Luminescence Imaging of Solar cells - New Developments

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Outline

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3. Correct imaging of the calibration constant
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1. Introduction

- Camera-based (Si detector) luminescence imaging (EL + PL) is used for solar cell investigation since 2005\textsuperscript{1,2}
- Starting from 2009, the evaluation was extended to imaging of $J_{01}$\textsuperscript{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\textsuperscript{7}

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

Model of independent diodes (Trupke 2007)

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

\textsuperscript{1}T. Fuyuki et al., APL \textbf{86} (2005) 262108
\textsuperscript{2}T. Trupke et al., APL \textbf{90} (2007) 093506
\textsuperscript{3}M. Glatthaar et al. JAP \textbf{105} (2009) 113110
\textsuperscript{4}M. Glatthaar et al., PSS RRL \textbf{4} (2010) 13
\textsuperscript{5}M. Glatthaar et al. JAP \textbf{108} (2010) 014501
\textsuperscript{6}Chao Shen et al., SOLMAT \textbf{109} (2013) 77
\textsuperscript{7}O. Breitenstein et al., SOLMAT \textbf{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.\textsuperscript{1}

• In 2016 a new method for measuring the PSF for correcting photon scattering in the detector was proposed\textsuperscript{2}, enabling accurate Laplacian-based $J_{01}$ imaging.\textsuperscript{3}

• Also in 2016 the „nonlinear Fuyuki“ method was proposed as another alternative PL-based $J_{01}$ imaging method.\textsuperscript{4}

• In 2018 it was shown that the luminescence ideality factor may be smaller than unity\textsuperscript{5}, and a luminescence-based method to fit a Griddler model to an existing solar cell was proposed.\textsuperscript{6}

• This lecture reports about these new developments.

\textsuperscript{1}O. Breitenstein et al., SOLMAT 142 (2015) 92
\textsuperscript{2}O. Breitenstein et al., J-PV 6 (2016) 522
\textsuperscript{3}F. Frühauf et al., SOLMAT 146 (2016) 87
\textsuperscript{4}O. Breitenstein et al., J-PV 6 (2016) 1243
\textsuperscript{5}F. Frühauf et al., SOLMAT 180 (2018) 130
\textsuperscript{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$^1$

\begin{align*}
1 \text{ pA/cm}^2 & \quad 1 \text{ pA/cm}^2 \\
3 \text{ pA/cm}^2 & \quad 3 \text{ pA/cm}^2 \\
3 \text{ pA/cm}^2 & \quad 3 \text{ pA/cm}^2
\end{align*}
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
2. Why conventional PL-$J_{01}$ imaging is wrong

1-dimensional analog: Resistively coupled diode chain

- 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
3. Correct imaging of the calibration constant

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

$$V_d = V_{oc}$$

$$\Delta V(0.2 \text{ suns}) = \Delta V(0.1 \text{ suns}) \times (1 + X)$$

$X$ = 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 we know that this voltage error should be proportional to the illumination intensity $I(\text{suns})$
- For higher intensities the dependence becomes non-linear

$^1$O. Breitenstein et al., SOLMAT 142 (2015) 92

3. Correct imaging of the calibration constant

\[
\Delta V(0.2 \text{ suns}) = \Delta V(0.1 \text{ suns}) \times (1 + X)
\]

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

- 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 \( V_{oc}(0.1 \text{ sun}) \) 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).

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\(^1\)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
4. Easy correction of photon scattering

measured EL image
0 to 1 a.u.

dehconvolution
after Teal

dehconvolution after our method

measured EL profile

dehconvolution
after Teal

dehconvolution after our method

Easy correction of photon scattering
4. Easy correction of photon scattering

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

- 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
1. Laplacian evaluation

- First proposed by Glatthaar\(^1\)

Emitter voltage between two gridlines

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

- Laplacian evaluation delivers \(J_{\text{vert}}(J_d)\)
- One-diode model delivers \(J_{01}\)
- Main problems: Noise and photon scattering in the detector (blur)

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

1. Laplacian evaluation

- In a pixel image the Laplacian operator $[\text{div(grad)}]$ 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 $\rho_s$ necessary to describe the correct $J_{01}$) came out a factor of 2...5 too low.
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 $\rho_{em}$.

- However, noise is still a problem for Laplacian PL evaluation.

- Challenge: exclusion of gridlines (spurious signals).

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\(^1\)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 \( L_d < 50 \, \mu m \)).

- **Breitenstein\(^1\):** non-linear Fuyuki, approximate formula for \( L_{\text{eff}} \) for low wavelengths

\[
\frac{C_i}{C_{\text{max}}} = 1 - \frac{L}{L_{\text{eff}} + L}
\]

“information depth”

- \( C_{\text{max}} \) and \( L \) are fitting parameters (fit to DLIT or spectral LBIC).

\[
J^b_{01} = \frac{e D n_i^2}{N_A L_{\text{eff}}}
\]

\(^1\)O. Breitenstein et al., J-PV 6 (2016) 1243
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\textsuperscript{1}).

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

before correction

EL, no filtering

EL, band-pass filtering

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

after correction

\textsuperscript{1}O. Breitenstein et al., J-PV 6 (2016) 1243
2. Nonlinear Fuyuki evaluation

- If the parameters $C_{\text{max}}$ 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 $J_{01} / L_{\text{eff}}$, which may be combined.
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