Advanced Parameter Imaging of Solar Cells

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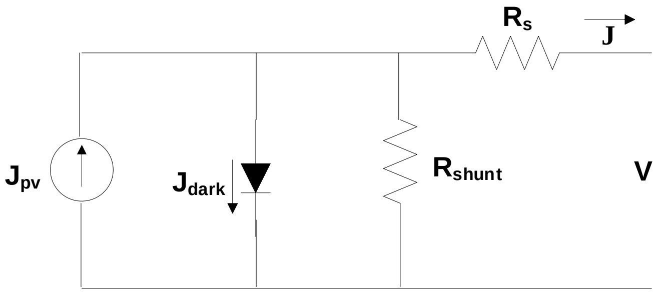
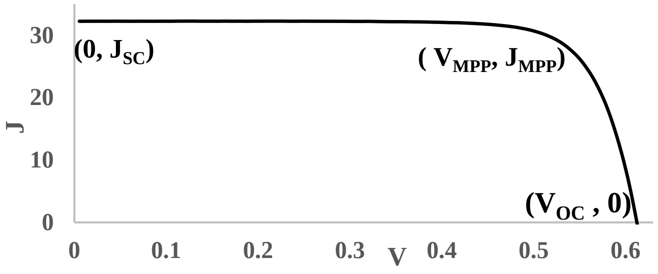
Solar Cell Characterization

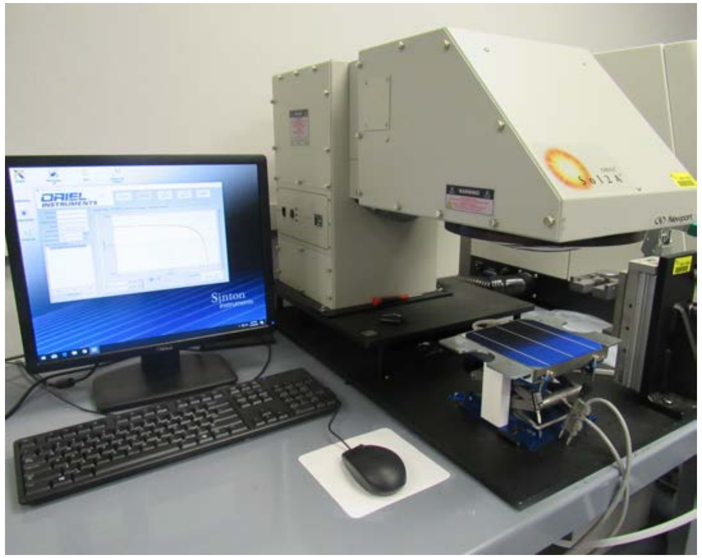
- Need for characterization
  - How they operate
  - Engineering them to be better
- Parameters
  - Open circuit voltage, V_{OC}
  - Short circuit density, J_{SC}
  - Fill factor, FF
  - Series resistance, R_S
  - Dark sat. current density, J_0



Equivalent circuit



J-V characteristics



Solar simulator

$$J = J_{pv} - J_{dark} - J_{shunt}$$

$$J = J_{pv} - J_0 \left[exp\left(\frac{V + R_S * J}{nKT}\right) - 1 \right] - \frac{V + R_S * J}{R_{shunt}}$$

Efficiency

$$\eta = \frac{V_{MPP} * J_{MPP}}{P_{in}} = \frac{V_{OC} * J_{SC} * FF}{P_{in}}$$

- Variation of parameters over surface
  - Identify, decouple and quantify losses; better design; quantifying variation and process control

Luminescence Imaging

- Key features
  - 808 nm laser
  - 920 nm filter, 1MP CCD camera
- Luminescence measurement
  - PL: optical excitation
  - EL: electrical excitation
  - Biased PL: optical + electrical

Luminescence measurement

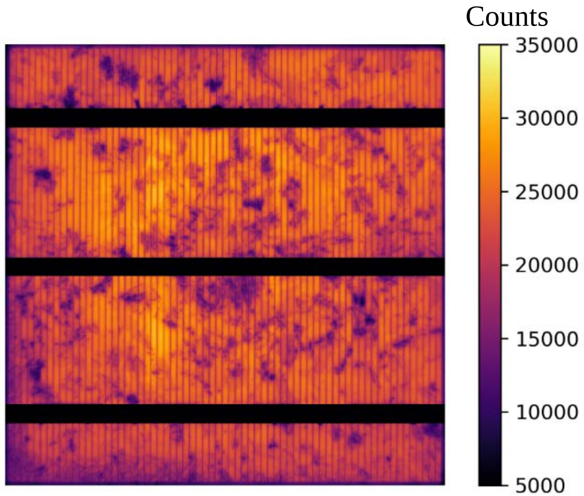
- Key equations

$$V_{xy} = V_T\,.\log\left(\frac{I_{Hxy} - B_{xy} \cdot I_H}{C_{xy}}\right)$$

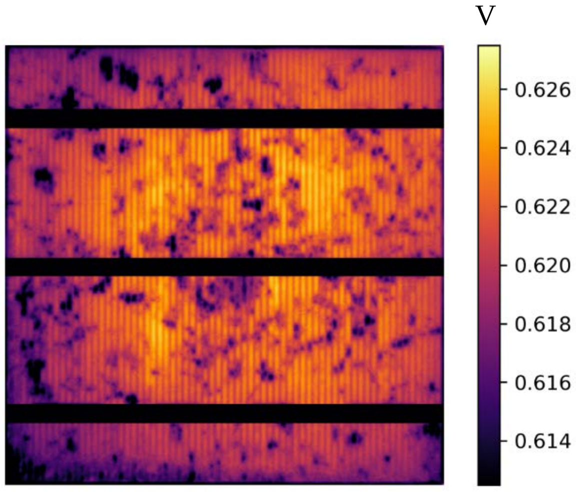
$$B_{xy} = \frac{I_{xy-SC}}{I_{L-SC}}$$

$$C_{xy} = I_{Lxy} \cdot \exp\left(\frac{V_{OC-L}}{V_T}\right)$$

  - B: background, C: calibration constant



PL at 1 sun intensity

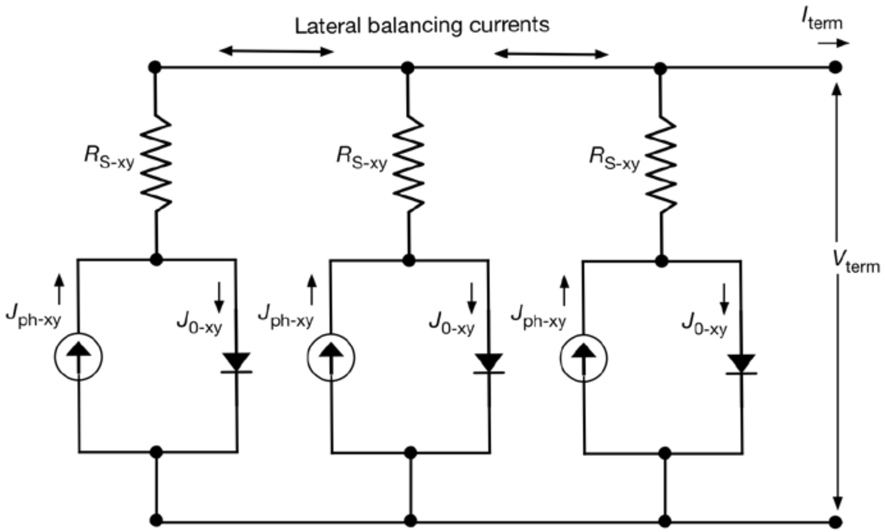


V_{OC} image

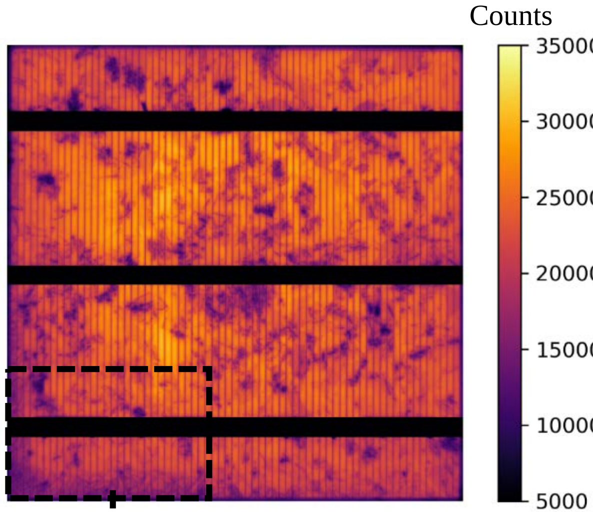
Ref: M. Glatthaar *et al.*, *Appl. Phys.*, 108, 1 (2010), T. Trupke *et al.*, *Appl. Phys. Lett.*, 90, 093506-1 (2007), Hallam *et al.*, *Appl. Phys.*, 115, 044901(2014)

Identifying and Quantifying Losses

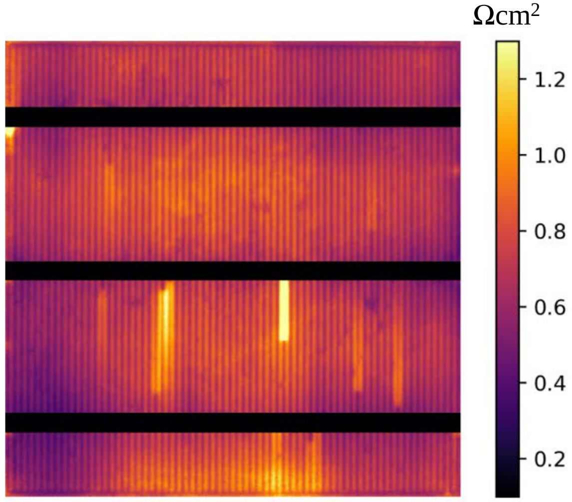
- Terminal connected diode model
  - Combination of parallel diodes
  - Local parameters are different



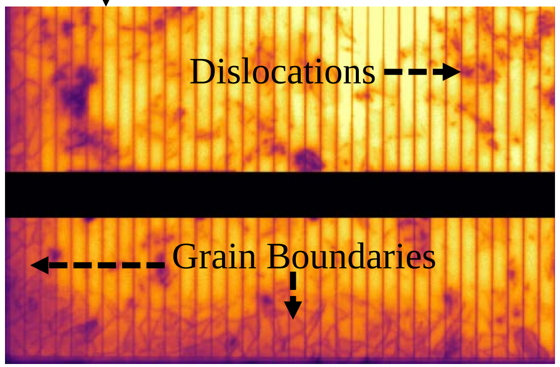
$$V_{term} - V_{xy} = R_{xy}\left[J_{0-xy} * \exp\left(\frac{V_{xy}}{nV_T}\right) - J_{ph-xy}\right]$$



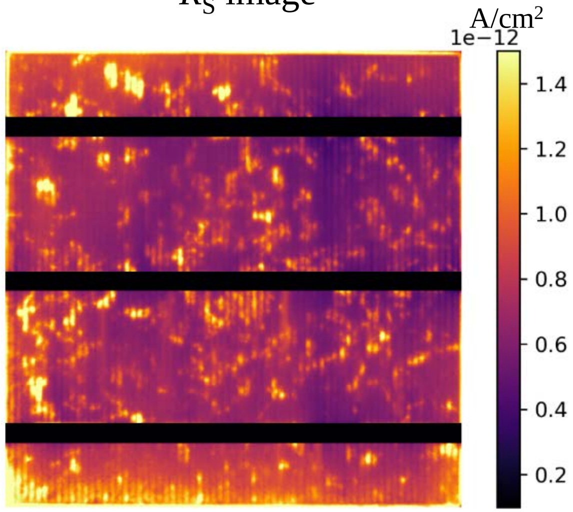
PL at 1 sun intensity



R_S image



Cropped and zoomed in image



J_0 image

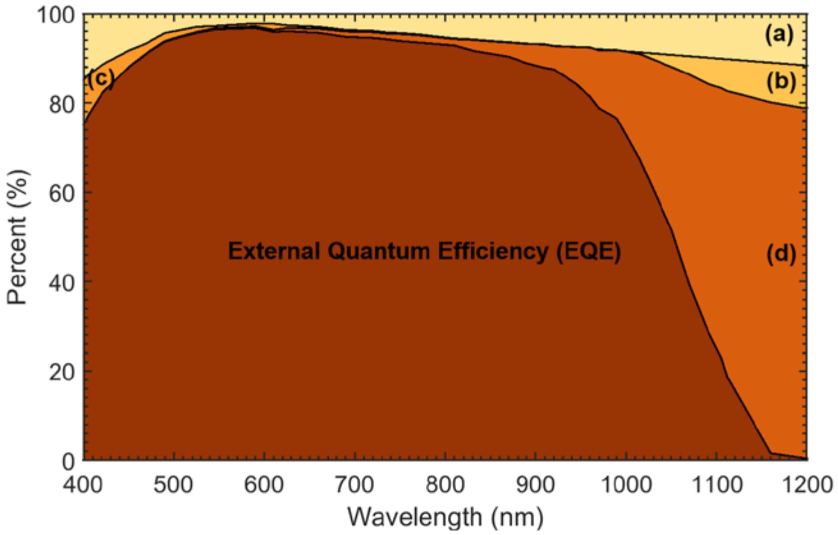
Ref: M. Glatthaar *et al.*, *Appl. Phys.*, 108, 1 (2010), T. Trupke *et al.*, *Appl. Phys.* Lett., 90, 093506-1 (2007), Hallam *et al.*, *Appl. Phys.*, 115, 044901(2014)

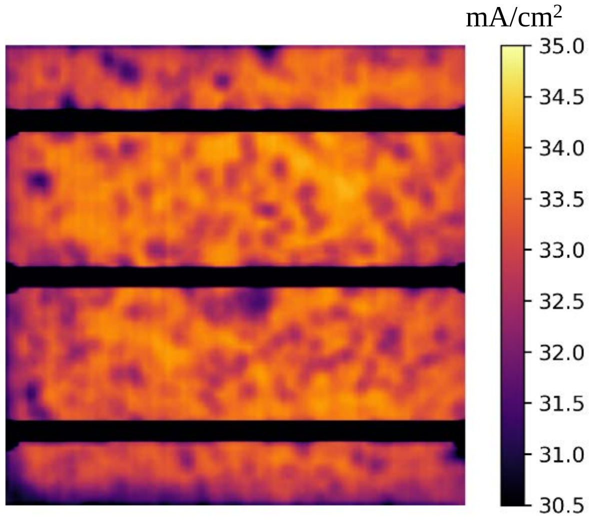
High Speed Quantum Efficiency Imaging

- *EQE* and *R* measurement (FlashQE)
  - *EQE* and Reflectance (*R*)
  - Point by point scanning
  - Discrete wavelengths
  - 365 nm to 1280 nm
  - Integrated sphere

FlashQE (for *EQE* and *R* measurement)

$$J_{sc} = e\int_{365\ nm}^{1280\ nm} EQE(\lambda)\phi_{in}(\lambda)\ d\lambda \qquad IQE(\lambda) = \frac{EQE(\lambda)}{1-R}$$





J_{SC} image

Reflection loss

a. Front reflection
b. Escape reflection

Parasitic Absorption & Recombination

c. Emitter loss
d. Loss in bulk and rear

Ref: M.J. Hossain *et al.*, *WCPEC-7* (2018), E. J. Schneller *et al.*, *IEEE J.PV*, 7, 4, (2017)

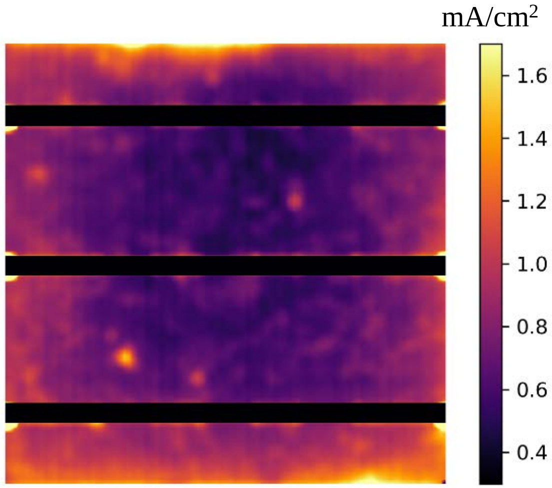
High Speed Quantum Efficiency Imaging (Cont…)

- EQE measurement

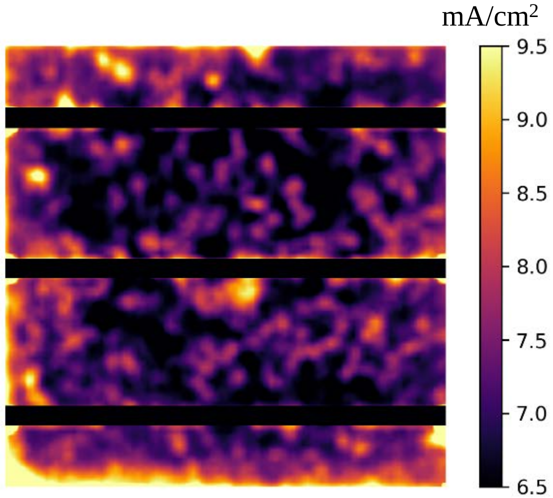
$$IQE(\lambda) = \frac{1}{k}\exp\left(-\frac{W_d}{L_a(\lambda)}\right)\frac{1}{1+\frac{L_a(\lambda)}{L_{eff}}}$$

$$A_{e,I}(\lambda) = 1 - IQE(\lambda)\cdot\left(1-\frac{L_a(\lambda)}{L_{eff}}\right)$$

$$A_{e,\,II}(\lambda) = 1 - \exp\left(-\frac{W_d}{L_a(\lambda)}\right)$$



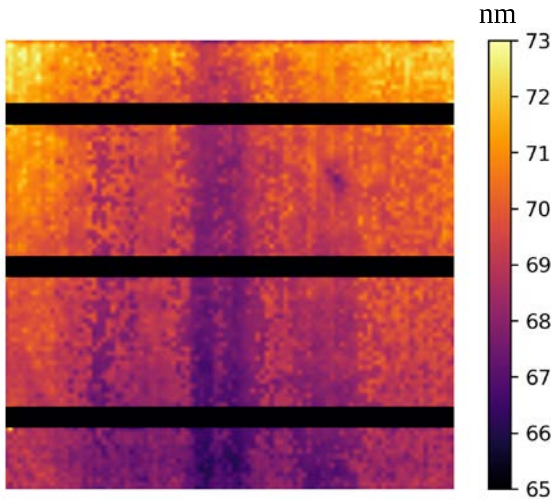
Emitter loss



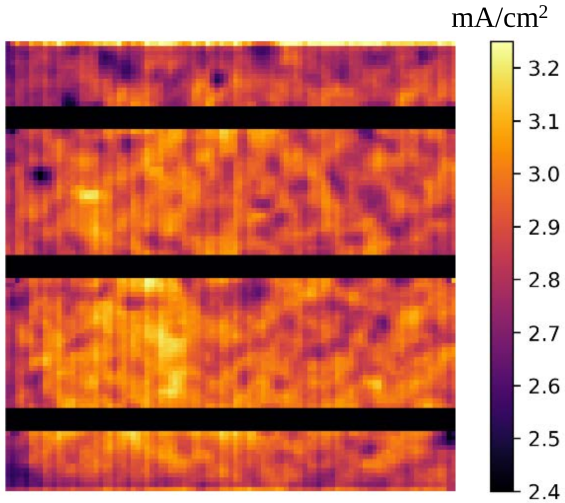
Bulk & rear loss

- R measurement

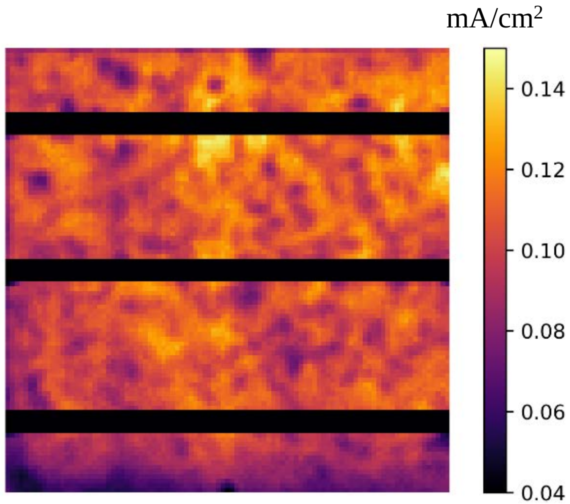
$$t = \frac{\lambda_{\min}}{4n}$$



ARC thickness



Front reflectance loss



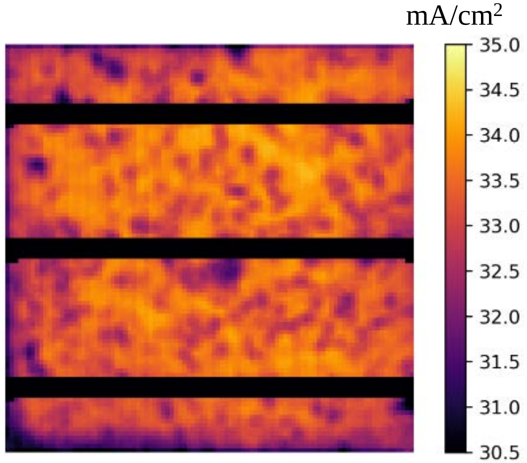
Escape reflectance loss

Ref: M.J. Hossain *et al.*, *WCPEC-7* (2018), E. J. Schneller *et al.*, *IEEE J.PV*, 7, 4, (2017)

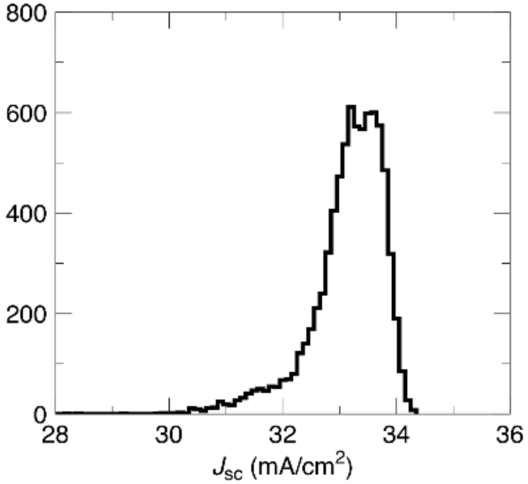
Incorporation of $J_{SC\text{-}xy}$ with PL

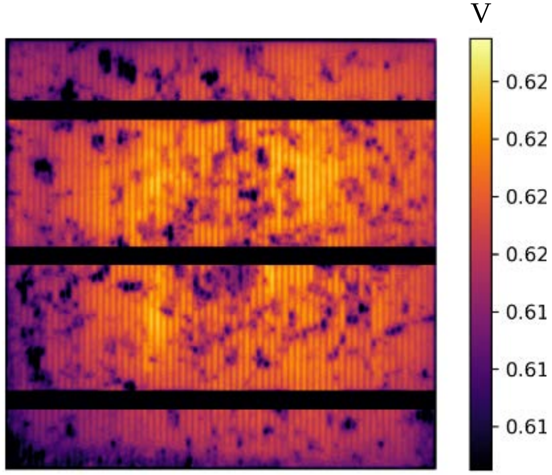
$$V_{term} - V_{xy} = R_{xy}\left[J_{0-xy} * \exp\left(\frac{V_{xy}}{nV_T}\right) - J_{ph-xy}\right]$$

- Spatially resolved J_{SC}
  - A uniform J_{SC} is normally used in literature
  - Concerns about accuracy with J_{SC}[1,2,3]
- Cell parameters from *IV* measurement
  - J_{SC}: 32.2 mA/cm^2, V_{OC}: 0.612 V
  - n: 1.3, R_S: 0.2 Ωcm^2, J_0: 3.39x10^{-10} A/cm^2

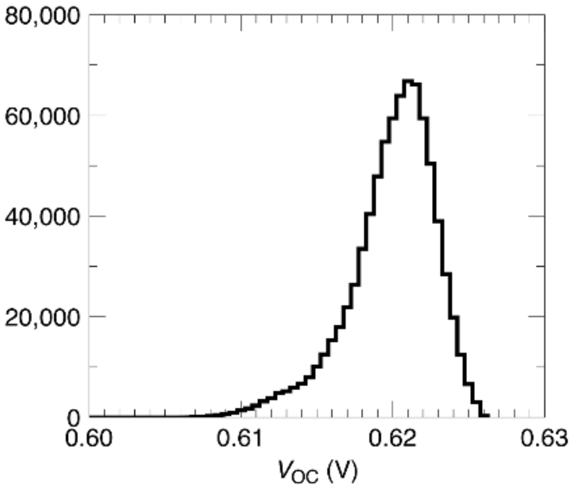


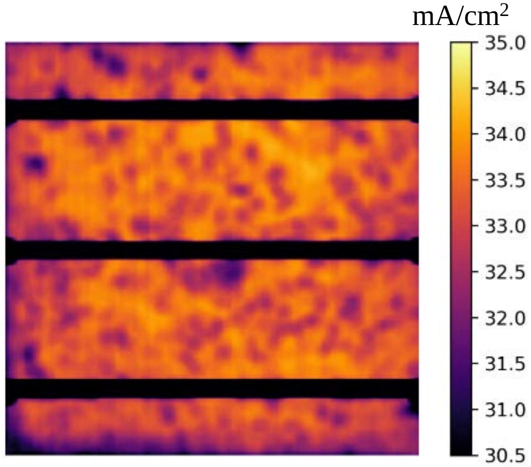
J_{SC} image: original



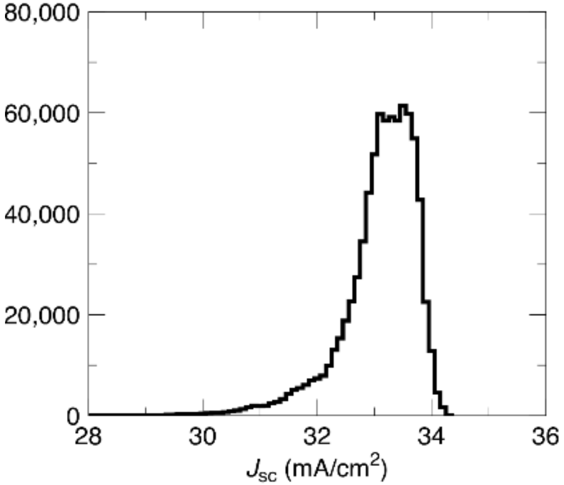


V_{OC} image





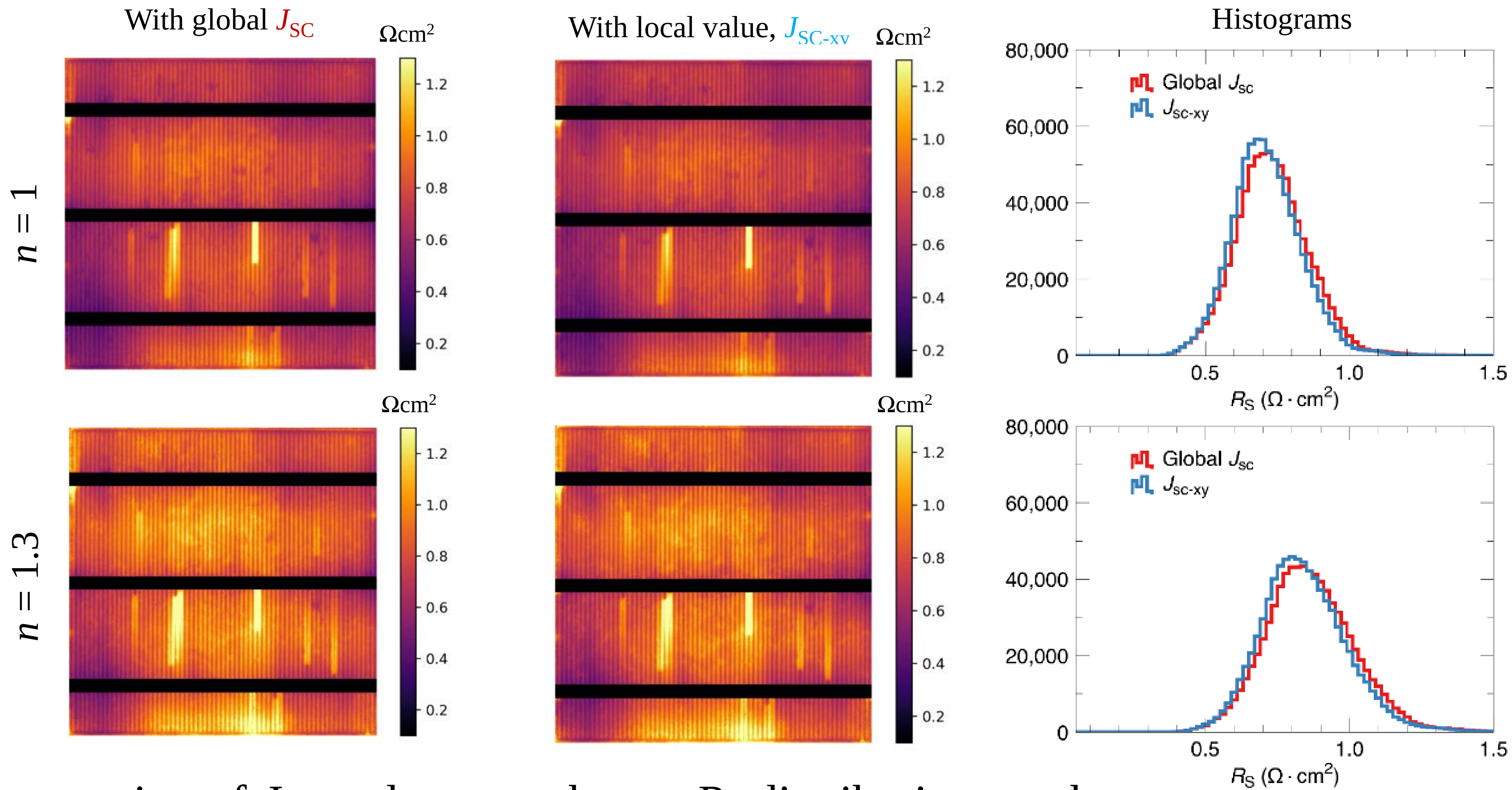
J_{SC} image: interpolated



[1]C. Shen et al., *Sol. En. Mat. Sol. Cells* **123**, 41–46 (2014) [2]H. Hoffler et al., *IEEE J. PV.* **5**, 613–618 (2015) [3]F. Fertig et al, *Energy Procedia* **77**, 43–56 (2015)

Incorporation of $J_{SC\text{-}xy}$ with PL: R_S

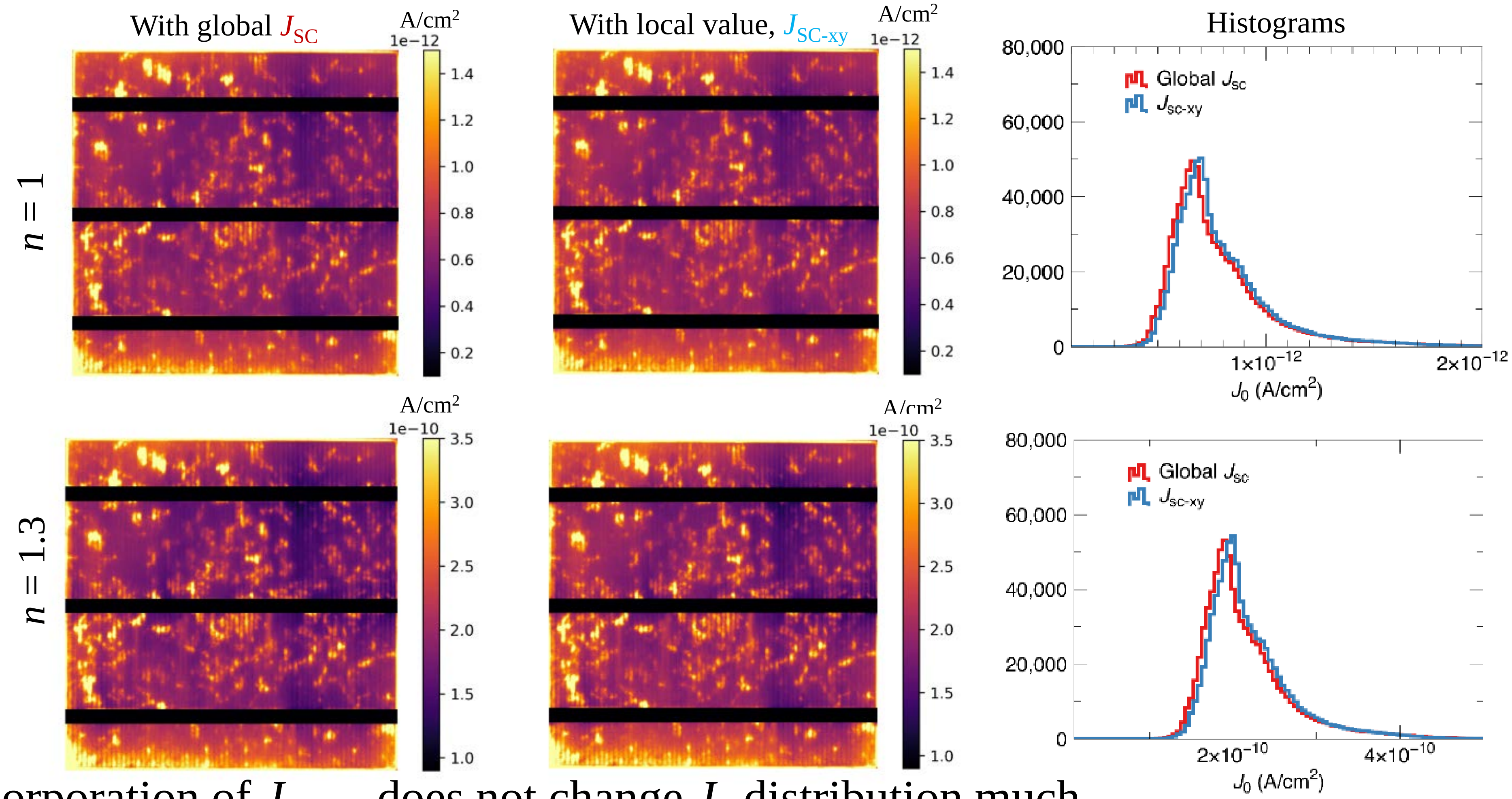
Cell R_S=0.2 Ωcm^2



- Incorporation of $J_{SC\text{-}xy}$ does not change R_S distribution much
  - Using J_{SC} is safe
  - With n=1.3, distribution widens, mode being unchanged

Incorporation of $J_{SC\text{-}xy}$ with PL: J_0

Cell J_0= 3.39 x 10^{-10} A/cm^2

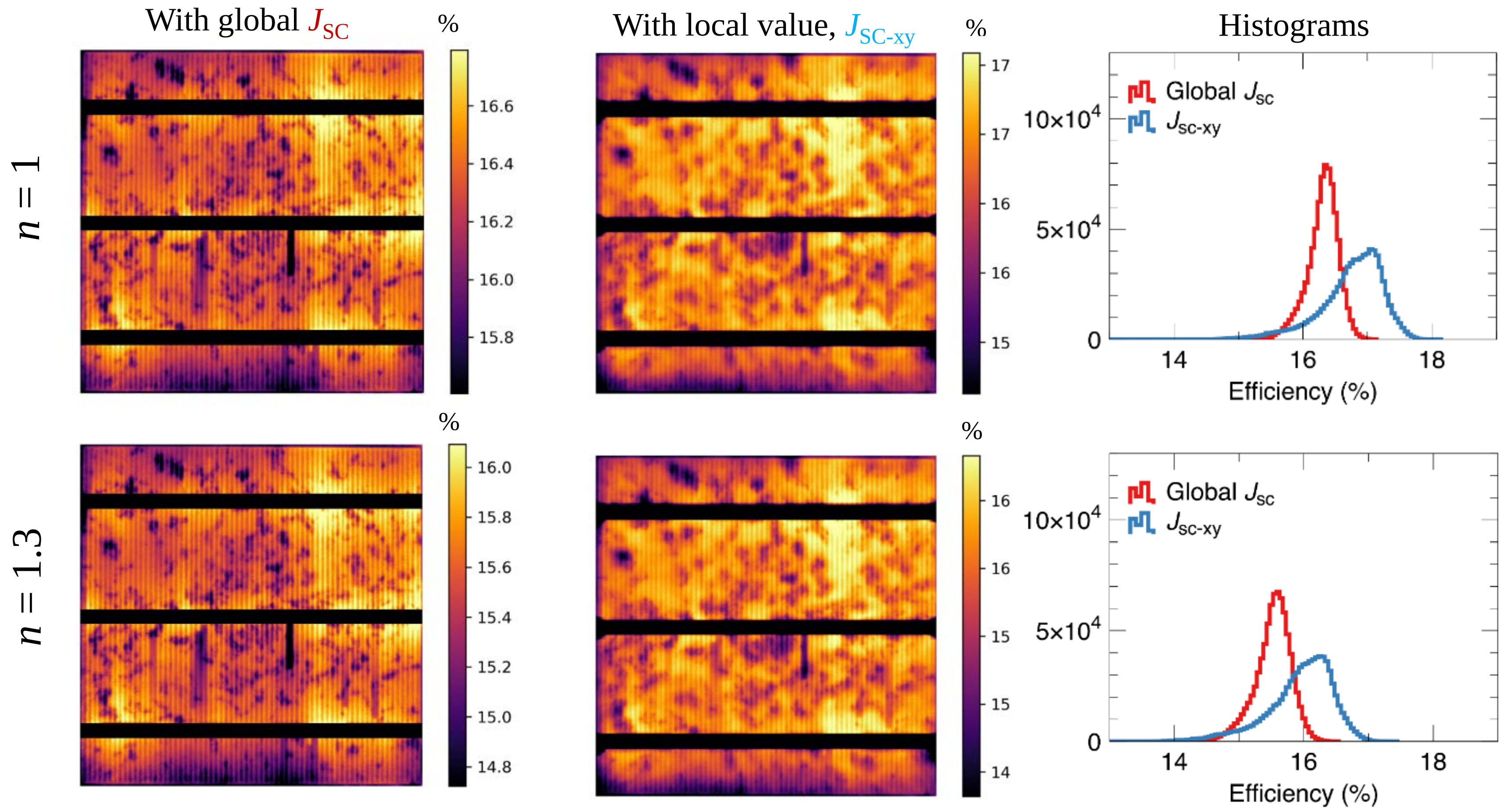


- Incorporation of $J_{SC\text{-}xy}$ does not change J_0 distribution much
  - Using J_{SC} is safe
  - Recombination shifts to higher value with n=1.3 (practical diode)

Incorporation of $J_{SC\text{-}xy}$ with PL: Efficiency (J-V curve fitting)

Cell η= 15.4%

$$J_{xy} = J_{sc-xy} - J_{0-xy}\left[exp\left(\frac{V_{xy} + R_{xy} * J_{SC-xy}}{nV_T}\right) - 1\right]$$



- Incorporation of $J_{SC\text{-}xy}$ changes efficiency distribution drastically
  - Using $J_{SC\text{-}xy}$ is better
  - n=1.3 provides reduced efficiency

Conclusion and Acknowledgement

- Parameter images are important
  - Decoupling losses and finding their root causes
  - Making better performing solar cells
- Incorporation of $J_{SC\text{-}xy}$ with PL
  - More accurate representation of parameter images
  - Not so much impact on R_S and J_0 but big impact on efficiency images

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UCF

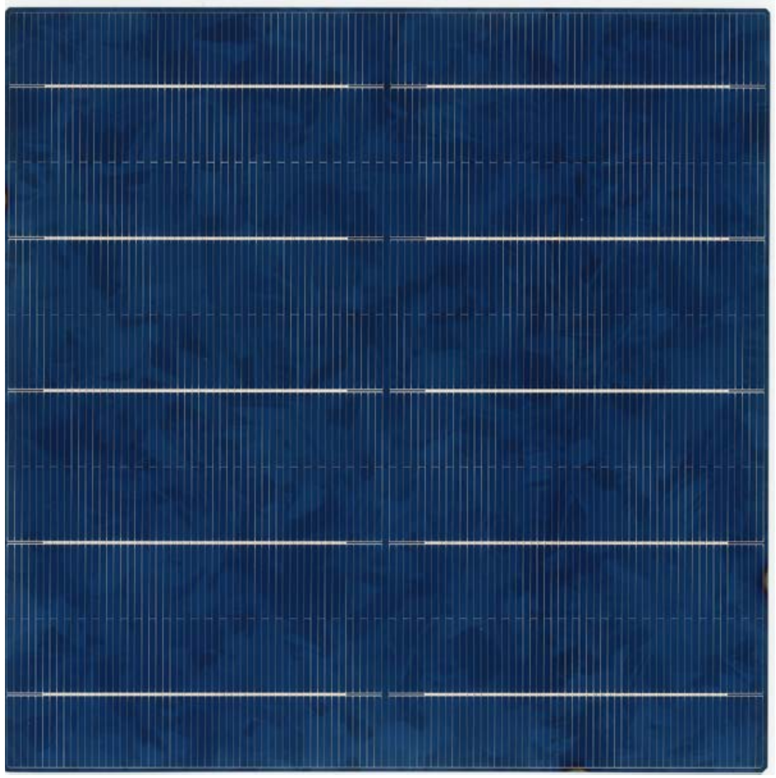




Thank You
Questions?




Solar Cell Structure



15.6 cm

15.6 cm