance increases monotonically from the bottom to the top; a **homogeneous** density of shunts exists in the Si-material
- The shunts do not correlate with the recombination active defects

SUMMARY AND OUTLOOK

- The CELLO system allows to measure several parameters which are relevant for the solar cell efficiency with
  - high spatial resolution
  - good reproducibility
- It is not restricted to crystalline Si solar cells
- A large number of independent linear response measurements are available for each positon at the solar cell:
  - potentiostatic / galvanostatic
  - various constant potentials / current along the IV-curve
  - various local illumination intensities
  - whide range of Lock-in frequencies
- A quantitative model allows to fit all data in order to calculate the local IV-curve for each position (in the low frequency limit)
- This allows to identify and quantify all relevant defects for the solar cell efficiency (not only recombination in the bulk!)
- Including the higher frequency range into the evaluation of a solar cell would allow to analyse "gradients" in parameters which are quite important for the efficiency of solar cells
- Including this data into a complete simulation of a solar cell would allow to suggest optimal improvements for a solar cell with minimal effort