Lock-in Thermography - Special Investigation Techniques

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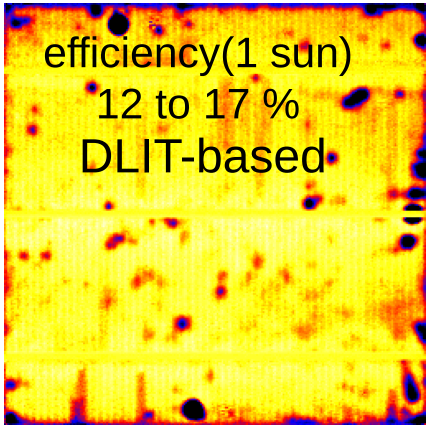
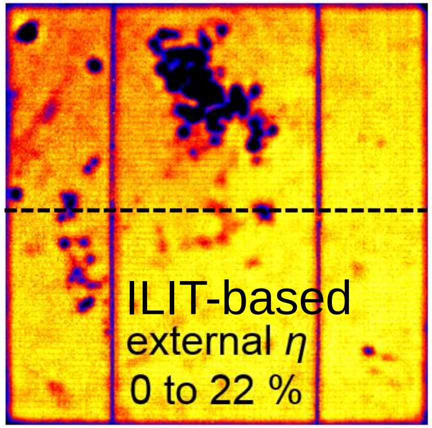
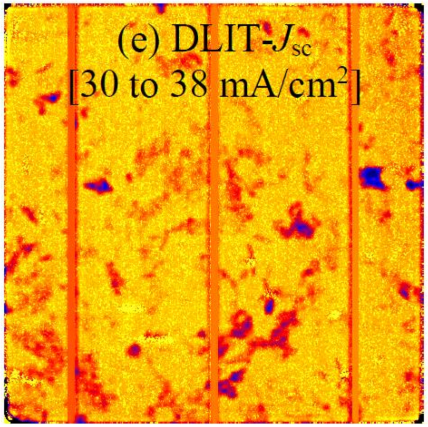
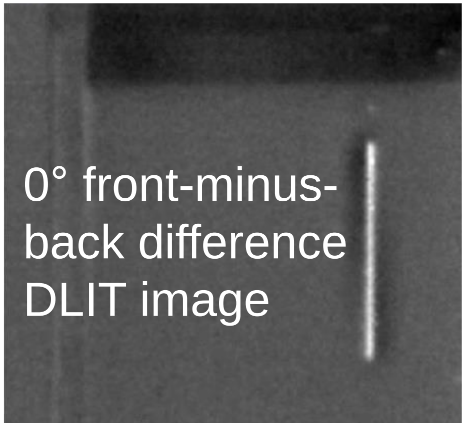
Outline

1. Introduction
2. The „Local I-V“ method
3. DLIT- versus ILIT-based local efficiency analysis
4. ILIT- and DLIT-based J_{sc} Imaging
5. A new DLIT method for depth-dependent investigations
6. Conclusions









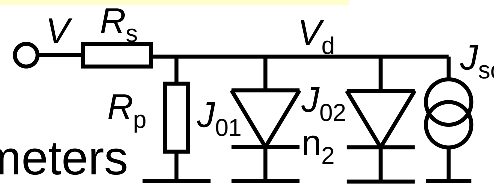
1. Introduction

- Dark lock-in thermography (DLIT) is the technique of choice for shunt imaging, but LIT can do much more on solar cells.
- DLIT results can easily be quantified in terms of local current densities, which is used in the „Local I-V“ method providing local efficiency analysis.
- The locally contributing efficiency in a cell can alternatively be imaged directly under realistic conditions by ILIT.
- The local short circuit current density J_{sc}, which is important for local efficiency analysis, can be imaged both by DLIT and ILIT.
- Recently a new method has been developed for distinguishing heat sources in different depths in a solar cell.
- In this talk all these special methods will be introduced.

2. The „Local I-V“ method

- Voltage-dependent DLIT signal evaluation (images for 3 forward biases + one reverse bias), each pixel is fitted to a local 2-diode model[1].

$$J(V) = J_{01}\left(\exp\frac{V - R_s J(V)}{n_1 V_T} - 1\right) + J_{02}\left(\exp\frac{V - R_s J(V)}{n_2 V_T} - 1\right) + \frac{V - R_s J(V)}{R_p} - J_{sc}$$



- This method is based on the model of independent diodes.
- Result of the ‘Local I-V’ procedure: images of local diode parameters J_{01}, J_{02}, n_2, and $G_p = 1/R_p$. n_1 is assumed to be homogeneous, but can be > 1.
- Local series resistance or local diode voltage must be known, e.g. from PL / EL analysis.
- After the local diode parameters are known, the software calculates images of the local cell parameters (V_{oc}, J_{sc}, FF, η, n_{eff}, $V_{oc;mpp}$, $V_d(V_{oc;mpp})$, $J_d(V_{oc;mpp})$ ...) [2].
- This software is commercially available[3].

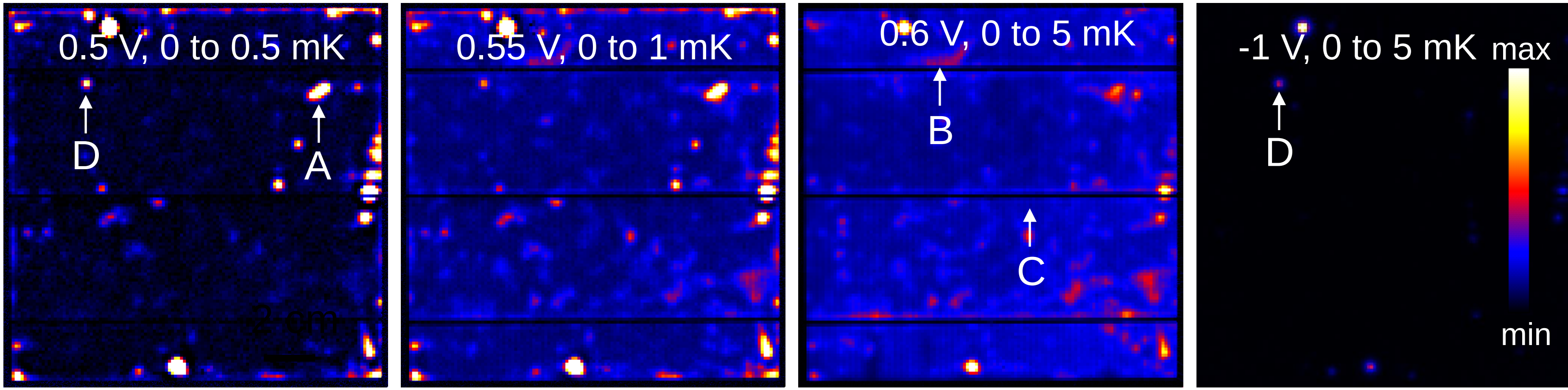
potential (expectation) values

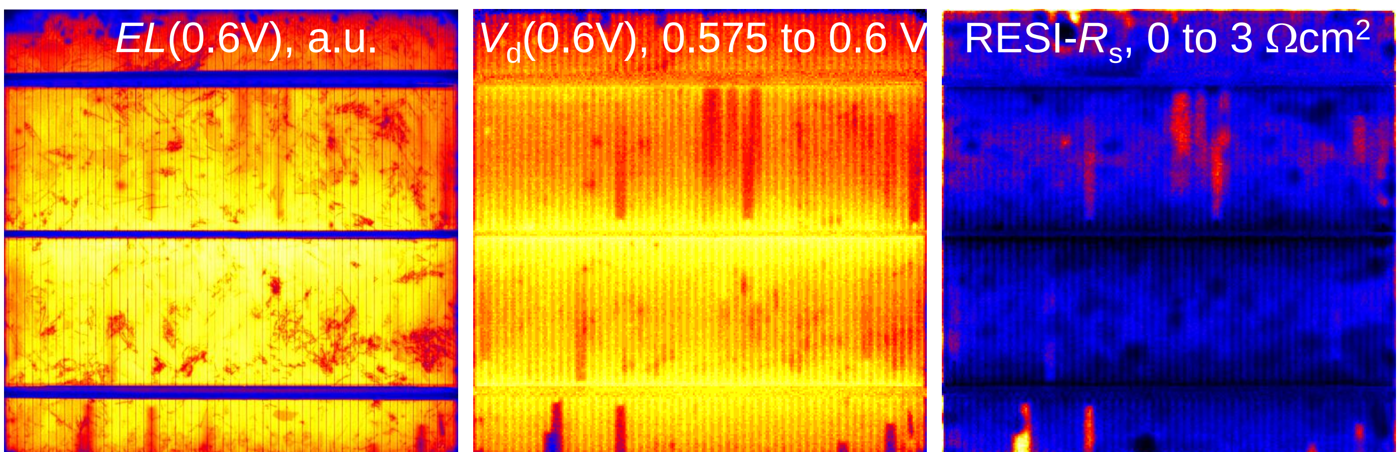
in-circuit values

[1]O. Breitenstein, Solar En. Mat. & Solar Cells 95 (2011) 2933
[2]O. Breitenstein, Solar En. Mat. & Solar Cells 107 (2012) 381
[3]www.maxplanckinnovation.com

2. The „Local I-V“ method

Input images



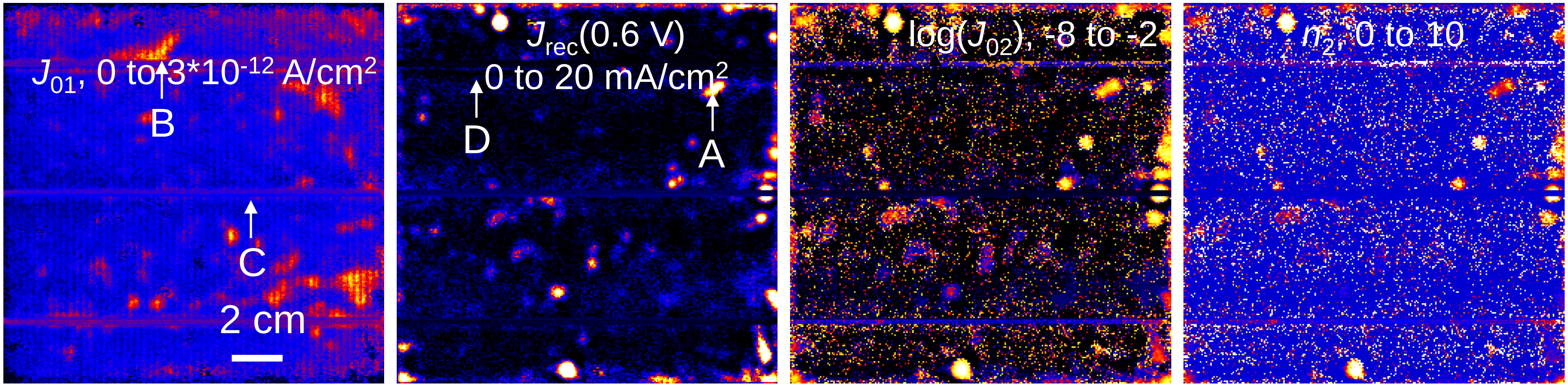


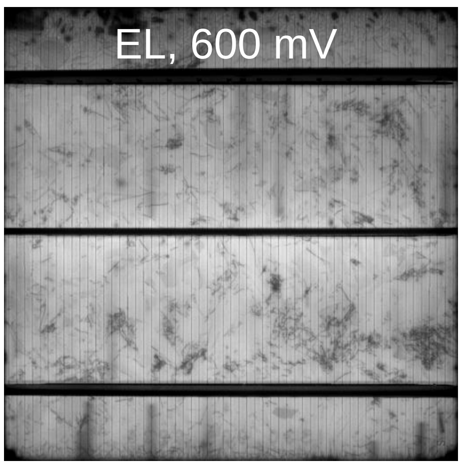
The dark spots in the RESI-R_s image[1] in defect positions are a natural result of the assumed model of indepen-dent diodes

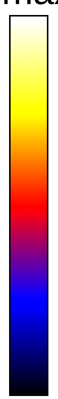
[1]K. Ramspeck et al., APL *90* (2007) 153502

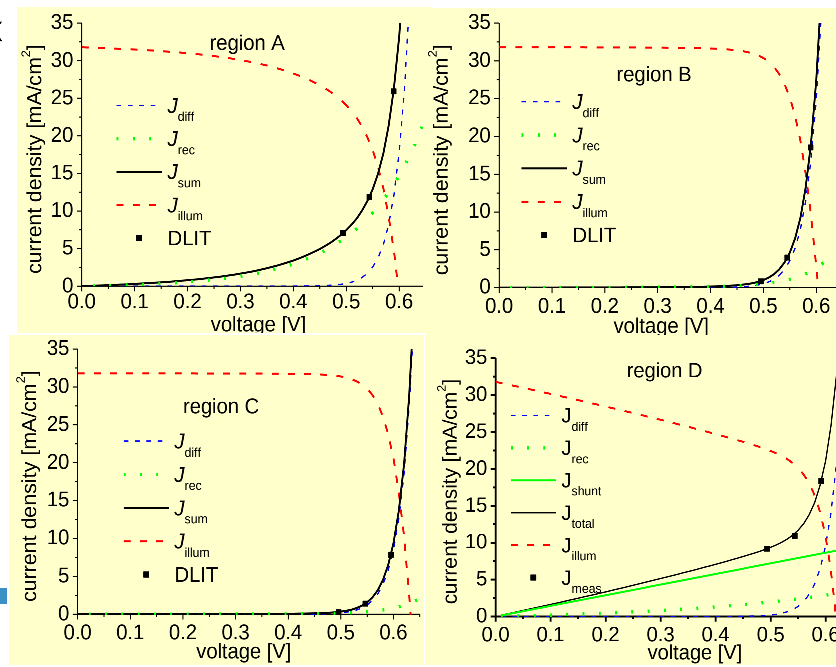
2. The „Local I-V“ method

Dark current data, local characteristics







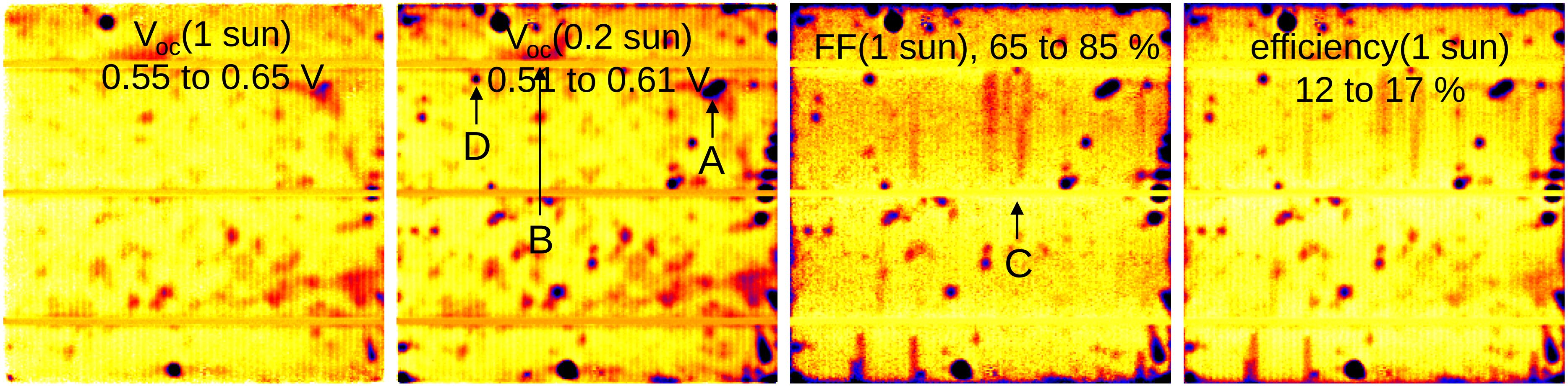


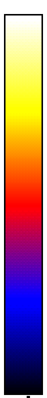
- Only J_{01} correlates with crystal defects (EL image), not J_{rec}

- A: J_{02}-shunt
- B: J_{01}-shunt
- C: good region
- D: ohmic shunt

2. The „Local I-V“ method

Local efficiency parameter potential data

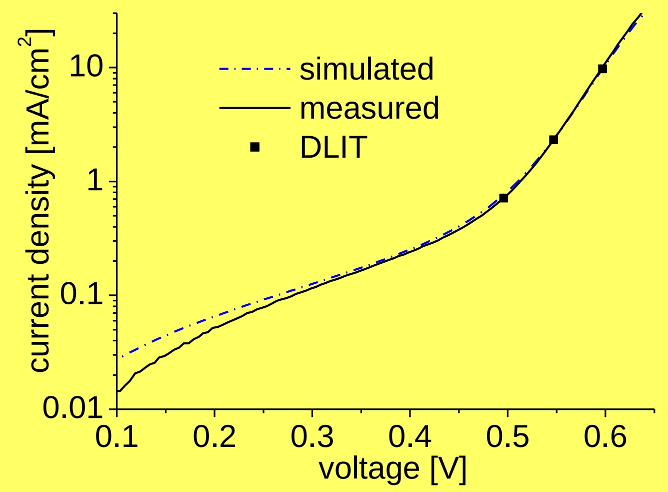




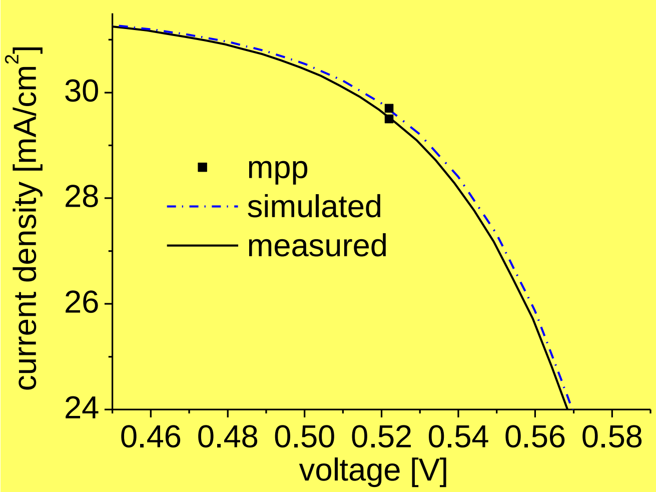
- Region A (J_{02} shunt): influences mostly *FF* und V_{oc}(0.2 suns)
- Region B (J_{01}-Shunt): influences mostly V_{oc}
- Region C (good region): best efficiency parameters
- Region D (ohmic shunt): influences mostly *FF* and V_{oc}(0.2 suns)
- R_s inhomogeneities: influence only *FF*

Global characteristics

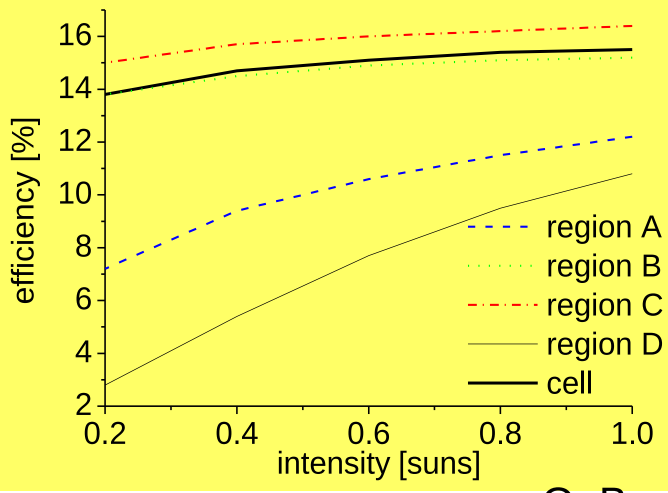
dark characteristic



illuminated characteristic



intensity-dependent efficiency



measured versus simulated global cell parameters

	Producer data	850 nm measured	simulated whole cell	simulated best region
J_{sc} [mA/cm²]	31.8	31.8	31.8	31.8
V_{oc} [mV]	625	624	625	632
FF [%]	76.5	77.6	78.0	81.6
η [%]	15.2	15.4	15.5	16.4

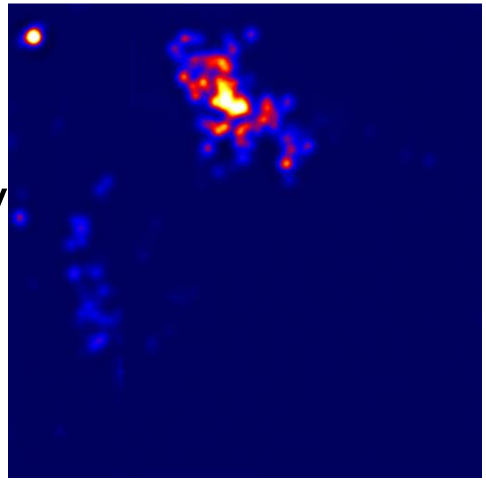
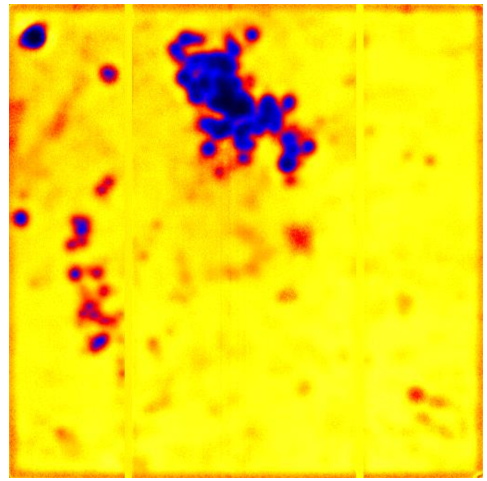
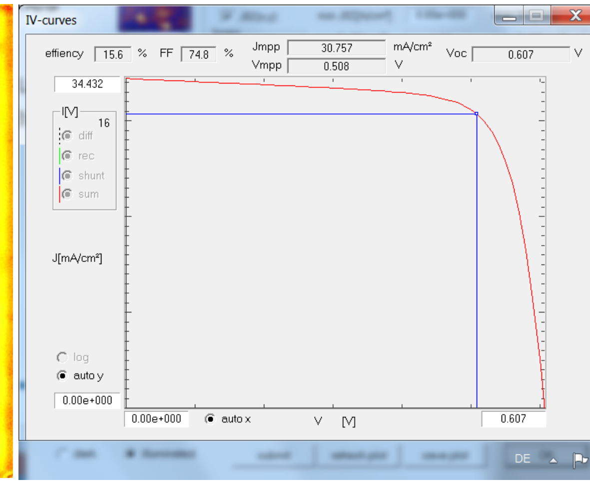
O. Breitenstein, Solar En. Mat. & Solar Cells **107** (2012) 381

2. The „Local I-V“ method

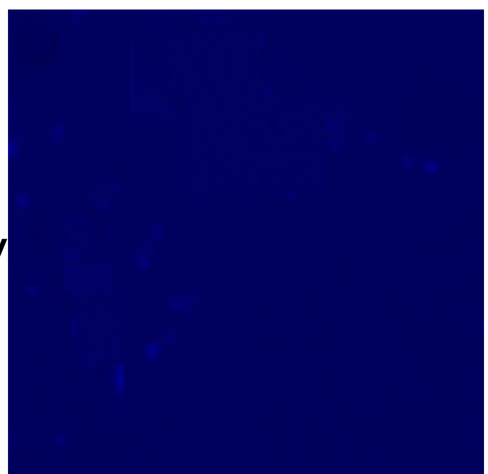
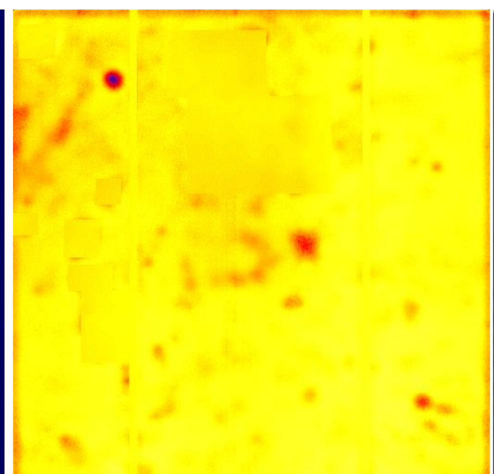
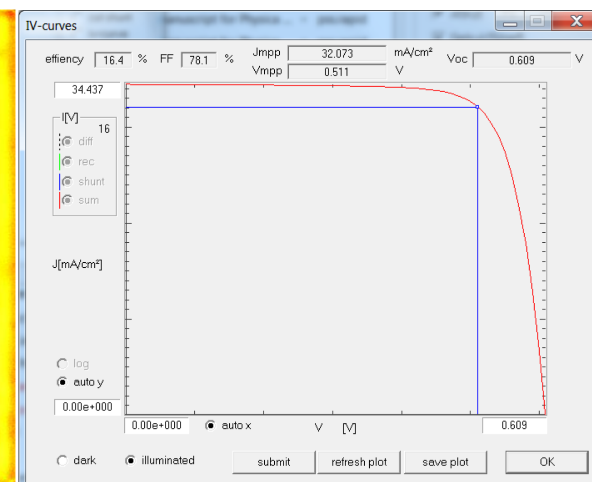
Demonstration of the „cut shunt“ option

T_{rev} (-5 ... 50 mK) efficiency pot. (0 ... 22 %) illuminated I-V (1 sun)

- Shunted cell (SiC)
- V_{oc}: 607mV
  FF: 74.8%
  η: 15.6%

- All strong ohmic shunts cut
- V_{oc}: 609mV
  FF: 78.1%
  η: 16.4%

2. The „Local I-V“ method

- This available DLIT evaluation method allows to perform a quantitative local efficiency analysis of solar cells.
- The obtained local efficiency parameter images allow to judge about the influence of different defect types on solar cell parameters.
- The possibility to evaluate selected regions (e.g. cell without edge, best region of a cell) gives quantitative information on the influence of certain regions on the efficiency (see talk: „The role of inhomogeneities ...“).
- The „cut shunt“ option allows to virtually cut out shunts and replace their properties by that of the surrounding. This allows to measure the influence of single shunts or other defect regions on the efficiency.
- The „Local I-V 2“ software is used already in various PV labs (Fraunhofer ISE, Fraunhofer CSP, SolarWorld, Hanwha Q-Cells, NREL, RWTH Aachen), UNSW is still missing ;-).

3. DLIT- versus ILIT-based local efficiency analysis

- In „Local I-V“, the operation of a solar cell is simulated, based on dark current measurements and the two-diode model (superposition principle).
- Already in 2008 K. Ramspeck et al.[1] (ISFH) have proposed an illuminated lock-in thermography (ILIT-) based method for imaging the locally contributing (in-circuit) efficiency.
- This measurement is performed under realistic illuminated mpp condition and does not assume any solar cell model.
- This method was originally restricted to measuring the internal (reflection-corrected, irradiation intensity-independent) monochromatic efficiency.
- We have extended this method to measuring also external and AM 1.5 efficiencies.[2]

[1] K. Ramspeck et al., J. Mater. Sci: Mater. Electron. **19** (2008) S4-S8
[2] F. Frühauf and O. Breitenstein, SOLMAT **169** (2017) 195-202

3. DLIT- versus ILIT-based local efficiency analysis

Efficiency potential versus in-circuit efficiency

- It is assumed that each pixel is electrically isolated from its surrounding and works at its individual (local) mpp.
- This definition needs a solar cell model (e.g. one- or two-diode).
- The local efficiency potential is always positive.
- The efficiency potential parameters (V_{oc}, FF, η) in position (x,y) mean that an extended cell showing the parameters of position (x,y) would have these parameters.

- It describes the locally contributing efficiency, if the cell is at its V_{mpp}^{cell}.

$$\eta_{ic}(x,y) = \frac{J(x,y)V_{mpp}^{cell}}{p_{ill}} \qquad V_{oc,ic} = V_d(V_{oc}^{cell})$$

- The in-circuit $V_{oc,ic}$ is the local diode voltage, if the cell is at its V_{oc}^{cell}.
- In inhomogeneous cells, local variations of the V_{oc}-potential are always larger than that of $V_{oc,ic}$
- These in-circuit definitions needs no cell model.
- The in-circuit efficiency may become negative in shunt positions

3. DLIT- versus ILIT-based local efficiency analysis

- Basic ideas of the Ramspeck ILIT method: At J_{sc} condition the complete locally irradiated power is internally converted into heat (DLIT(J_{sc}) ~ p_{ill}).
- At mpp some fraction of the irradiated power is converted into electric energy, the local heating becomes correspondingly lower.

$$p_{\mathrm{el}} = C[ILIT(J_{\mathrm{sc}}) - ILIT(\mathrm{mpp})] \qquad \eta_{\mathrm{ic,ext}} = \frac{\mathrm{p_{el}}}{p_{\mathrm{rad}}}$$

- One can get rid of the proportionality factor C by defining the internal (in-circuit) efficiency:[1]

$$p_{\mathrm{abs}} = C < ILIT_{\mathrm{sc}} > \qquad \eta_{ic,\mathrm{int}} = \frac{C[ILIT(J_{\mathrm{sc}}) - ILIT(\mathrm{mpp})]}{p_{\mathrm{abs}}} = \frac{ILIT(J_{\mathrm{sc}}) - ILIT(\mathrm{mpp})}{ILIT(J_{\mathrm{sc}})}$$

- This magnitude refers to the irradiated wavelength (monochromatic efficiency) and is independent of the irradiation intensity.

[1] K. Ramspeck et al., J. Mater. Sci: Mater. Electron. **19** (2008) S4-S8

3. DLIT- versus ILIT-based local efficiency analysis

- We have proposed to measure *C* by DLIT:[1]

$$C = \frac{I\,V^{\mathrm{dark}}}{A < DLIT(V) >}$$

$$\eta_{ic,ext} = \frac{C\left(ILIT_{\mathrm{sc}} - ILIT_{\mathrm{mpp}}\right)}{p_{\mathrm{ill}}}$$

- Here for p_{ill} the 100 mW/cm^2 (valid for AM 1.5) can be inserted.
- The illuminated power density p_{ill} is:[1]

$$p_{\mathrm{ill}} = \frac{p_{abs}}{1-R} = \frac{C < ILIT_{\mathrm{sc}} >}{1-R}$$

- Regarding the „monochromatic-to-AM1.5“ factor, the internal AM1.5 efficiency for arbitrary illumination intensity (*suns*) at AM1.5 is:[1]

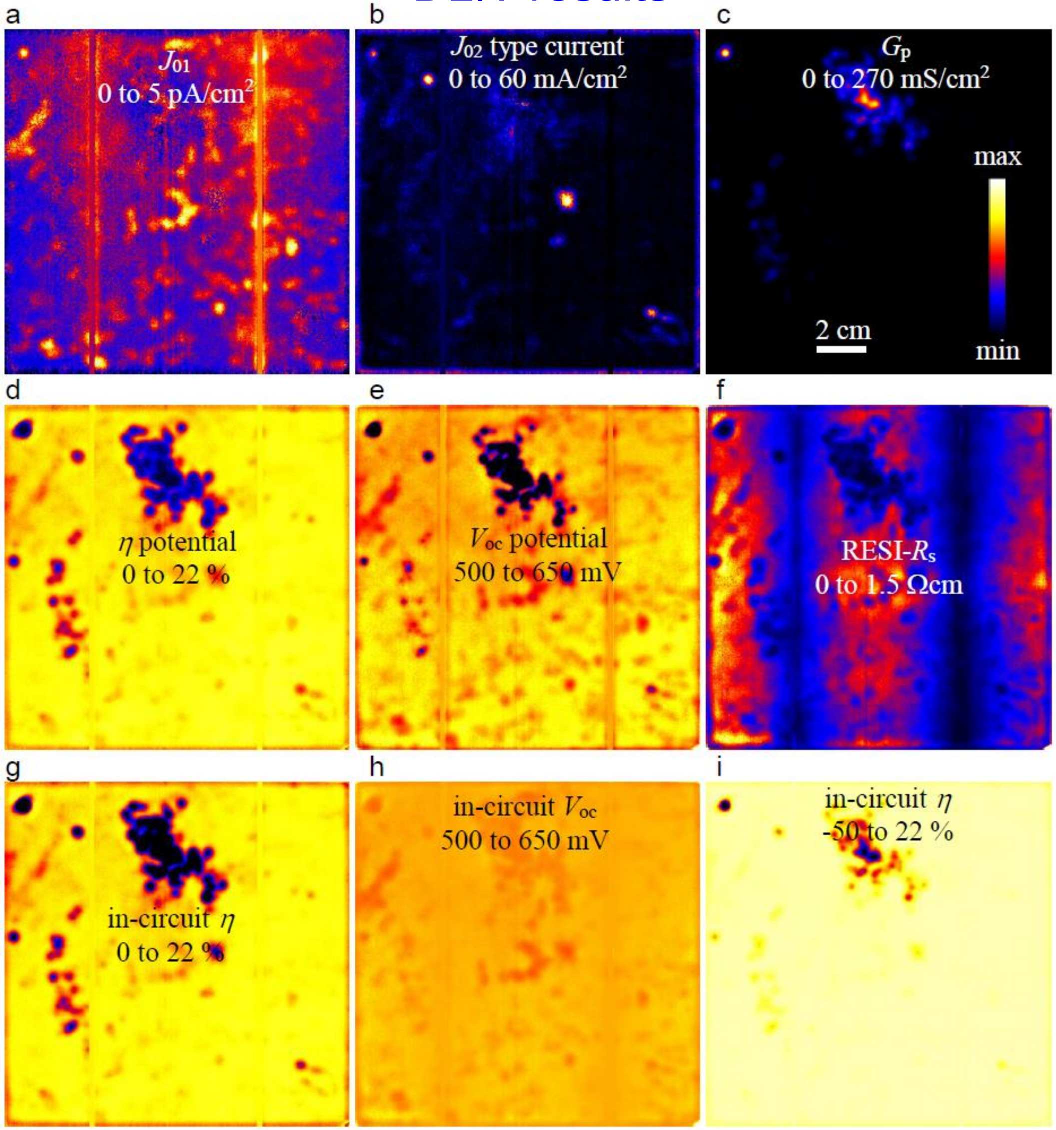
$$\eta_{ic,int}^{AM1.5} = \frac{p_{ill}\left(ILIT_{sc} - ILIT_{mpp}\right)}{100\,\frac{mW}{cm^2}\,suns\;ILIT_{sc}} = \frac{C < ILIT_{sc} > \left(ILIT_{sc} - ILIT_{mpp}\right)}{100\,\frac{mW}{cm^2}\,suns(1-R)ILIT_{sc}}$$

[1]F. Frühauf, O. Breitenstein, SOLMAT **169** (2017) 195-202

3. DLIT- versus ILIT-based local efficiency analysis

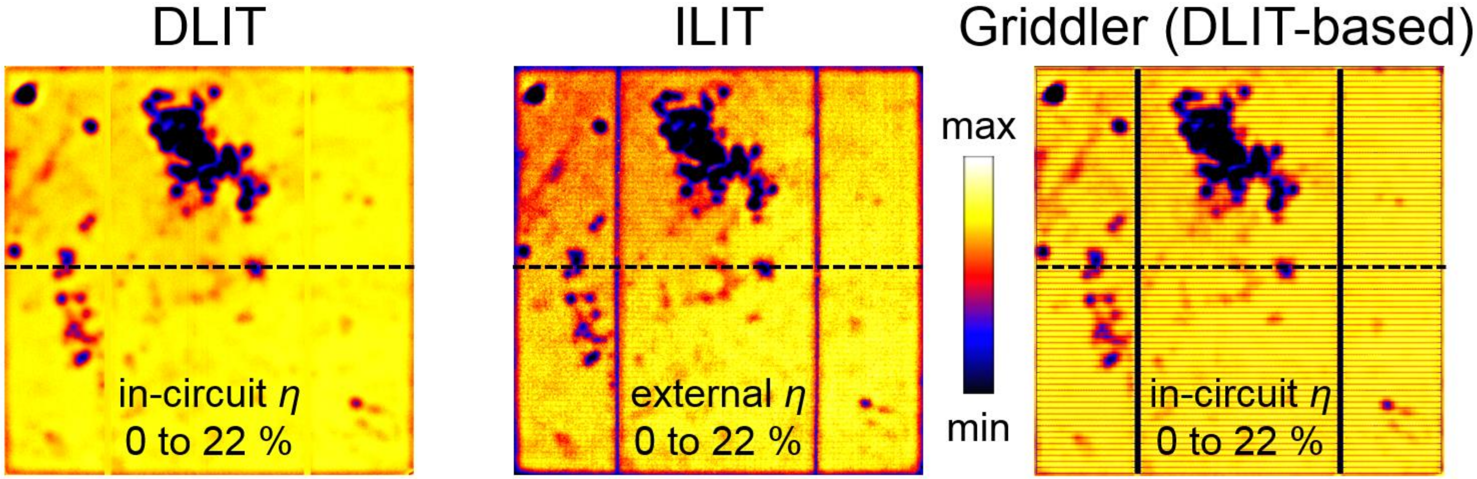
- Example: shunted mc cell (SiC filaments).
- η potential and in-circuit η do only differ in shunt regions (there η_{ic} becomes negative).
- V_{oc} potential and in-circuit V_{oc} differ substantially, as expected.
- Reason: horizontal balancing currents.

DLIT results

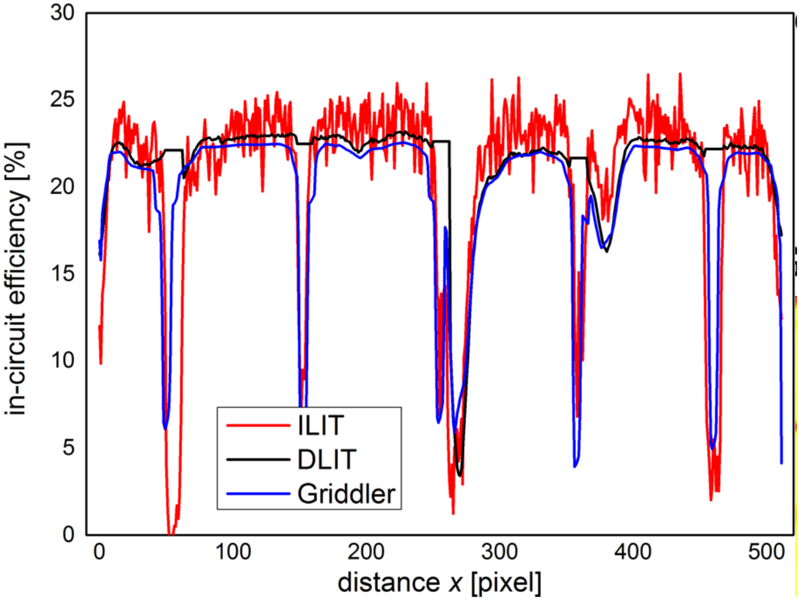


3. DLIT- versus ILIT-based local efficiency analysis

in-circuit external efficiencies



- ILIT only images in-circuit efficiency, it cannot predict V_{oc} or FF
- DLIT (Local I-V) and DLIT-based Griddler analysis agree well (there is no significant influence of the R_s model).
- ILIT leads to similar efficiency results as DLIT, but SNR is clearly worse.
- There are weak residual differences to DLIT-η_{ic}, their origin is still unclear.



F. Frühauf, O. Breitenstein, SOLMAT **169** (2017) 195-202

4. ILIT- and DLIT-based J_{sc} Imaging

- J_{sc} is one of the dominant local solar cell parameters, it can be imaged by LBIC.
- LBIC is available only monochromatically, AM 1.5 results needs several wavelengths, this is not always available (e.g. LOANA, PV-Tools).
- The average J_{sc} is available from flasher I_{sc}. If no LBIC is available, inhomogeneities of J_{sc} can be obtained by by LIT-based J_{sc} imaging.

- ILIT-based J_{sc} imaging[1] and DLIT-based J_{sc} imaging[2] have been developed.

[1]F. Fertig et al., APL **104** (2014) 201111

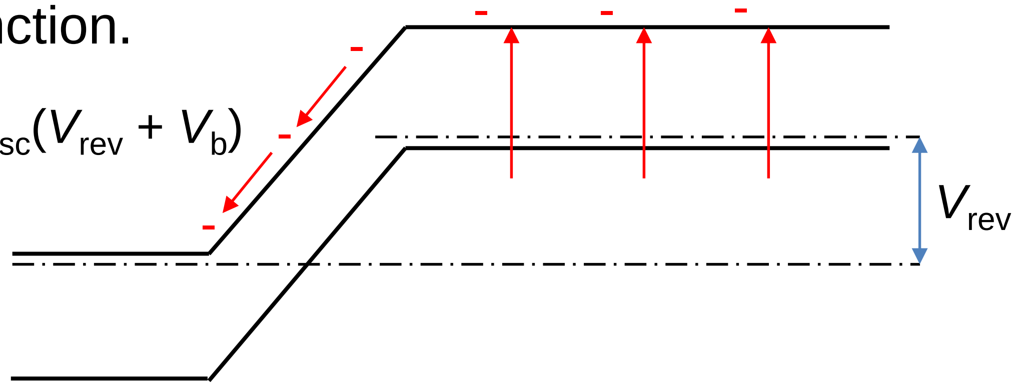
[2]O. Breitenstein et al., SOLMAT **143** (2015) 406 and **154** (2016) 99.

4. ILIT- and DLIT-based J_{sc} Imaging

ILIT-based J_{sc} imaging

- It is based on the reverse bias-dependent thermalization heat of the photocurrent across the pn-junction.

heat generation ~ $J_{sc}(V_{rev} + V_b)$



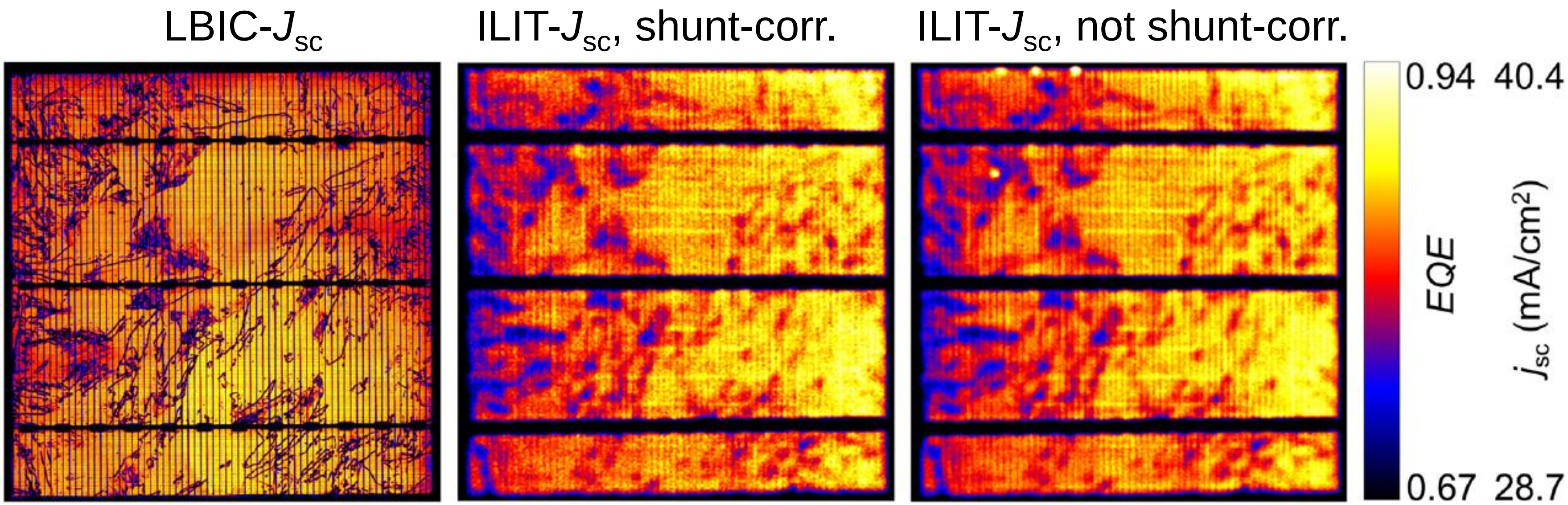
- Continuous illumination, bias pulsed between 0 and -1 V. ILIT signal is proportional to J_{sc}.
- Local emissivity correction should be used.
- If there are ohmic shunts, a corresponding DLIT signal taken under the same biasing conditions has to be subtracted.
- The absolute scaling in mA/cm^2 occurs by fitting the result to the flasher I_{sc} data.

[1]F. Fertig et al., APL **104** (2014) 201111

4. ILIT- and DLIT-based J_{sc} Imaging

ILIT-based J_{sc} imaging

- Typical results:[1]



- The bright lines are traces of the grooves below the cell used for sucking-on the cell. They can be avoided by placing a thin woven metal net below the cell.

[1]F. Fertig et al., APL **104** (2014) 201111

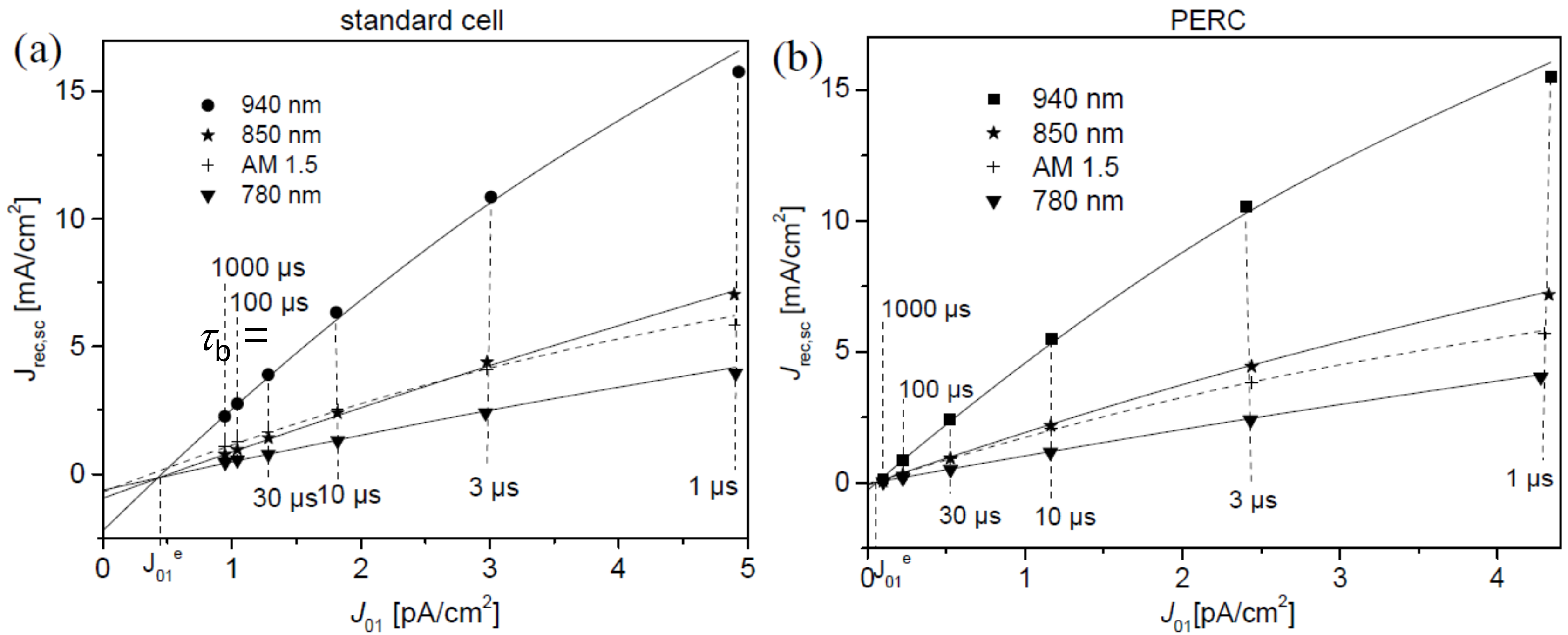
DLIT-based J_{sc} imaging

- This method is based on the fact that J_{01} is a measure of the bulk recombination probability. The generated current density is homogeneous.
- This also holds for J_{sc} condition. Therefore J_{01} also influences J_{sc}.[1]

$$J_{sc} = J_{gen} - J_{rec,sc}$$

J_{gen} = homogeneous

PC1D simulations:



[1]O. Breitenstein et al., SOLMAT **143** (2015) 406.

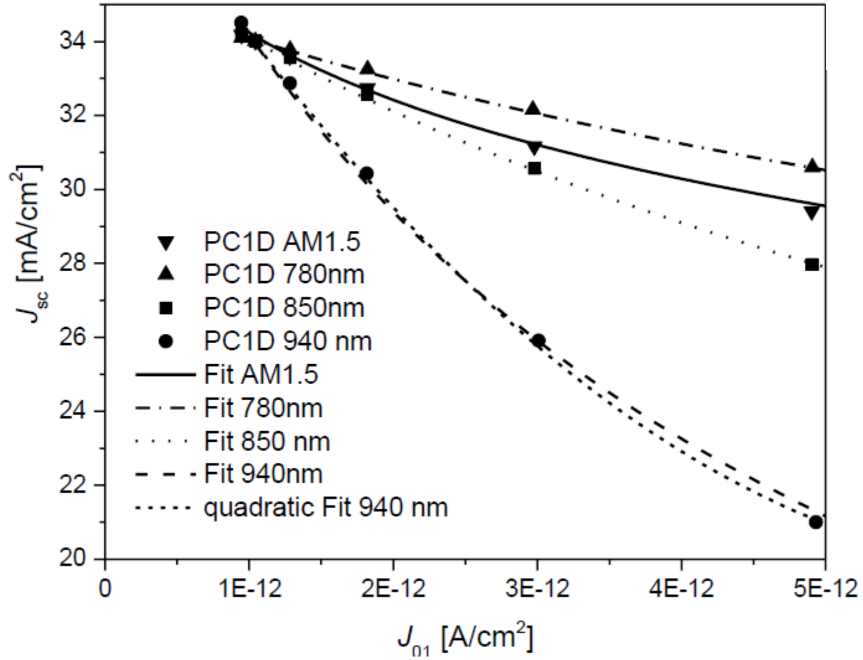
DLIT-based J_{sc} imaging

- The following empirical formula for $J_{rec,sc}$ has been found:

$$J_{rec,sc} = \frac{A\,J_{01}}{\left[1 + \frac{A\,J_{01}}{B}\right]}$$

- Regarding the measured mean value $<J_{sc}>$, this leads to:

$$J_{sc} = <J_{sc}> - \frac{A\,J_{01}}{\left[1 + \frac{A\,J_{01}}{B}\right]} + \sum_i \frac{A\,J_{01}}{N\left[1 + \frac{A\,J_{01}}{B}\right]}$$



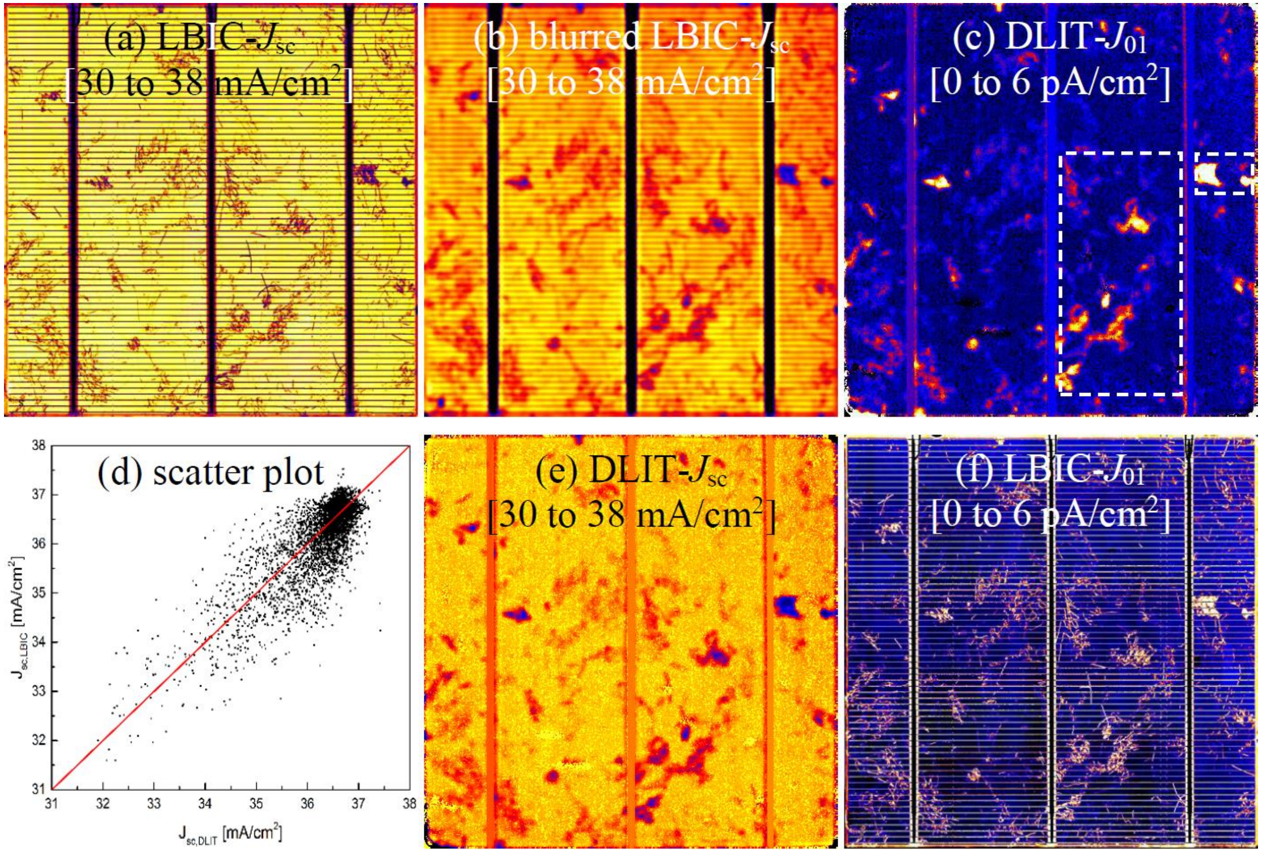
[1]O. Breitenstein et al., SOLMAT **154** (2016) 99.

4. ILIT- and DLIT-based J_{sc} Imaging

DLIT-based J_{sc} imaging

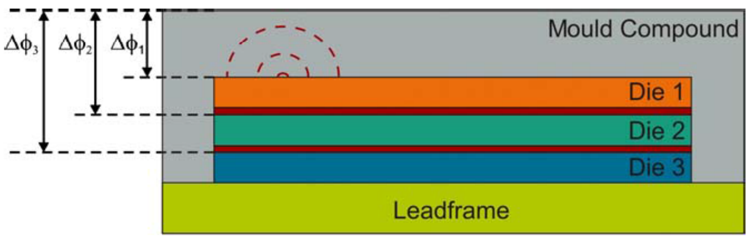
- The parameters *A* and *B* must be fitted to LBIC results.
- We have found for BSF-type cells $A = 10^9$ and $B = 0.01$ A/cm^2

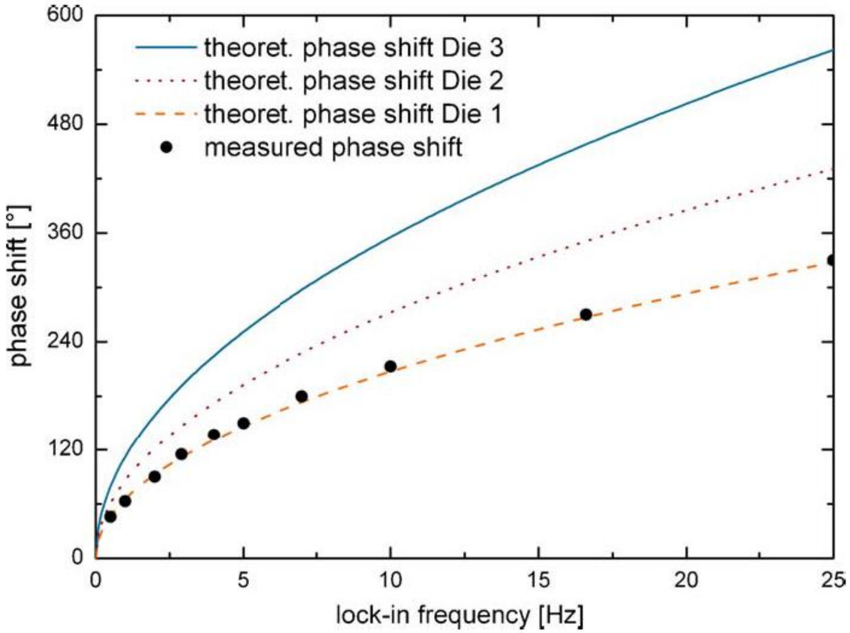
- This method for estimating J_{sc} from J_{01} inhomogeneities is now included in the „Local I-V 2“ software.
- It can inversely be used to image J_{01} from one LBIC image, if the parameters *A* and *B* are known.



5. A new DLIT method for depth-dependent investigations

- Until now DLIT results of Si solar cells have been evaluated only 2-dimensionally.
- Reason: Si cell is „thermally thin“ (d = 180 µm, thermal diffusion length Λ = 1.7 mm).
- In non-destructive testing (NDT) and in IC failure analysis the depth of a fault is estimated by the phase of the LIT signal.[1]



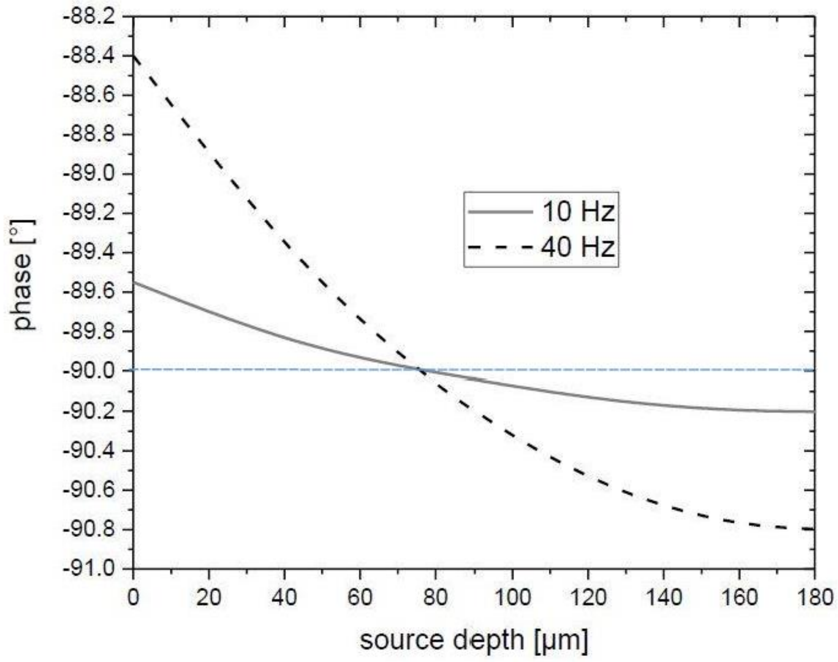


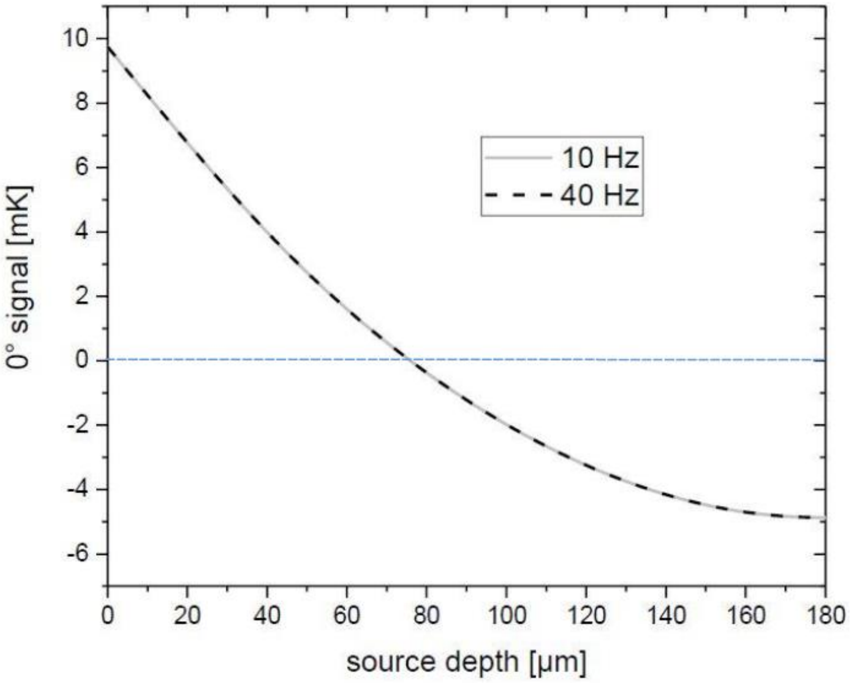
- Here different thin wafers („dies“) are glued together. Therefore the phase shift is much larger than within a compact sheet of Si.

[1]Ch. Schmidt et al., Mat. Sci. Engng B **177** (2012) 1261.

5. A new DLIT method for depth-dependent investigations

- DECONV software (available[1]) simulated phase and 0° signals for a homogeneous heat source in different depths in a 200 µm thick Si wafer:[2]





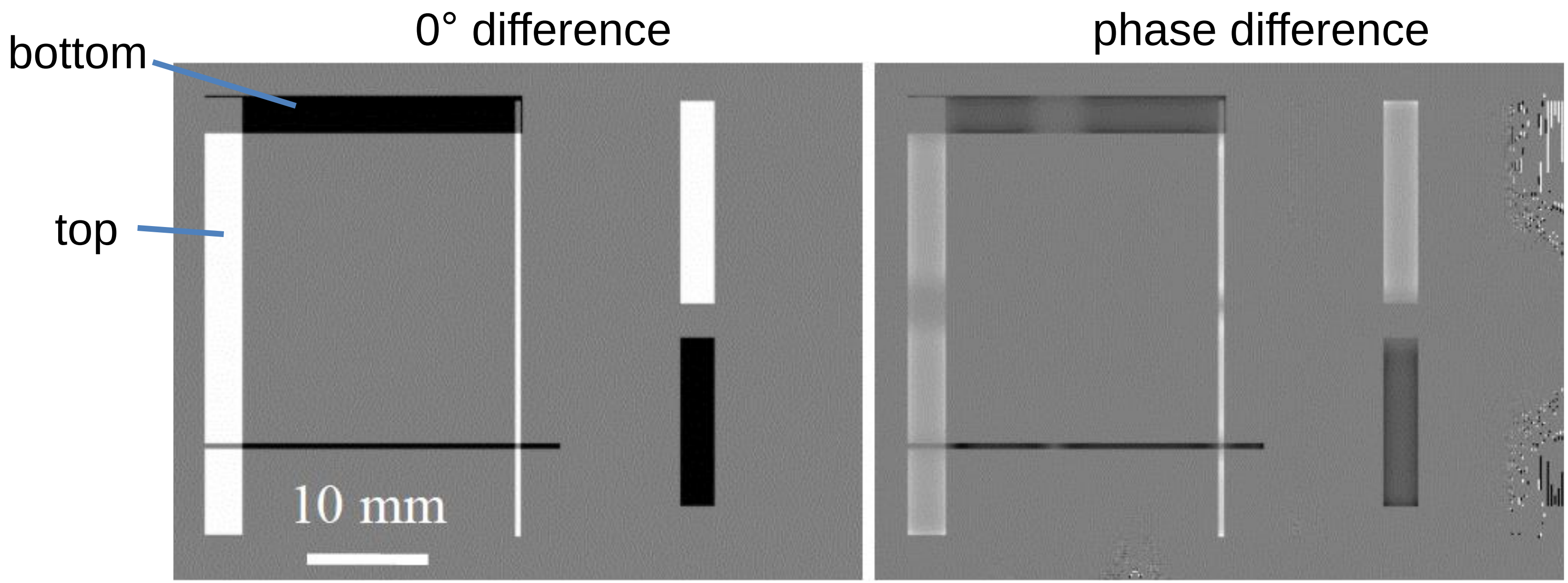
- Both signals depend only little of the depth position, the natural variation of both signals due to an inhomogeneous power source distribution is much higher

[1]See www.maxplanckinnovation.de

[2]O. Breitenstein , SOLMAT (2018) in print

5. A new DLIT method for depth-dependent investigations

- However, the front-minus-back difference between signals measured at the top and at the bottom of the cell could be useful (both sides black painted).
- Simulation for an inhomogeneous heat source distribution in a 180 µm thick Si wafer in different depths (top and bottom):[1]

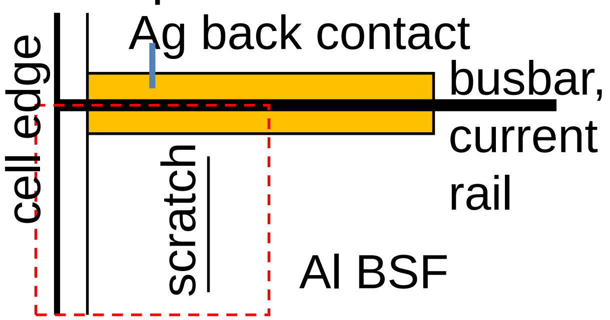


- Interestingly, these difference images are not blurred, though the input images are.

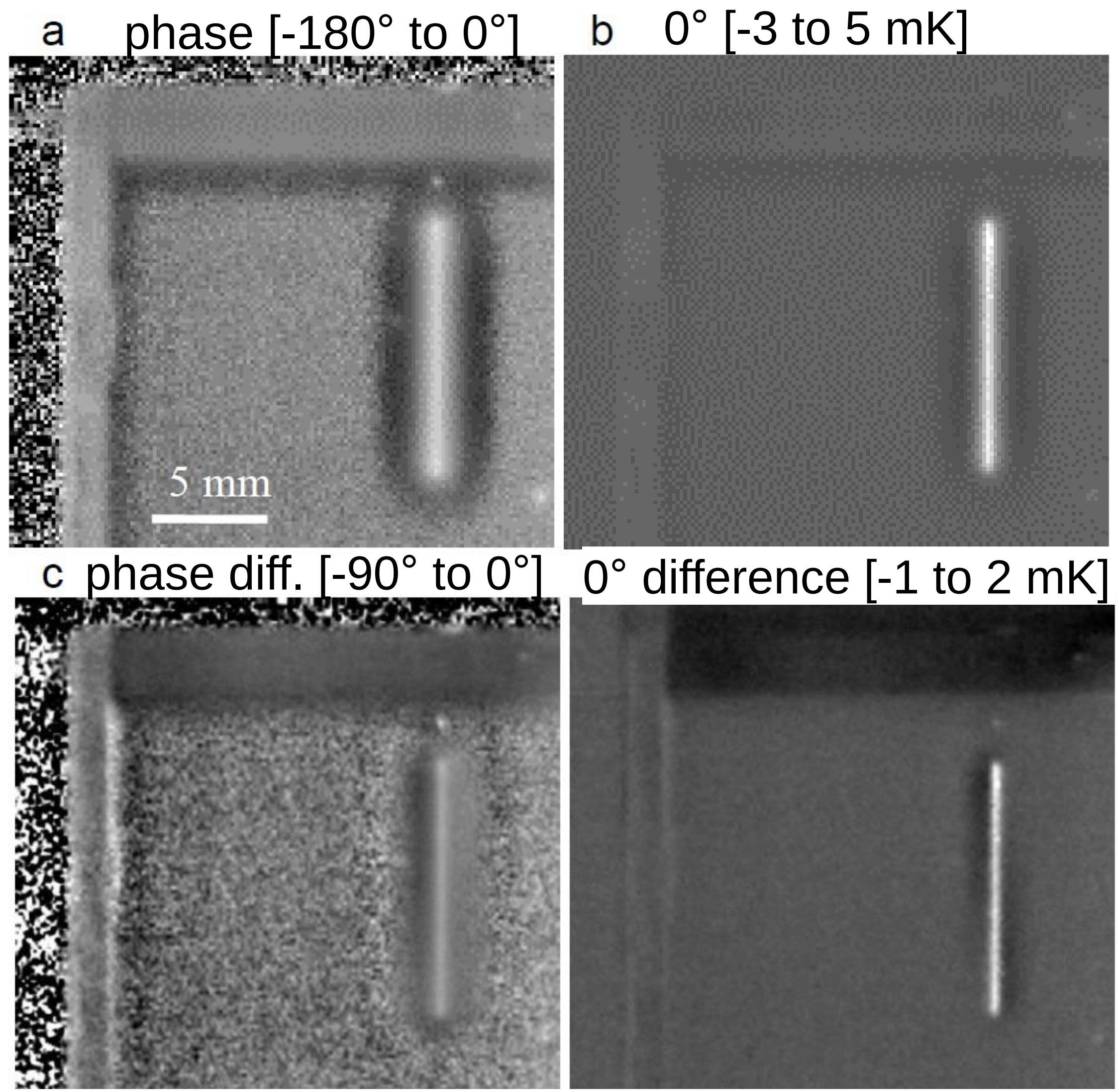
[1]O. Breitenstein , SOLMAT (2018) in print

5. A new DLIT method for depth-dependent investigations

- First experimental results:[1]



- Ag back contact and non-metallized stripe at the edge are heat sources at the back.
- A scratch at the emitter is a heat source at the top.
- Indeed, the Ag back contact appears dark both in the phase and in the 0° difference image, and there is little blurring.



5. Further LIT options

- Ideality factor mapping (contained in “Local I-V”) [1]
- Efficiency imaging by illuminated LIT (ILIT) [2]
- Imaging of breakdown parameters (*I-V* slope, *I-V* TC, avalanche multiplication factor) [3]
- Imaging of breakdown voltages [4]
- J_{sc} mapping by ILIT and DLIT (contained in “Local I-V”) [5,6]
- Imaging of Peltier effects, measurement of Peltier coefficients [7]
- CDI/ILM lifetime mapping on wafers by ILIT [8,9]

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6. Conclusions

- Lock-in thermography is more than qualitative shunt imaging.
- By using the „Local I-V“ method, DLIT images can be evaluated quantitatively, leading to a realistic local modelling of inhomogeneous solar cells. The influence of local defects on the efficiency can be evaluated and quantified.
- The results may be cross-checked by ILIT-based efficiency imaging, which needs no cell model.
- Also J_{sc} can be imaged quantitatively by DLIT or ILIT, if I_{sc} is known.
- There is a proposal to perform depth-dependent DLIT investigations, hence to judge whether a heat source is at the top or at the bottom of the cell. This method still has to be improved.
- There are many further LIT options, some more will become invented.

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