Luminescence Imaging of Solar cells - New Developments

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Outline

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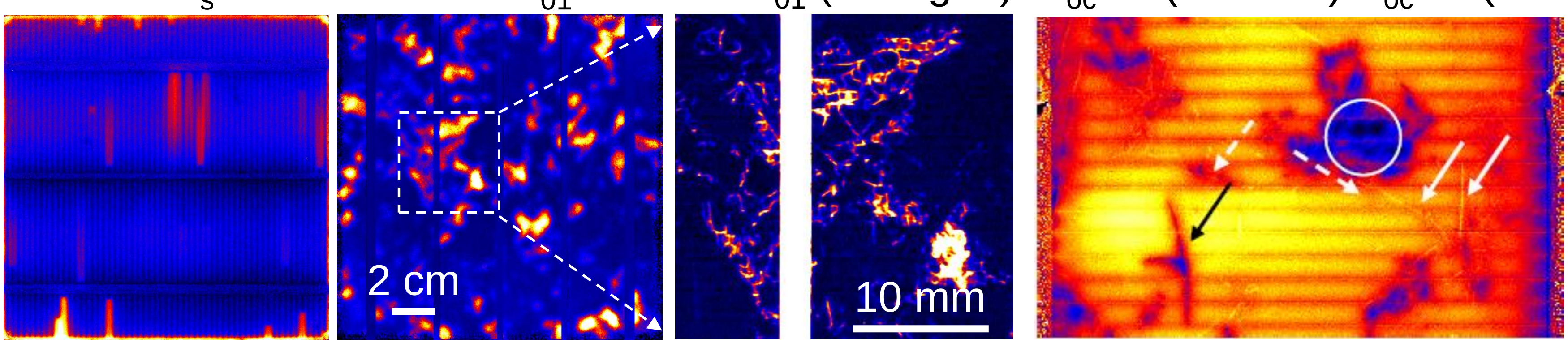
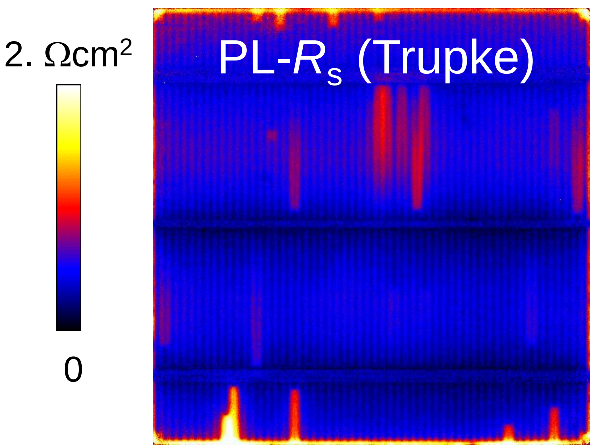
2. Why conventional PL-J_{01} imaging is wrong
3. Correct imaging of the calibration constant
4. Easy correction of photon scattering
5. New PL methods for imaging J_{01}
6. Conclusions



1. Introduction

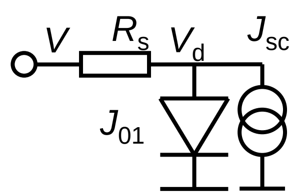
μΦ

- Camera-based (Si detector) luminescence imaging (EL + PL) is used for solar cell investigation since 2005[1,2]
- Starting from 2009, the evaluation was extended to imaging of J_{01}[3-6]
- In 2015 we have shown that this PL-based J_{01} is not correct, since it does not consider the distributed nature of R_s and the action of horizontal balancing currents[7]



$$\Phi = C_i(L_{\mathrm{eff}})\exp\frac{V_d}{V_T} \qquad V_d = V_T \ln\left(\frac{\Phi}{C_i}\right) = V_T\left(\ln(\Phi) - \ln(C_i)\right)$$

Model of independent diodes (Trupke 2007)



$$V_d = V - R_s\left(J_{01}\exp\frac{V_d}{V_T} - J_{sc}\right)$$

[1]T. Fuyuki et al., APL **86** (2005) 262108
[2]T. Trupke et al., APL **90** (2007) 093506
[3]M. Glatthaar et al. JAP **105** (2009) 113110
[4]M. Glatthaar et al., PSS RRL **4** (2010) 13
[5]M. Glatthaar et al. JAP **108** (2010) 014501
[6]Chao Shen et al., SOLMAT **109** (2013) 77
[7]O. Breitenstein et al., SOLMAT **137** (2015) 50

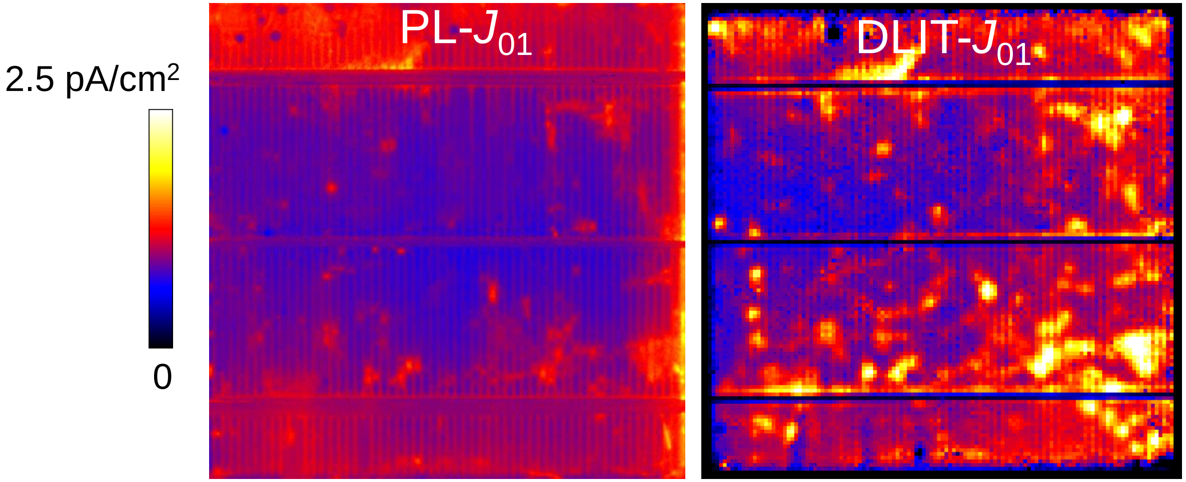
1. Introduction

- In 2015 we have found that the usual way for imaging C_i (V_{oc}-PL at 0.1 suns) leads to residual errors in mc cells, an improved method based on linear response principle was proposed.[1]
- In 2016 a new method for measuring the PSF for correcting photon scattering in the detector was proposed[2], enabling accurate Laplacian-based J_{01} imaging.[3]
- Also in 2016 the „nonlinear Fuyuki“ method was proposed as another alternative PL-based J_{01} imaging method.[4]
- In 2018 it was shown that the luminescence ideality factor may be smaller than unity[5], and a luminescence-based method to fit a Griddler model to an existing solar cell was proposed.[6]
- This lecture reports about these new developments.

[1] O. Breitenstein et al., SOLMAT **142** (2015) 92
[2] O. Breitenstein et al., J-PV **6** (2016) 522
[3] F. Frühauf et al., SOLMAT **146** (2016) 87
[4] O. Breitenstein et al., J-PV **6** (2016) 1243
[5] F. Frühauf et al., SOLMAT **180** (2018) 130
[6] F. Frühauf et al., submitted to SOLMAT

2. Why conventional PL-J_{01} imaging is wrong

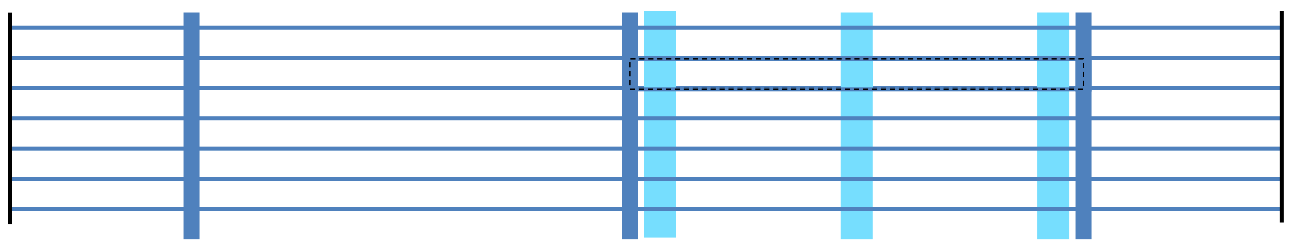
- It has been found regularly that PL-measured J_{01} images do not agree with DLIT-measured J_{01} images[1]
- Chao Shen[2] has proposed to use n_1 as a global fitting parameter for obtaining a better agreement between PL- and DLIT-J_{01}. However, in our simulations we could not confirm this improvement.



1. O. Breitenstein et al., J-PV **1** (2011) 159
2. Chao Shen et al., SOLMAT **123** (2014) 41

2. Why conventional PL-J_{01} imaging is wrong

- Which of the two results (PL- or DLIT-J_{01}) is correct?
- For answering this question, 2D finite element (SPICE) simulations of a symmetry element of an inhomogeneous solar cell have been performed[1]

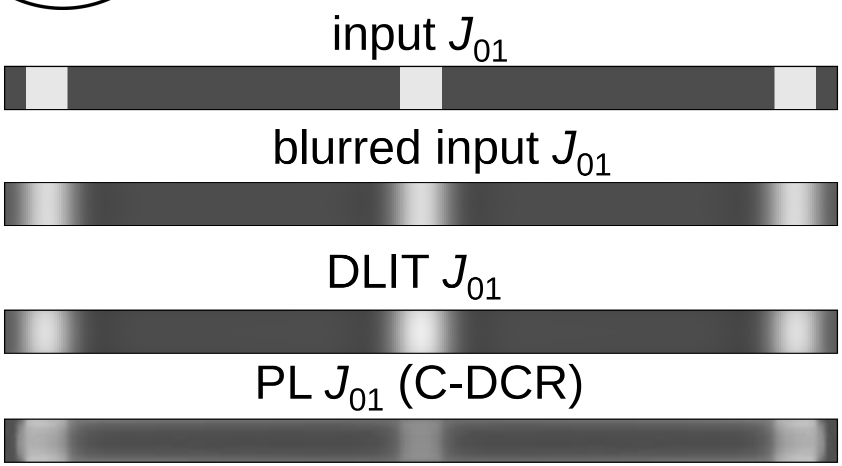


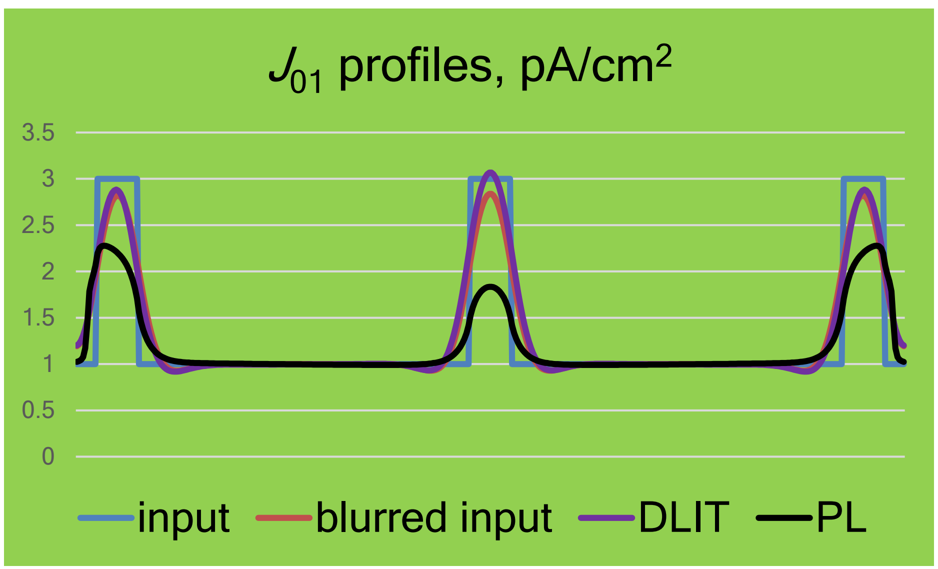
1 pA/cm^2 1 pA/cm^2

3 pA/cm^2 3 pA/cm^2 3 pA/cm^2

O. Breitenstein et al., SOLMAT **137** (2015) 50

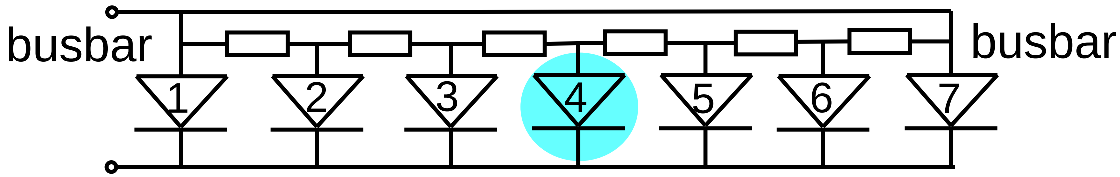
2. Why conventional PL-J_{01} imaging is wrong

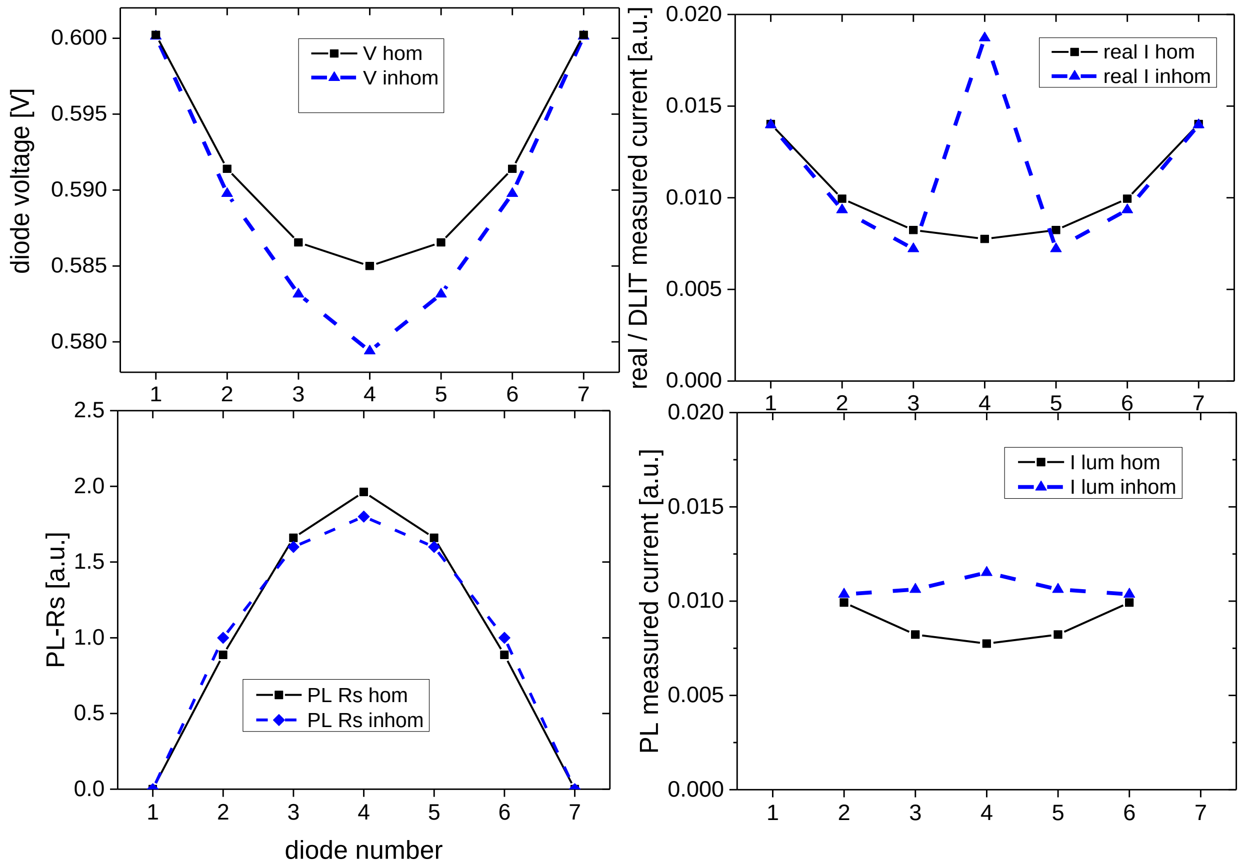




- SPICE simulation of the symmetry element, simulation of PL and DLIT results
- The local maxima of PL-J_{01} calculated by C-DCR appear clearly too weak, they also appear blurred
- This is due to the independent diode model used for C-DCR
- EL/PL can only measure local voltages, the currents follow from the model, which is here too simple
- Also the DLIT evaluation is based on the independent diode model
- However, since in DLIT the current is measured directly, the DLIT results are reliable, except of blurring

1-dimensional analog: Resistively coupled diode chain[1]



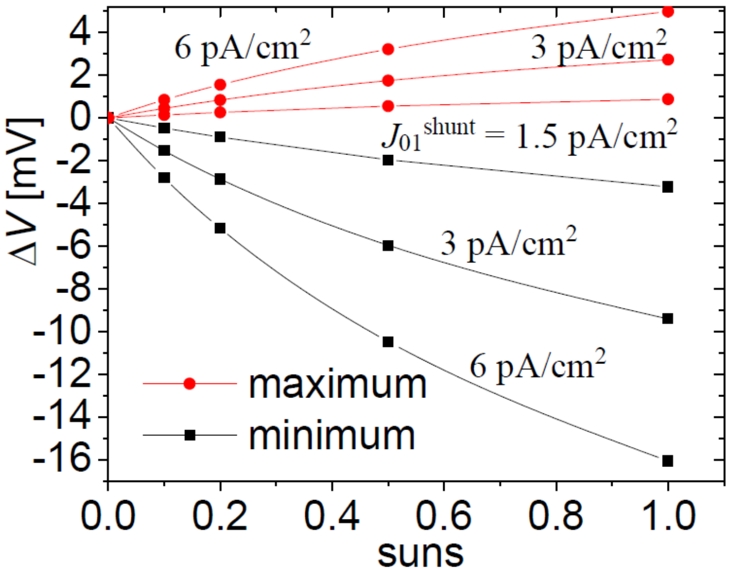


- Only for homogeneous J_{01}, DLIT- and PL-based current imaging results are identical
- If J_{01} shows local maxima, the resistive intercoupling leads to horizontal balancing currents, smoothing out the local voltage
- If J is calculated after the usual PL/EL method, local dark current maxima are underestimated and the result is blurred

[1]O. Breitenstein et al. SOLMAT **137** (2015) 50

3. Correct imaging of the calibration constant

- SPICE simulation of the symmetry element performed at V_{oc}, various intensities
- Even at V_{oc}(0.1 suns) the local diode voltages are not homogeneously $V_d = V_{oc}$ [1]



$$\Delta V(0.2\ suns) = \Delta V(0.1\ suns) * (1 + X)$$

X = nonlinearity parameter, typical value X = 0.86 for 0.1 and 0.2 suns

- For an unknown cell we do not know $\Delta V(x,y)$
- However, from the linear response principle[2] we know that this voltage error should be proportional to the illumination intensity I(suns)
- For higher intensities the dependence becomes non-linear

[1] O. Breitenstein et al., SOLMAT **142** (2015) 92

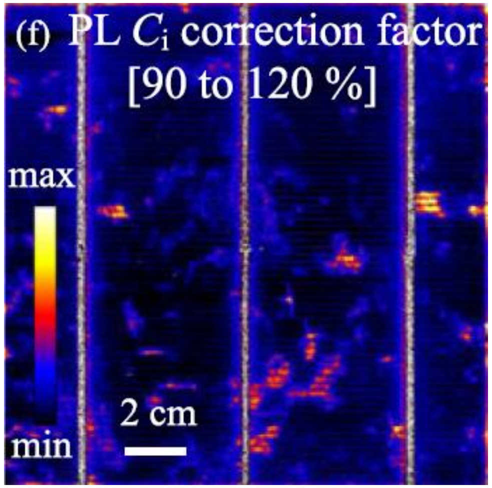
[2] J.-M. Wagner et al., Energy Procedia **92** (2016) 255

3. Correct imaging of the calibration constant $\mu\Phi$

$$\Delta V(0.2\ suns) = \Delta V(0.1\ suns) * (1 + X)$$

$$PL^1 = C_i \exp\left(\frac{V_{oc}^1 + \Delta V^1}{V_T}\right) \qquad PL^2 = C_i \exp\left(\frac{V_{oc}^2 + \Delta V^2}{V_T}\right) = C_i \exp\left(\frac{V_{oc}^2 + (1+X)\Delta V^1}{V_T}\right)$$

$$C_i = \frac{PL^1 \exp\left(\frac{-V_{oc}^{\ 1}}{V_T}\right)}{\left[\frac{PL^2}{PL^1} \exp\left(\frac{V_{oc}^{\ 1} - V_{oc}^{\ 2}}{V_T}\right)\right]^{\frac{1}{X}}}$$



- This procedure extrapolates C_i to zero illumination intensity, based on the linear response principle[1].
- The only remaining unknown is the nonlinearity parameter X, which may be optimized e.g. by Spice or Griddler simulations[3].
- On a usual mc cell, the correction is as large as 20 %, leading to an error of the local V_{oc}(0.1 sun) of about 5 mV[2].
- The proposed method provides a clear improvement of the accuracy of C_i imaging. However, it fails in regions containing ohmic or J_{02}-type shunts (one-diode model).

[1]O. Breitenstein et al., SOLMAT **142** (2015) 92
[2]O. Breitenstein et al., J-PV **6** (2016) 1243
[3]F. Frühauf et al., SOLMAT **180** (2018) 130

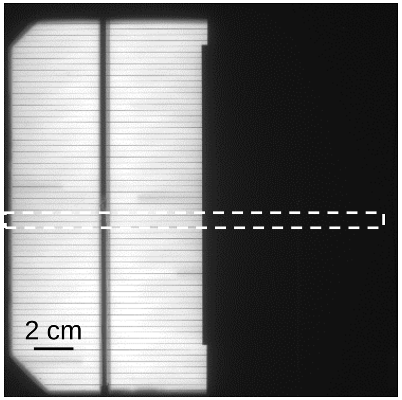
4. Easy correction of photon scattering

- The importance of photon scattering in the EL / PL detector was shown by Walter[1] and the influence of short-pass filtering on the PSF e.g. by Mitchell[2]
- Due to the limited dynamic range of luminescence detectors, the PSF was measured there by imaging circular apertures of different sizes[2]
- Teal and Juhl[3] have proposed to evaluate the edge spread function (ESF), easily leading to the line spread function (LSF), for obtaining the PSF from one luminescence image. Evaluation method: „backward substitution“
- In cooperation with A. Teal, we have found that this evaluation method leads to certain errors of the PSF and have proposed an iterative method for evaluating the LSF[4]
- Our method includes a „correction for diffuse scattering“ and leads to a very exact deconvolution of the input image (zero photon signal in the shadowed region)
- Our method is meanwhile included in the available „luminescence software suite“[5]

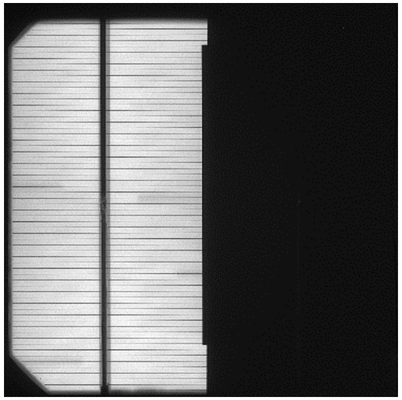
[1] D. Walter et al., Proc. 38th PVSC (2012) 307
[2] B. Mitchell et al., JAP **112** (2012) 063116
[3] A. Teal and M. Juhl, Proc. 42nd PVSC (2015)
[4] O. Breitenstein et al., J-PV **6** (2016) 522
[5] D.N.R. Payne et al., Comp. Phys. Comm. **215** (2017) 223

4. Easy correction of photon scattering

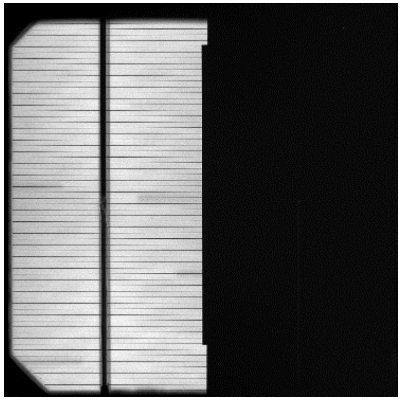
measuredEL image
0 to 1 a.u.



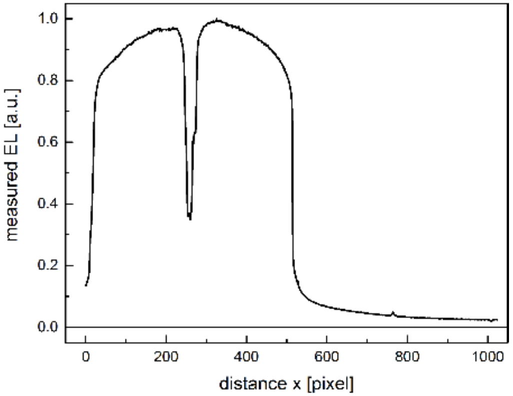
deconvolution
after Teal



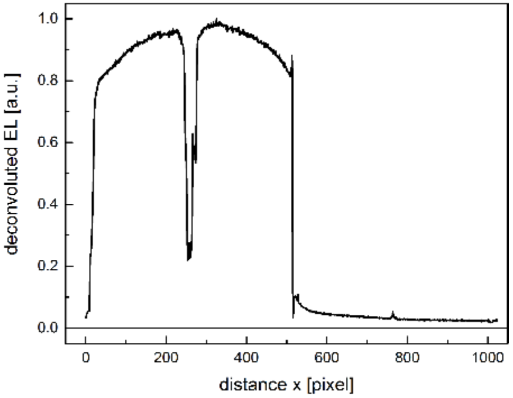
deconvolution after
our method



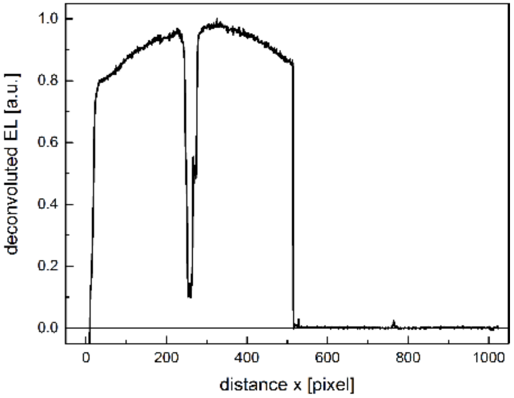
measured EL profile



deconvolution
after Teal



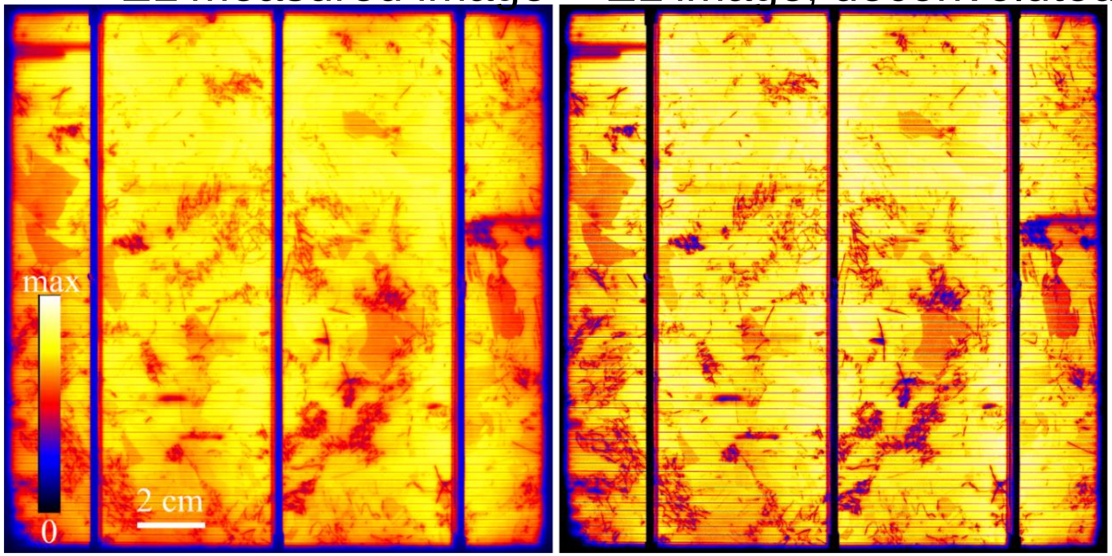
deconvolution after
our method



4. Easy correction of photon scattering

- Effect of deconvolution for a mc standard cell, Si detector without filtering

EL measured image   EL image, deconvoluted



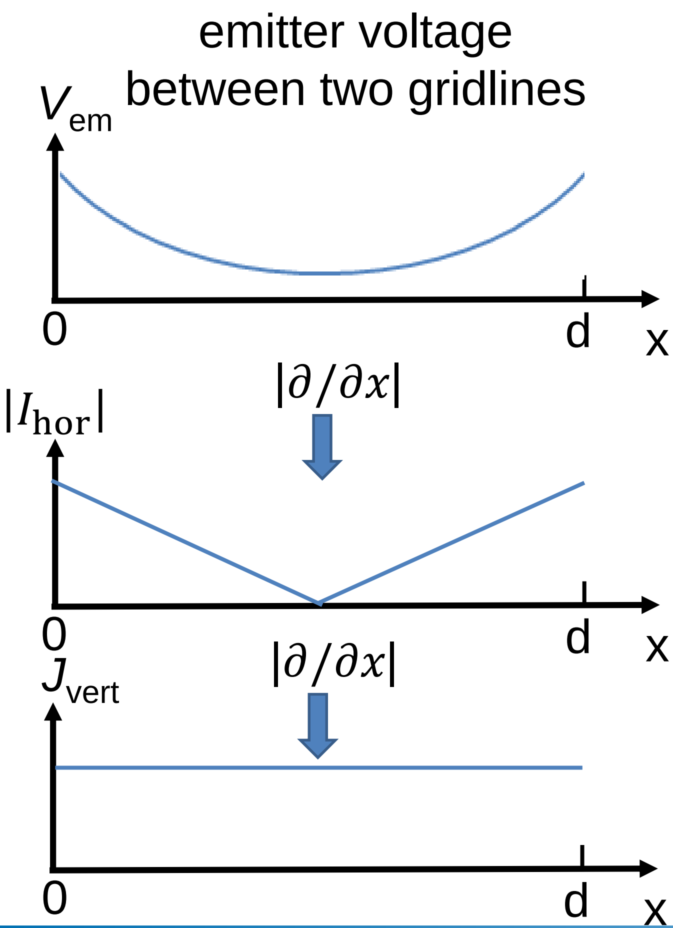
- If short- or band-pass filtering is used (e.g. 950 to 1000 nm), the effect of light scattering in the detector is strongly reduced, but image acquisition time is increased (x 3 ... 5)
- Then, in many cases, image deconvolution is not necessary anymore.
- If an InGaAs detector is used, photon scattering in the detector is negligible, but then lateral photon scattering in the cell strongly degrades the spatial resolution[1].

[1]S.P. Phang et al., APL **103** (2013) 192112

5. New PL methods for imaging J_{01} $\mu\Phi$

1. Laplacian evaluation

- First proposed by Glatthaar[1]



Laplacian operator

$$J_{vert}(x,y) = \frac{\partial^2 V_d(x,y)}{\varrho_{em}\partial x^2} = \frac{\Delta V_d(x,y)}{\varrho_{em}}$$

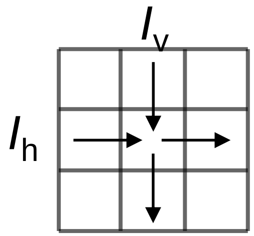
$$J_{vert}(x,y) = J_{sc} - J_{01}\, exp\left(\frac{V_{oc}^{loc}}{V_T}\right)$$

- $V_{oc}^{loc}(x,y)$ is measured by V_{oc}-PL
- Laplacian evaluation delivers J_{vert} (J_d)
- One-diode model delivers J_{01}
- Main problems: Noise and photon scattering in the detector (blur)

[1]M. Glatthaar et al., JAP **108** (2010) 014501

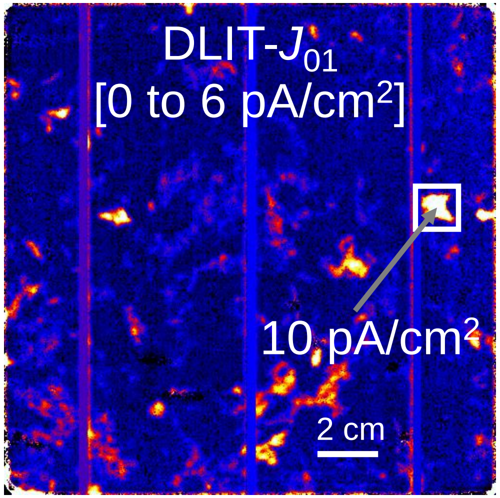
1. Laplacian evaluation

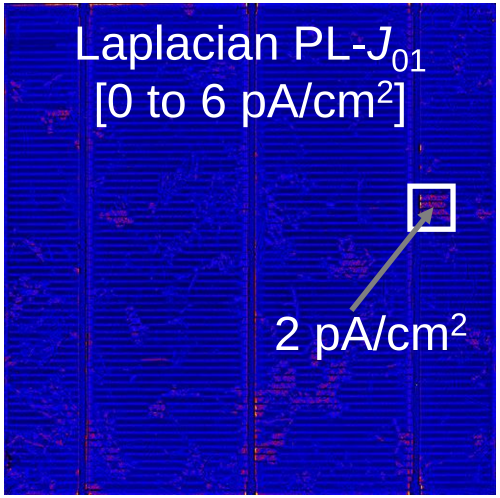
- In a pixel image the Laplacian operator [div(grad)] is realized by a pixel sum



$$I_d = (I_{v+} - I_{v-}) + (I_{h+} - I_{h-})$$

- In previous applications of this method data smoothing or pixel binning had to be used. Particularly, J_{01} (or the sheet resistance ρ_s necessary to describe the correct J_{01}) came out a factor of 2...5 too low.

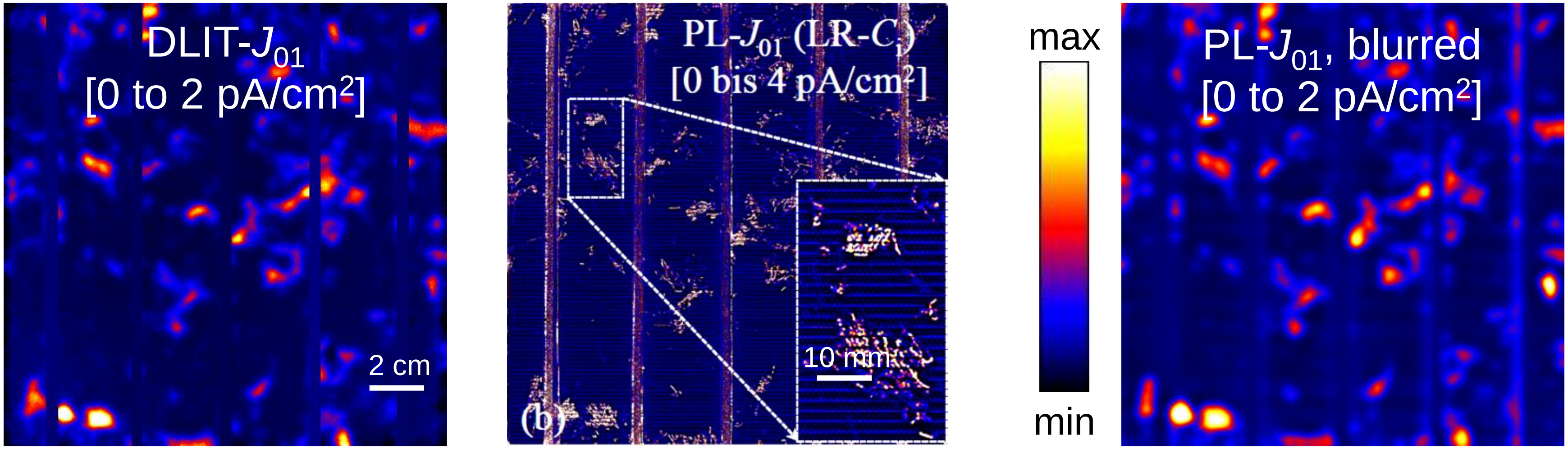




5. New PL methods for imaging $J_{01}\mu\Phi$

1. Laplacian evaluation

- Solution: band-pass filtering + image deconvolution + correct C_i imaging + correcting local diode back voltage[1]



- Now Laplacian PL-J_{01} is quantitatively comparable with DLIT-J_{01}, but its spatial resolution is greatly improved.
- Note that this PL evaluation method needs only one parameter, which is the emitter sheet resistance ρ_{em}.
- However, noise is still a problem for Laplacian PL evaluation.
- Challenge: exclusion of gridlines (spurious signals).

[1]F. Frühauf et al., SOLMAT **174** (2018) 277

2. Nonlinear Fuyuki evaluation

- Fuyuki (APL 2005): „C_i is proportional to L_d" (this only holds for very thick cells or low L_d < 50 µm).
- Breitenstein[1]: non-linear Fuyuki, approximate formula for L_{eff} for low wavelengths

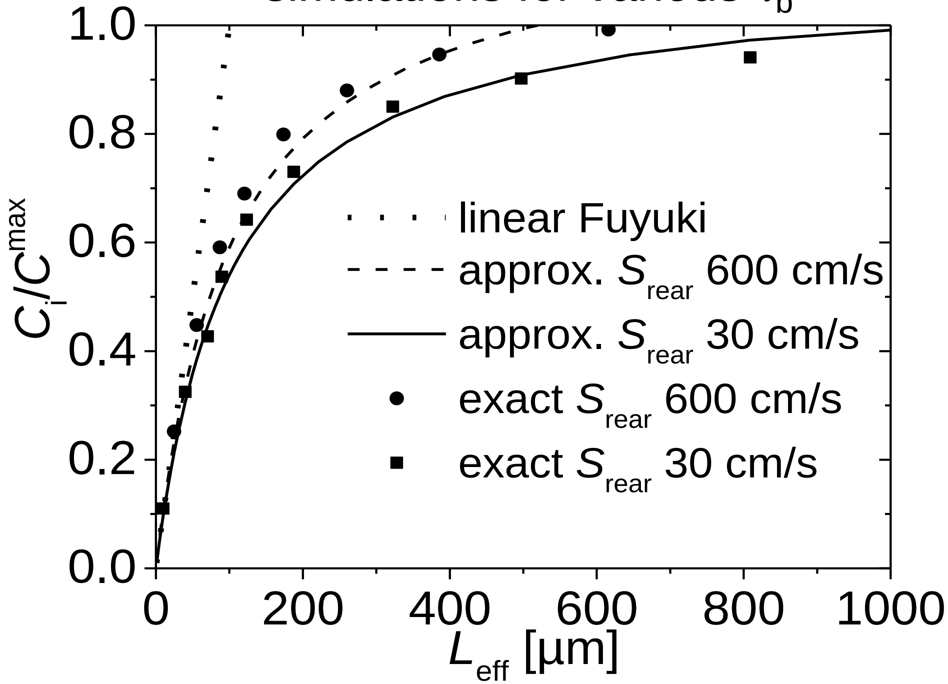
$$\frac{C_i}{C^{max}} = 1 - \frac{L}{L_{eff} + \mathrm{L}}$$

↑ "information depth"

- C^{max} and L are fitting parameters (fit to DLIT or spectral LBIC).

$$J_{01}^{\mathrm{b}} = \frac{e\,D\,n_i^2}{N_{\mathrm{A}} L_{\mathrm{eff}}}$$

simulations for various τ_b



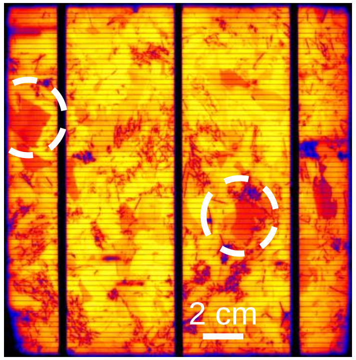
[1]O. Breitenstein et al., J-PV **6** (2016) 1243

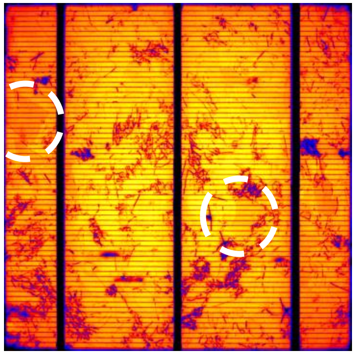
5. New PL methods for imaging J_{01}

2. Nonlinear Fuyuki evaluation

1. For non-linear Fuyuki evaluation, band-pass filtering from 950 to 1000 nm is necessary (inhomogeneous back reflection + theoretical reasons[1]).

EL, no filtering

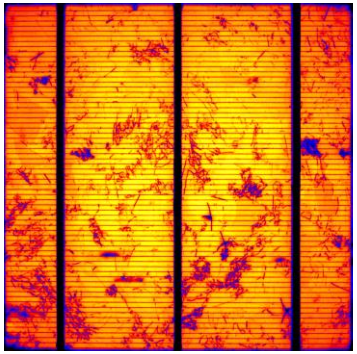


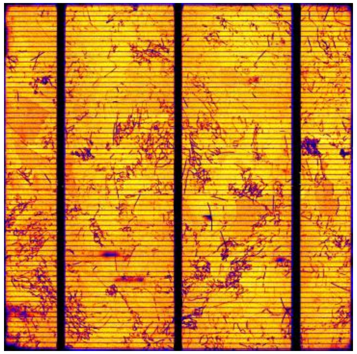


EL, band-pass filtering

2. For non-linear Fuyuki vignetting correction (brightness drop at the edges) is necessary.

before correction





after correction

$$C_i^{corr} = \frac{C_i}{cos^4(A\,\alpha(x,y))}$$

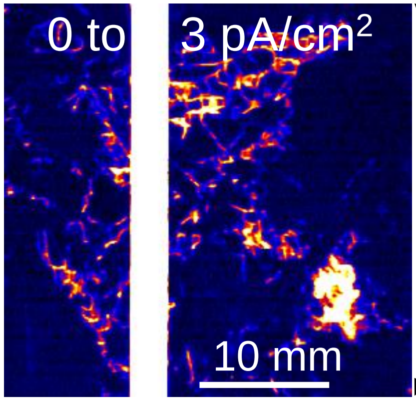
imaging angle

fitting factor (close to 1)

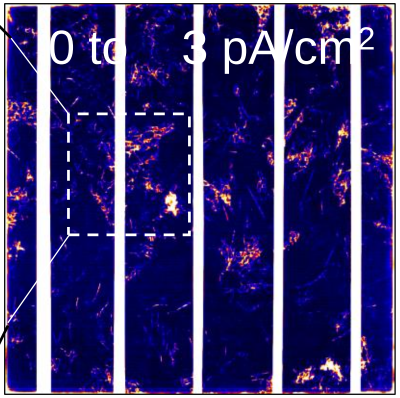
[1]O. Breitenstein et al., J-PV **6** (2016) 1243

2. Nonlinear Fuyuki evaluation

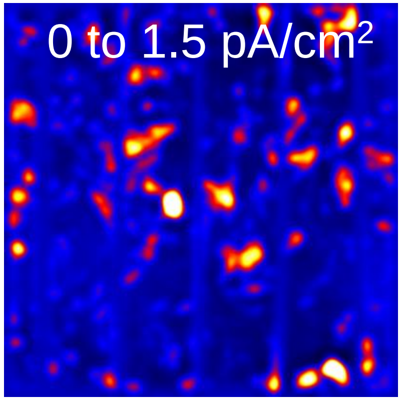
Nonl. Fuy.-J_{01} (magnified)



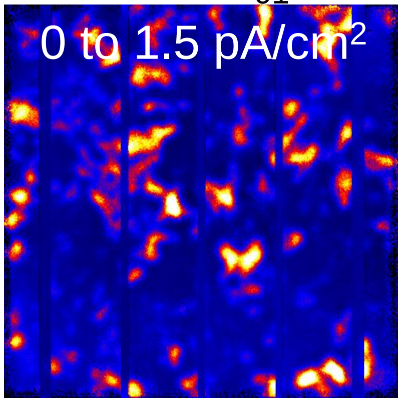
Nonl. Fuy.-J_{01}



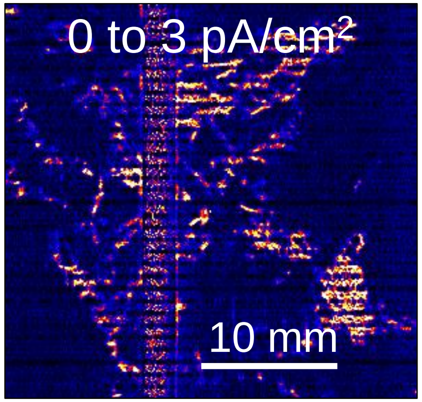
Nonl. Fuy.-J_{01} (blurred)



DLIT-J_{01}



Laplacian PL-J_{01} (magnified)



- If the parameters C_{max} and L are correctly fitted (e.g. to DLIT-J_{01}), nonlin. Fuyuki PL-J_{01} images are correct.
- Their SNR is clearly better than that of Laplacian J_{01}.
- Their spatial resolution is also excellent, but shows some residual blurring.
- This blurring is probably due to lateral excess carrier spreading in the cell.

8. Conclusions

- In the last 4 years we have made some significant contributions to PL imaging.
- These are improvements in calculating the luminescence calibration factor C_i and in the calculation of the PSF for correcting photon scattering.
- We have proposed two new methods for high-resolution PL-based imaging of J_{01} / L_{eff}, which may be combined.

Acknowledgements

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