Developments in Photoluminescence Characterisation for Silicon PV

Never Stand Still | Faculty of Engineering | School of Photovoltaic and Solar Energy Engineering

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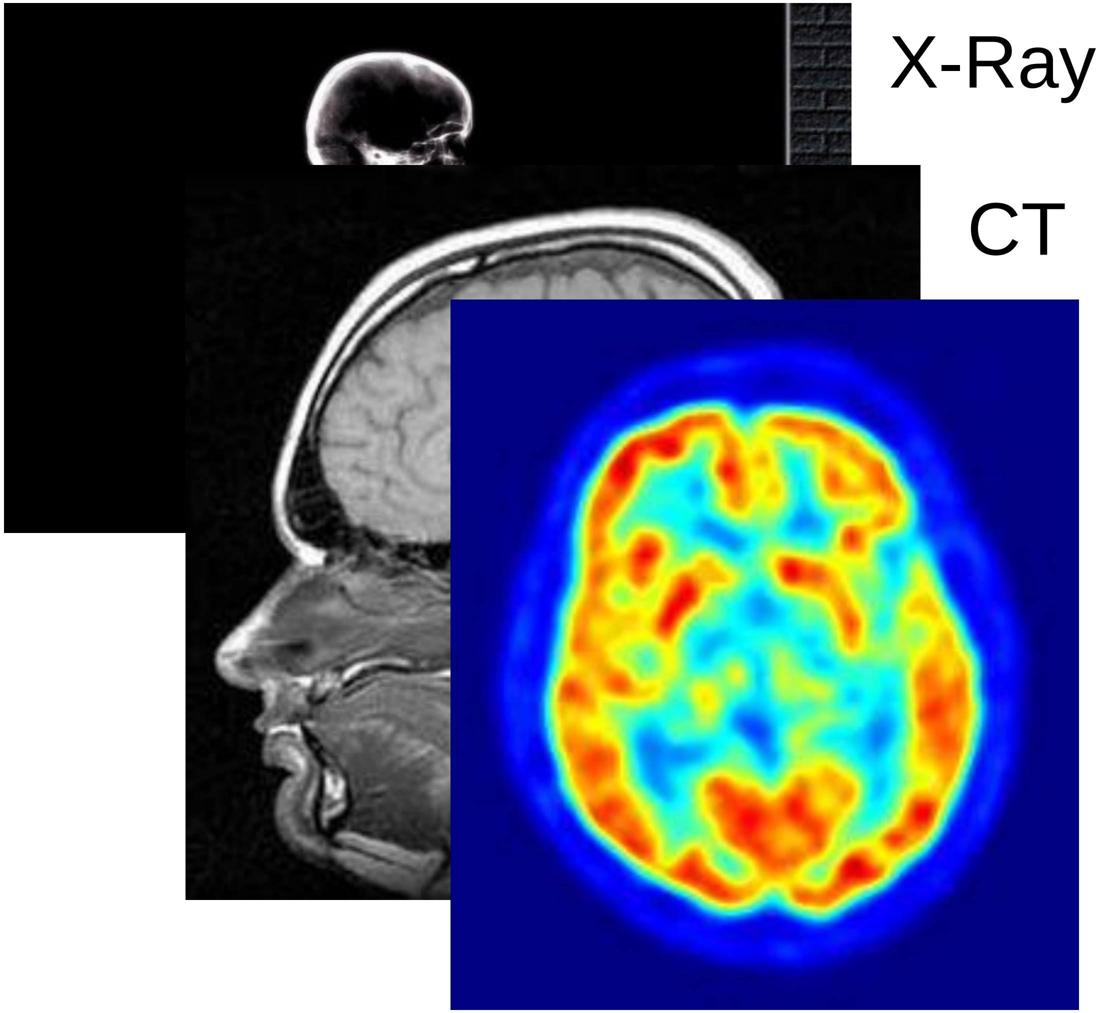
[3] Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany
[4] College of Engineering and Computer Science, The Australian National University, Canberra, Australia

Imaging internal properties of humans!

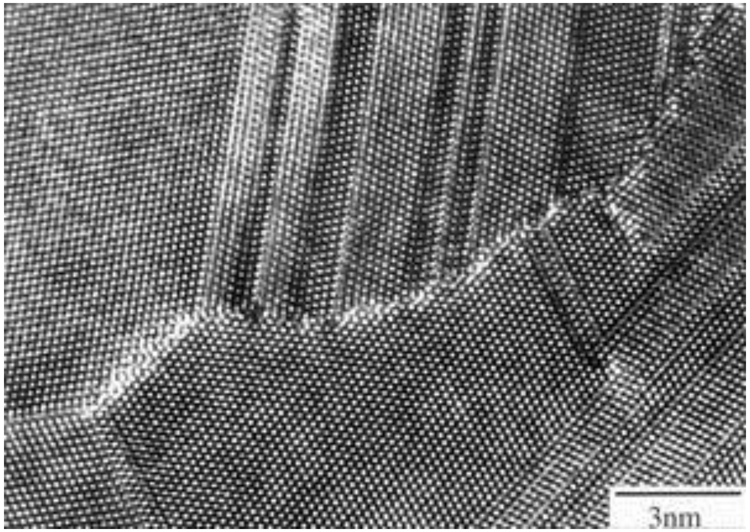


X-Ray

CT

PET-CT

Imaging internal properties of silicon!



TEM → lattice structure

Imaging material/device properties limited to DLIT, CDI/ILM

Scanning with EBIC/XBIC, MDP/μPCD, QSSPC, LBIC

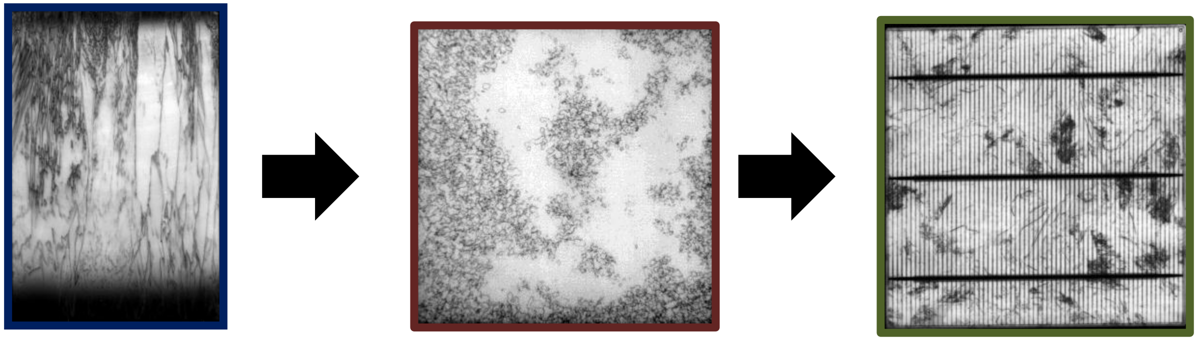
PL imaging visualises minority carrier properties!

Optical image

PL image

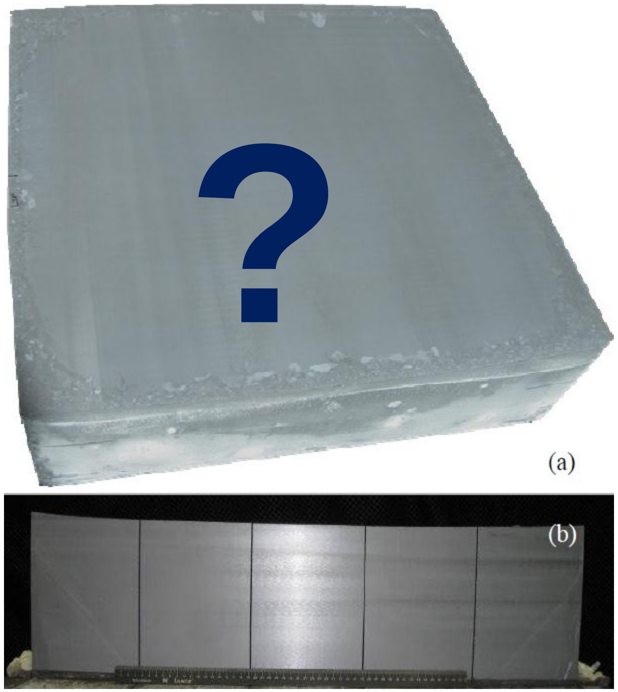
Outline:

- Spectral imaging on silicon bricks
  - ✓ Proof of concept
  - ✓ Overcoming experimental limitations
  - ✓ Quantifying physical limitations



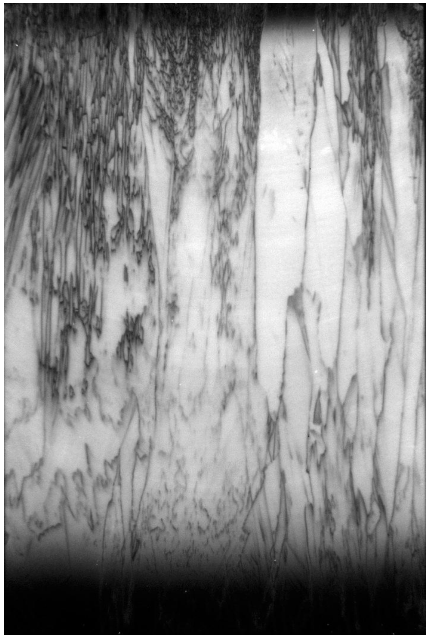
- Inline inspection and sorting
- Characterisation of next generation cell structures

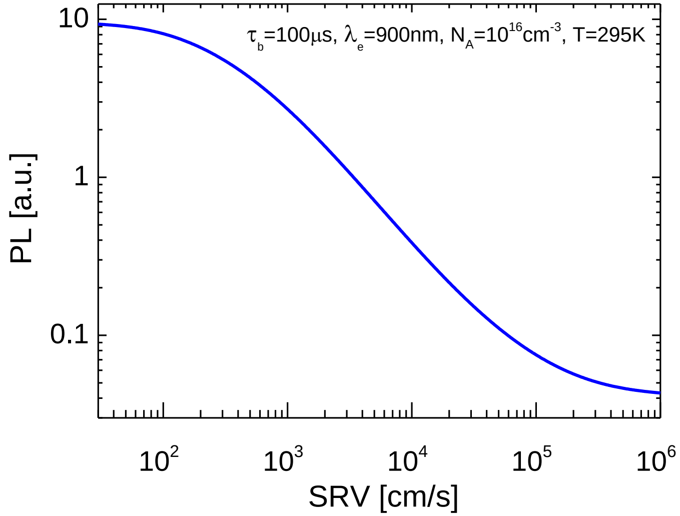
Why brick imaging?



- Bulk lifetime sufficient?
- Doping range?
- Dislocation density?
- Fe contamination?
- Where to cut off? Where dead?
- Which parts suitable for high efficiency devices?
- **What efficiency to expect?**
- **What cost/profit to expect?**

Challenges: Bulk but bare!

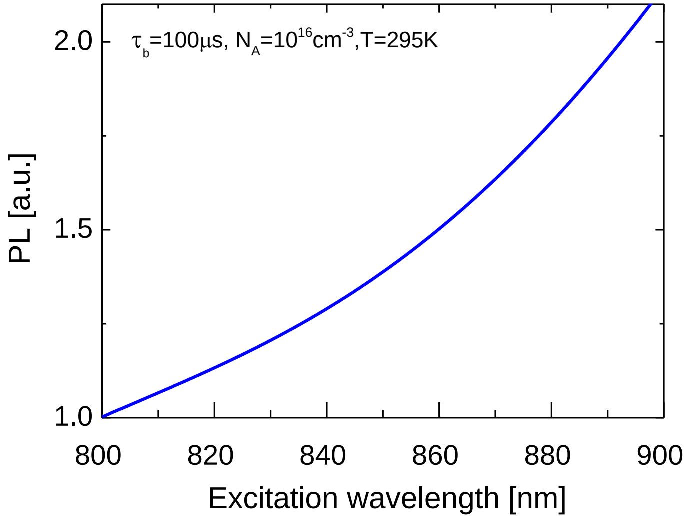




"Red zone"

Super low PL!

"Red zone"



Proof of concept study

JOURNAL OF APPLIED PHYSICS **109**, 083111 (2011)

Bulk minority carrier lifetimes and doping of silicon bricks from photoluminescence intensity ratios

Bernhard Mitchell,[1,a)] Thorsten Trupke,[1,2] Jürgen W. Weber,[2] and Jørgen Nyhus[3]
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[2]*BT Imaging, Surry Hills, NSW 2010, Australia*
[3]*REC Wafer, Norway AS, 3908 Porsgrunn, Norway*

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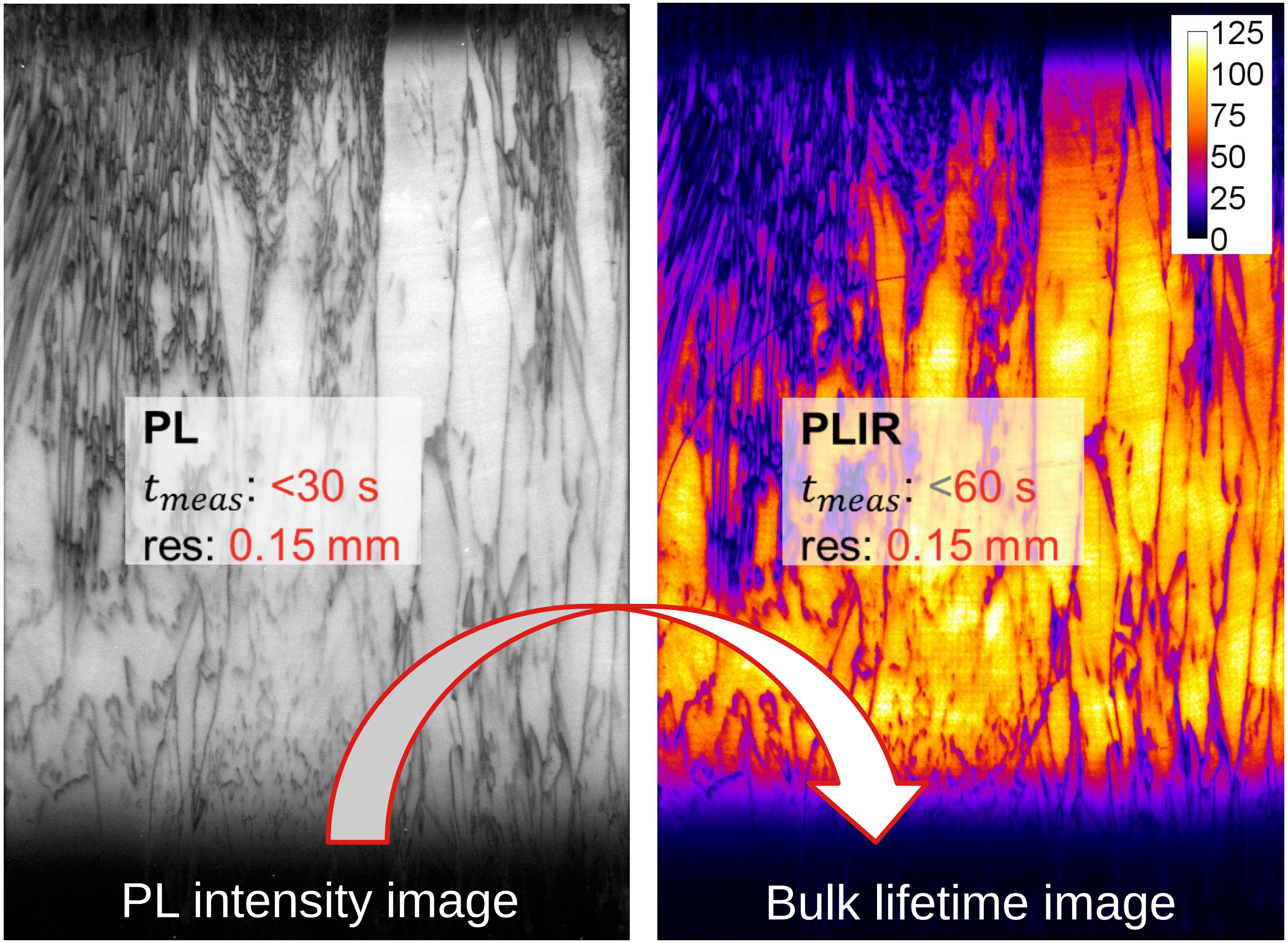
PLIR: from qualitative to quantitative images

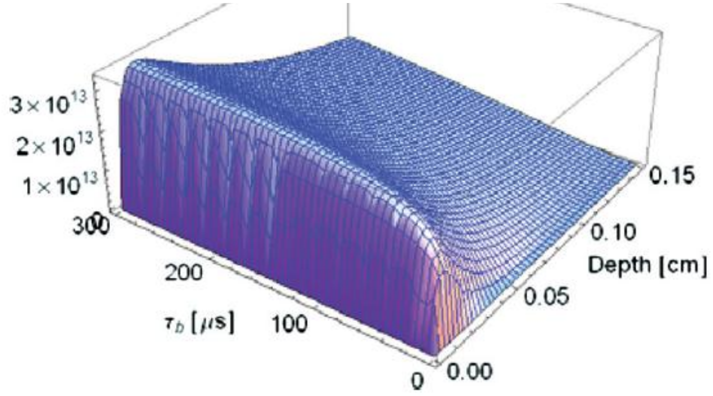


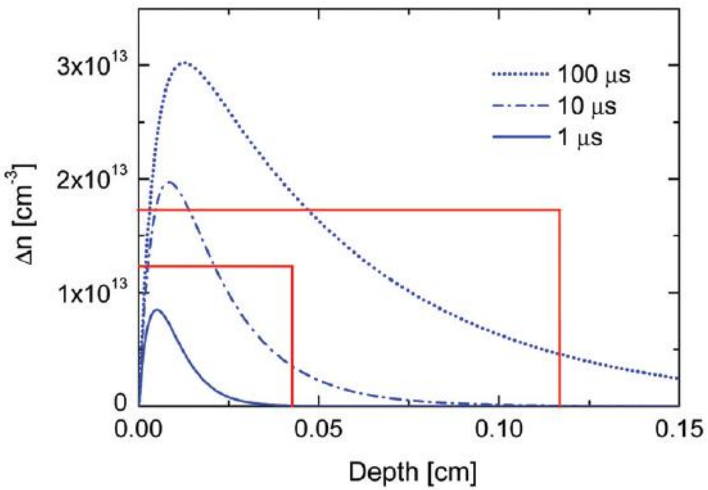
Modelling spectral PL response of brick

Assumptions: 1D model, bare surfaces, infinite depth, monochromatic excitation, thin surface damage layer (after polish), non-injection dependent bulk lifetimes

Includes: Temperature dependence (absorption coefficient, mobility), Free carrier absorption, SRV dependence, Excitation and filter selection

$$\Delta n(x) = \left(\frac{\alpha N_s L^2}{(\alpha^2 L^2 - 1) D} \right) (e^{-x/L} - e^{-\alpha x})$$





Spectral composition of luminescence

$$\Delta n(x) = \left(\frac{\alpha N_s L^2}{(\alpha^2 L^2 - 1)D}\right)(e^{-x/L} - e^{-\alpha x})$$

$$r_{sp}(\lambda, T) \propto \frac{\alpha(\lambda, T)}{\lambda^4} \exp\left(\frac{-e\hbar w}{kT}\right)$$

Reabsorption

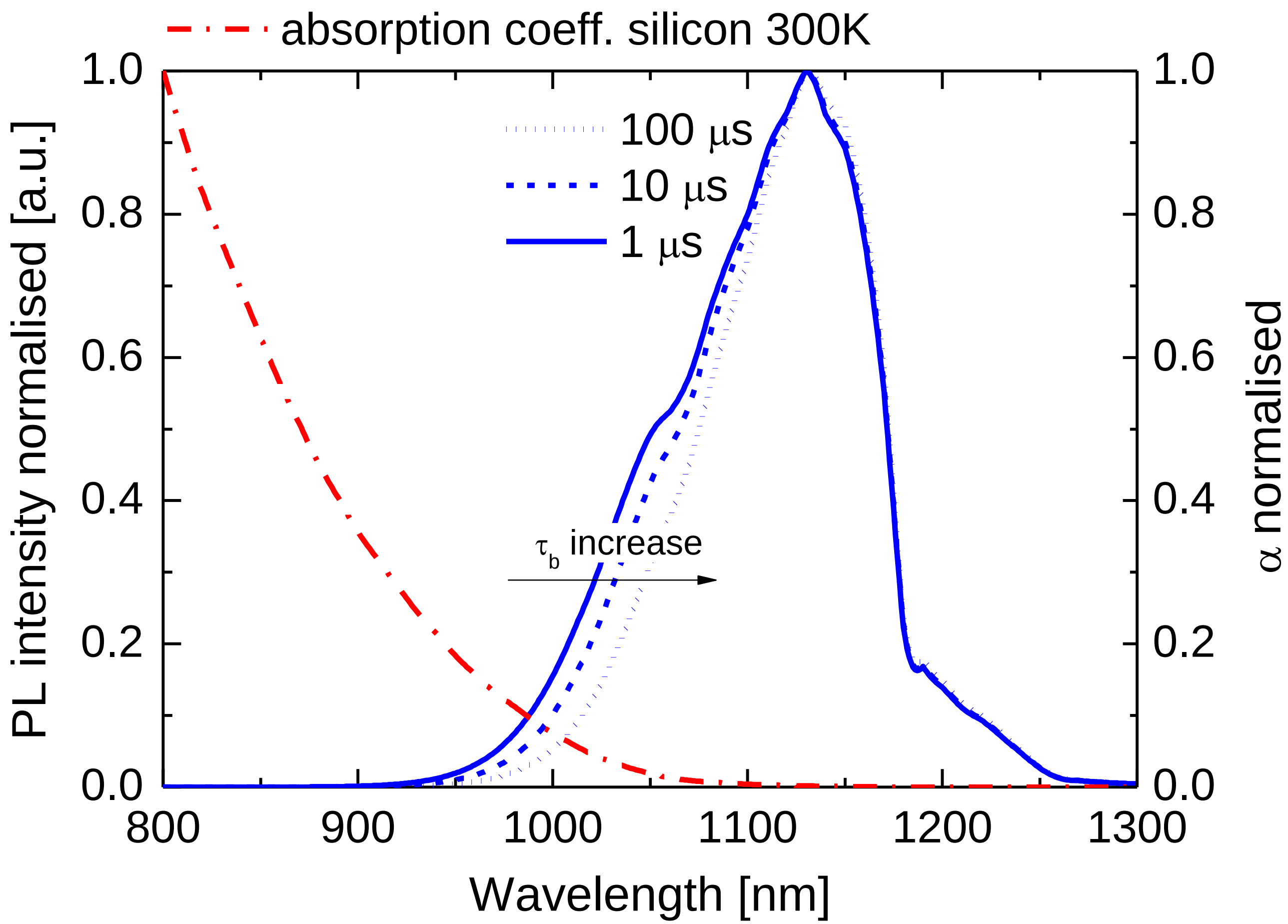
Experimental apparatus

$$PL(\tau_b) = \int_0^d \int_{\lambda_0}^{\lambda} r_{sp}(\lambda) \Delta n(x, \tau_b) e^{-\alpha(\lambda)x} \Theta(\lambda) d\lambda dx$$

*M. A. Green, Appl. Phys. Lett. 99, 131112 (2011)

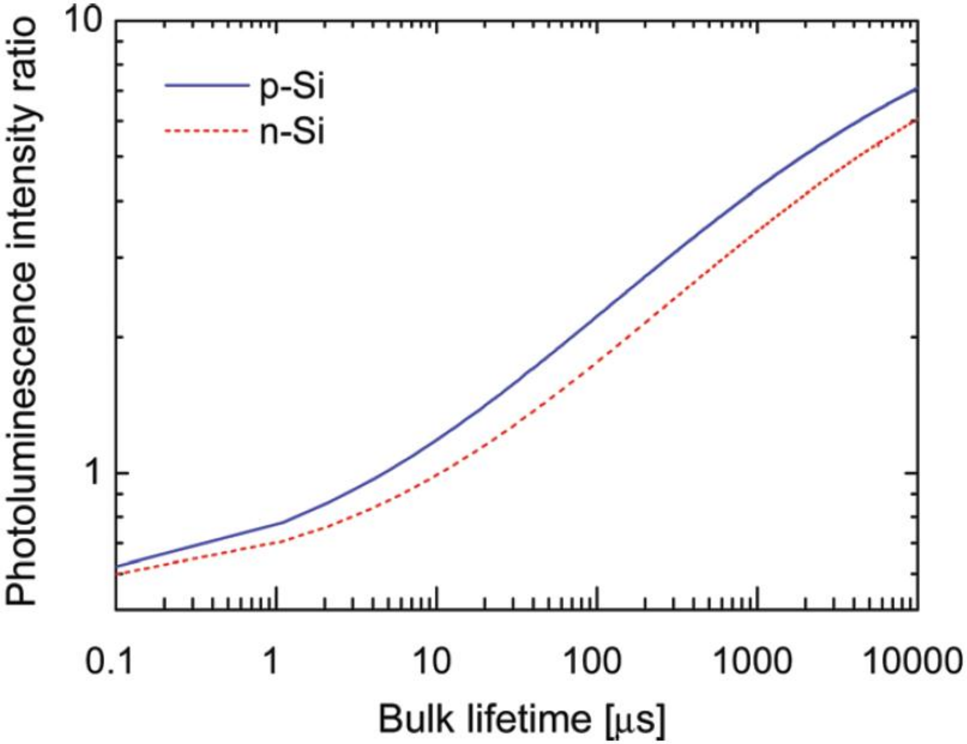
$$PL(\tau_b)\big|_{S\to\infty} \propto \int_{\lambda_0}^{\lambda} r_{sp}(\lambda) \frac{\alpha_{bb}(\lambda_{laser}) L^2(\tau_b)}{[\alpha_{tot}(\lambda_{laser}) + \alpha_{tot}(\lambda)][1 + \alpha_{tot}(\lambda_{laser}) L(\tau_b)][1 + \alpha_{tot}(\lambda) L(\tau_b)]} \Theta(\lambda) d\lambda$$

Spectral composition of luminescence



PL spectral intensity ratio

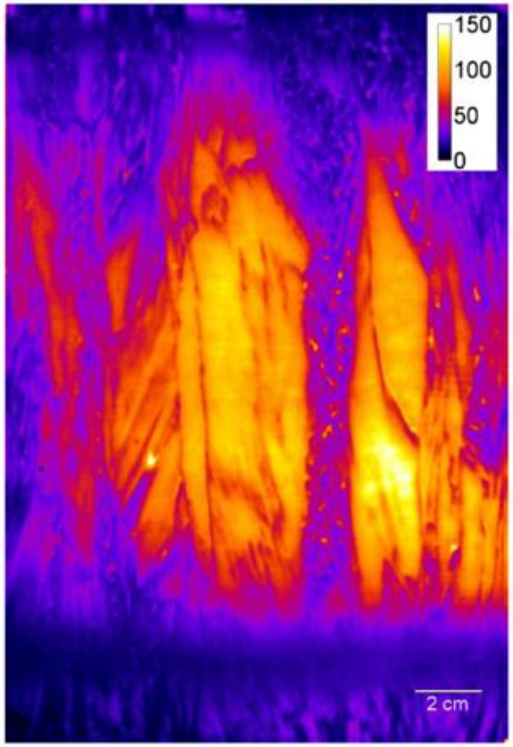
$$PL(\tau_b)\big|_{S\to\infty} \propto \int_{\lambda_0}^{\lambda} r_{sp}(\lambda)\frac{\alpha_{bb}(\lambda_{laser})L^2(\tau_b)}{[\alpha_{tot}(\lambda_{laser})+\alpha_{tot}(\lambda)][1+\alpha_{tot}(\lambda_{laser})L(\tau_b)][1+\alpha_{tot}(\lambda)L(\tau_b)]}\Theta(\lambda)d\lambda$$



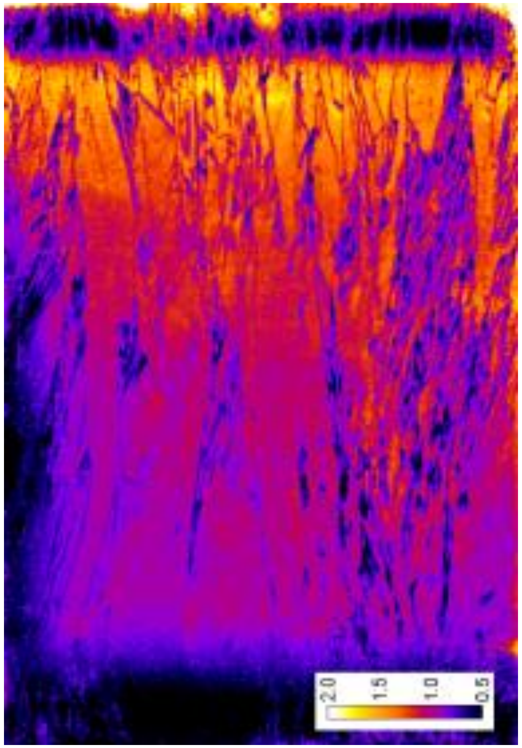
$$PLIR(\tau_b) = \frac{PL_{longpass}(\tau_b)}{PL_{shortpass}(\tau_b)}$$

Proof of concept images

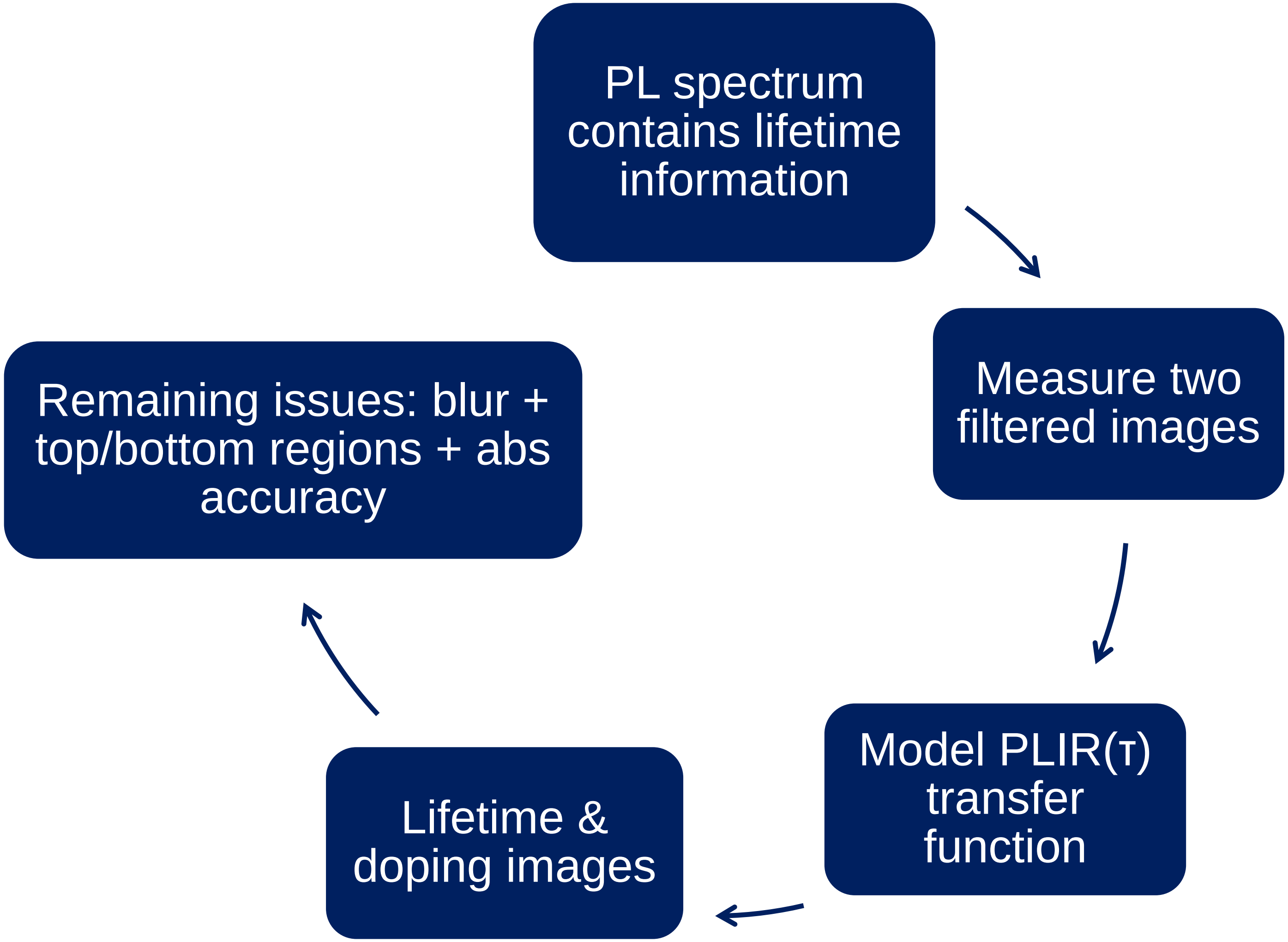
τ_b [μs]



N_A [$10^{16} cm^{-3}$]



What have we learned so far?



Overcoming experimental limitations

JOURNAL OF APPLIED PHYSICS **112**, 063116 (2012)

On the method of photoluminescence spectral intensity ratio imaging of silicon bricks: Advances and limitations

Bernhard Mitchell,[1,a)] Jürgen W. Weber,[2] Daniel Walter,[3] Daniel Macdonald,[3] and Thorsten Trupke[1,2]
[1]*School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, NSW 2052, Australia*
[2]*BT Imaging, 1 Blackburn St, Surry Hills, NSW 2010, Australia*
[3]*Research School of Engineering, College of Engineering and Computer Science, The Australian National University, Canberra, ACT 0200, Australia*

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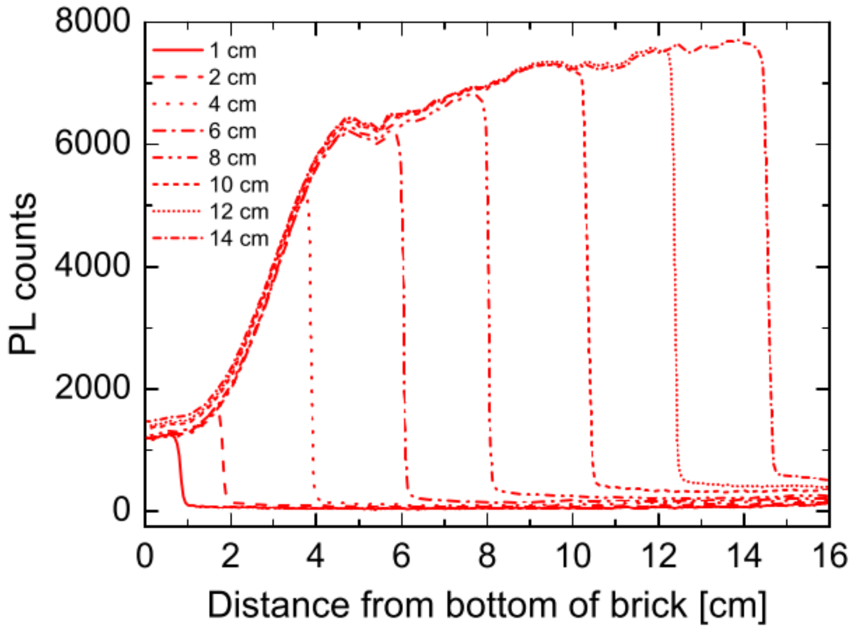
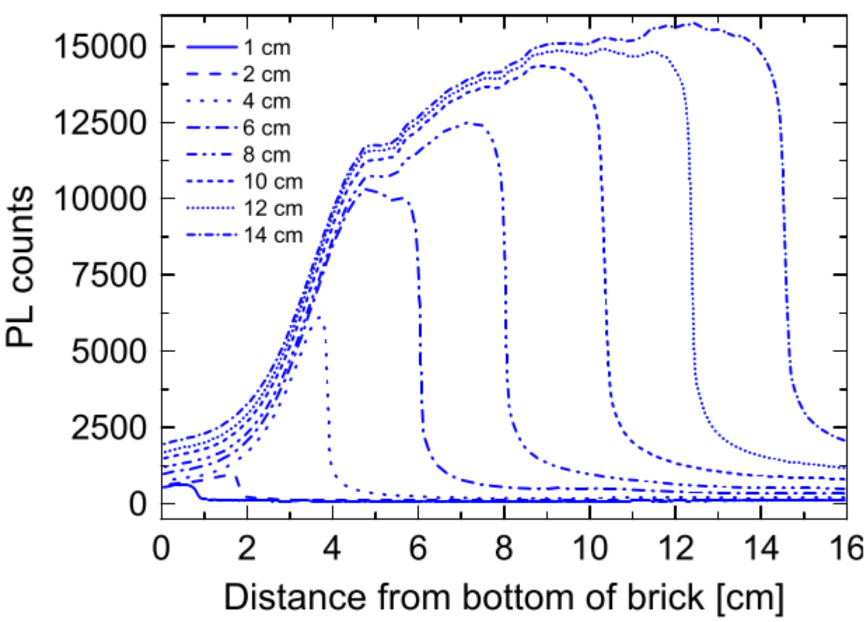
Optical light spread in detection CCD: Masking experiment

SP filtered

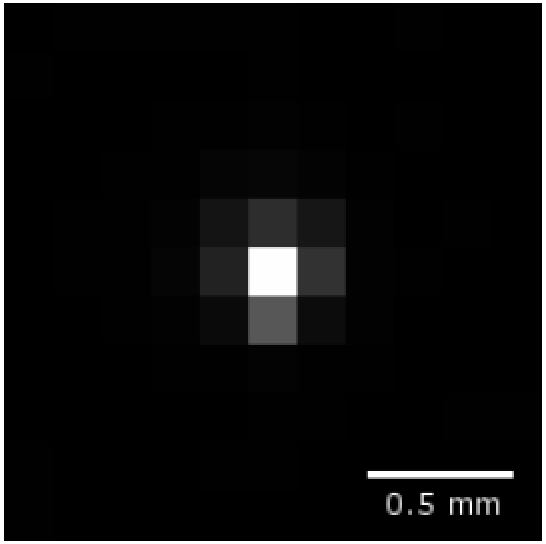


LP filtered

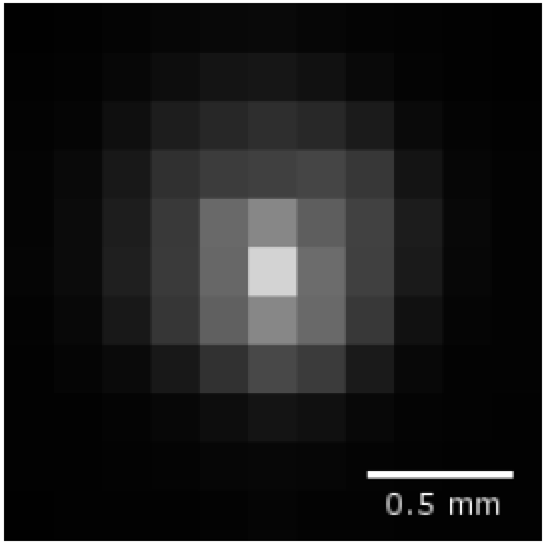


Optical light spread of localised illumination

SP filtered

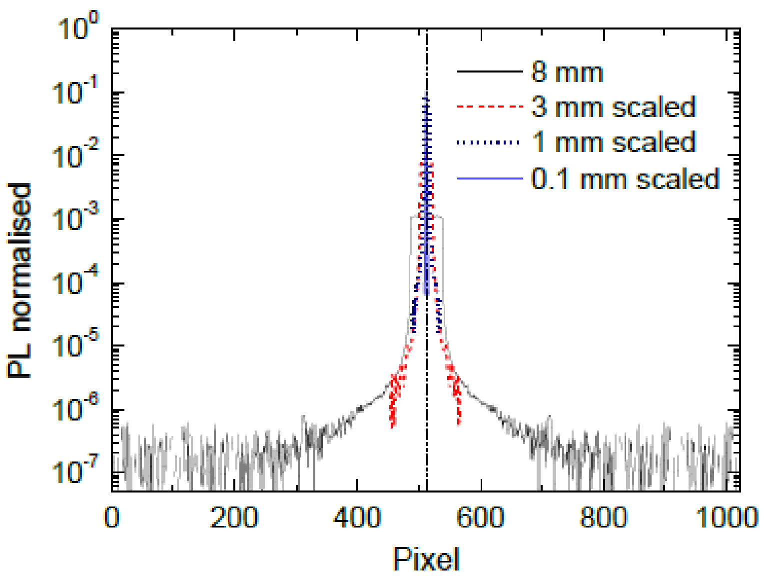


LP filtered

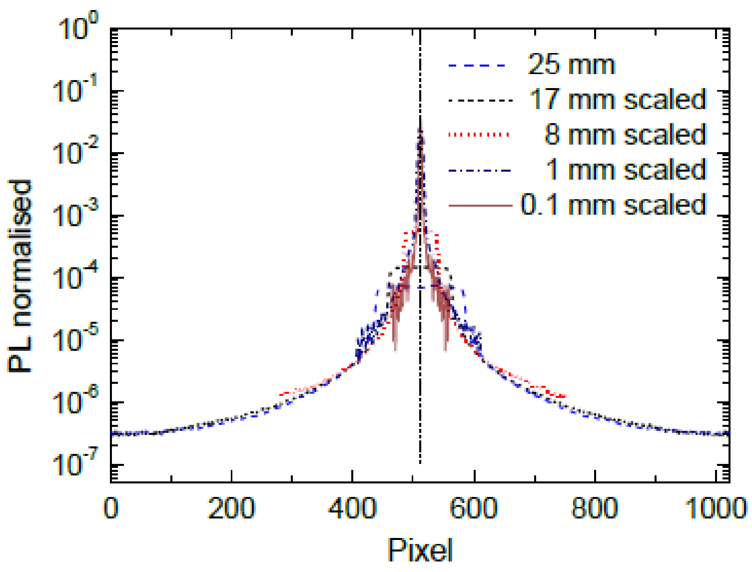


Measurement of Point Spread Functions (PSF)

SP detection

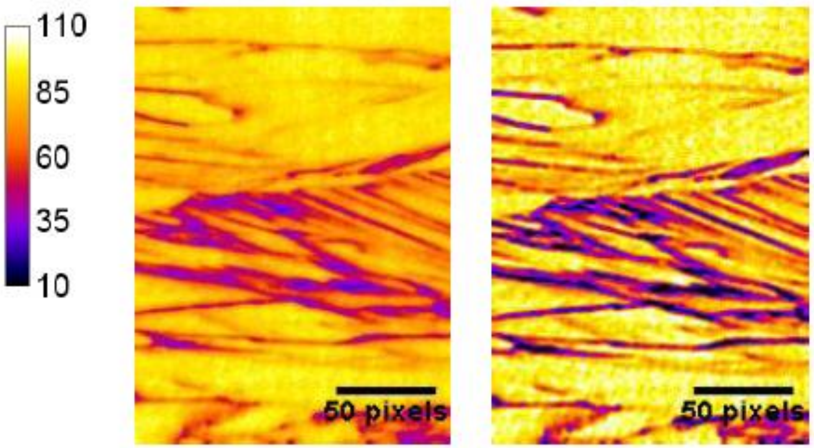


LP detection



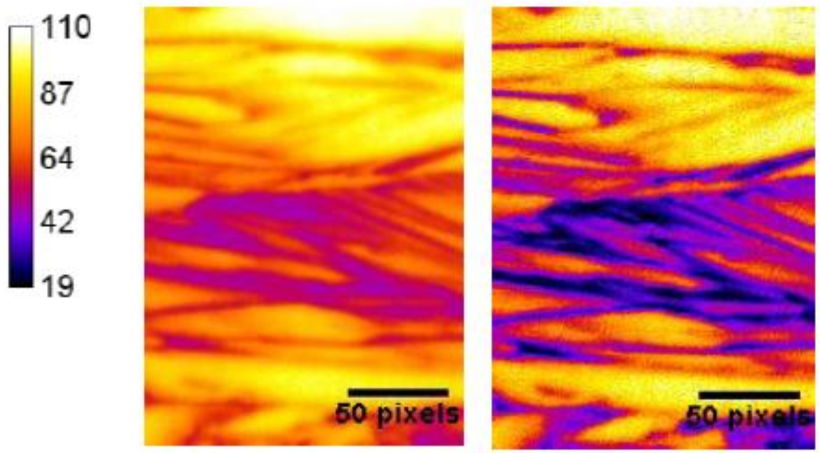
Deconvolution of single images

SP filtered



As measured   Deconvoluted

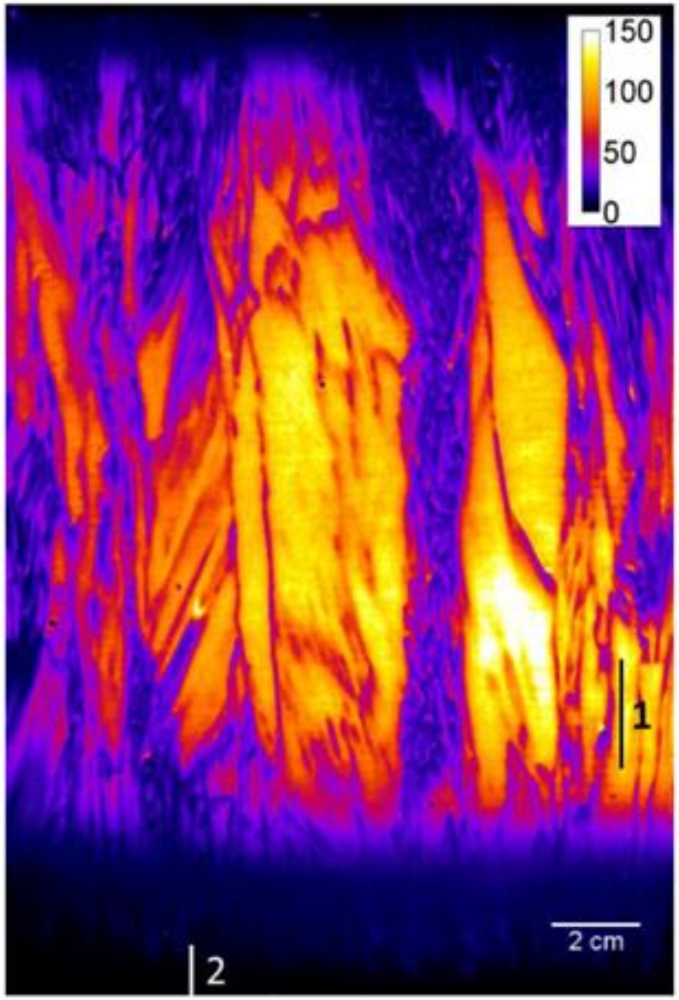
LP filtered



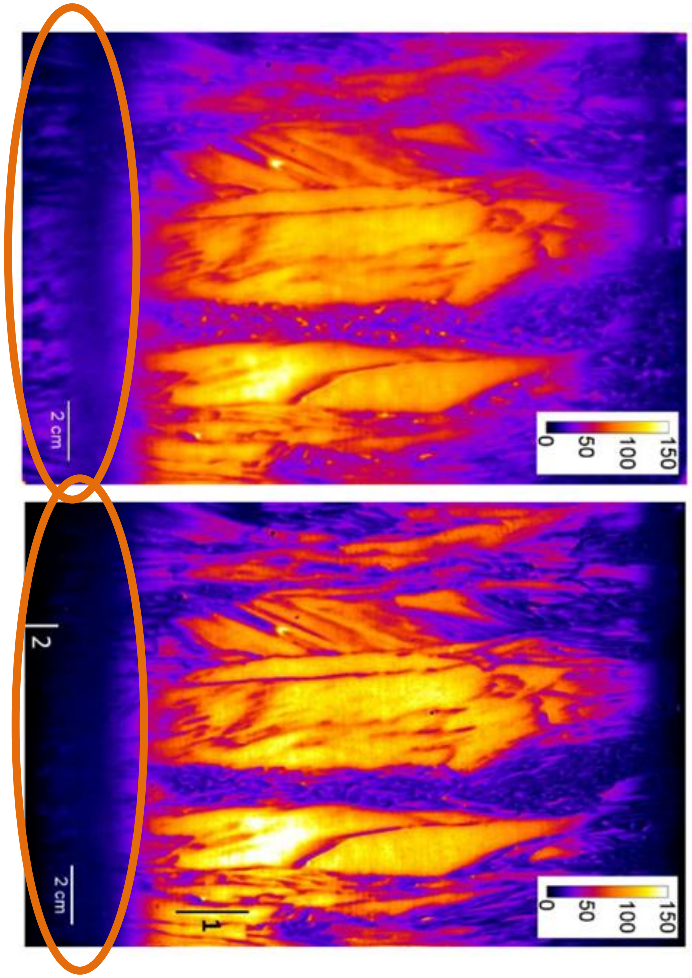
As measured   Deconvoluted

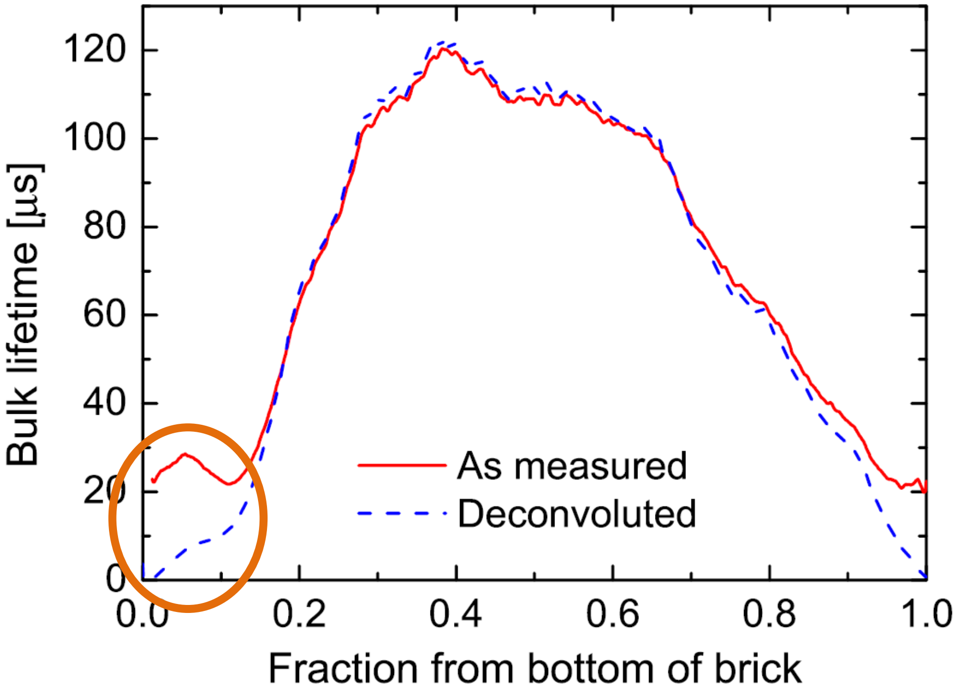
Improved bulk lifetime image

Deconvoluted:

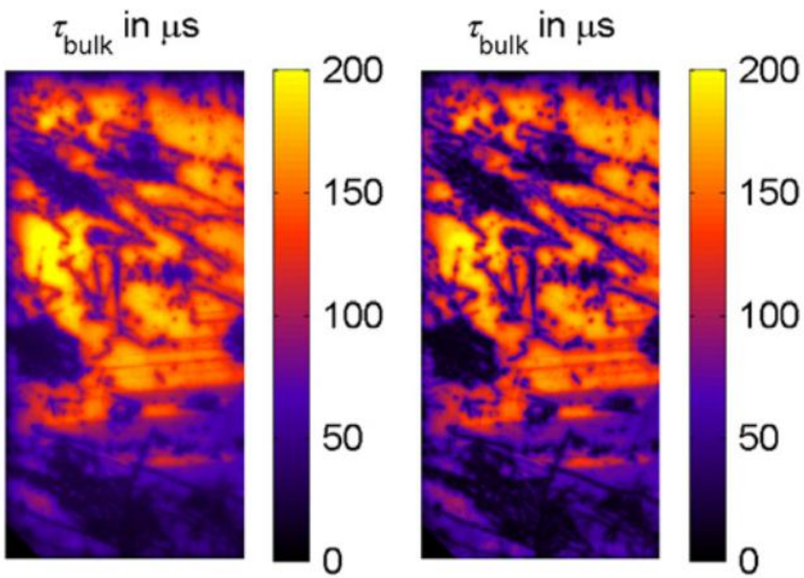


Bottom and top data strongly improved





Light spreading effects wafer measurements!



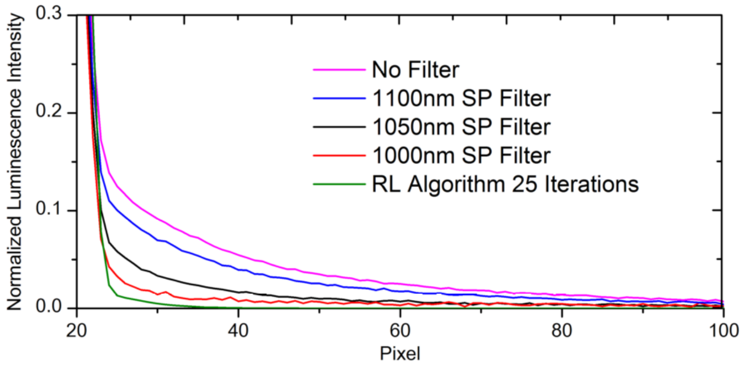
As measured

SP 1000 filtered

Example: Estimate of efficiency potential of mc-Si wafers

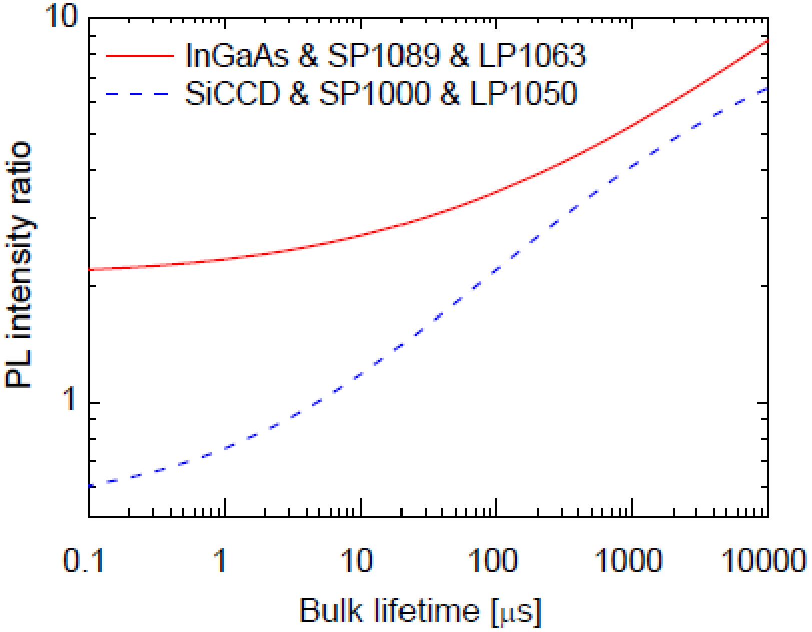
B. Michl, M. Rüdiger, J. A. Giesecke, M. Hermle, W. Warta, and M. C. Schubert, “Efficiency limiting bulk recombination in multicrystalline silicon solar cells,” Solar Energy Materials and Solar Cells, vol. 98, pp. 441-447, Mar. 2012.

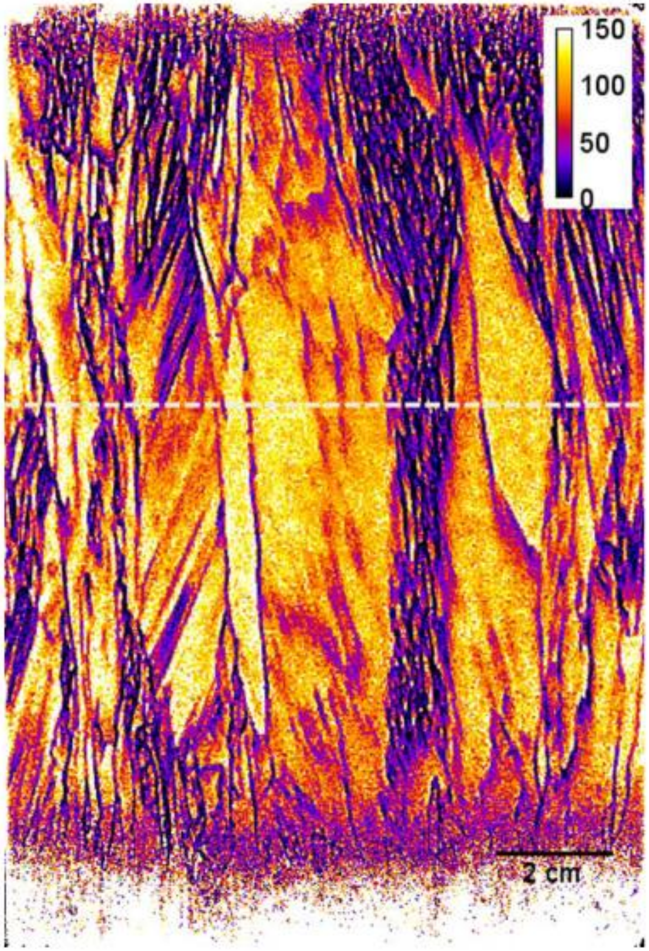
Low blur images crucial for quantitative evaluation of PL data!



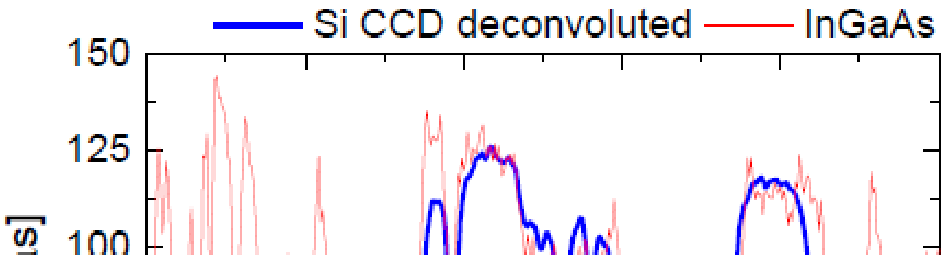
D. Walter, A. Liu, E. Franklin, D. Macdonald, B. Mitchell, and T. Trupke, in IEEE 38th Photovoltaic Specialists Conference, Austin, TX, 3–8 June 2012

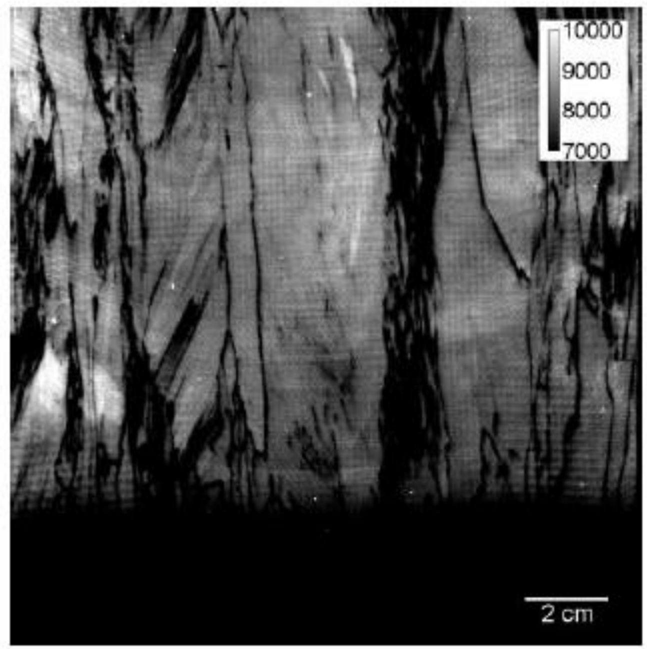
Alternative InGaAs detected PLIR?

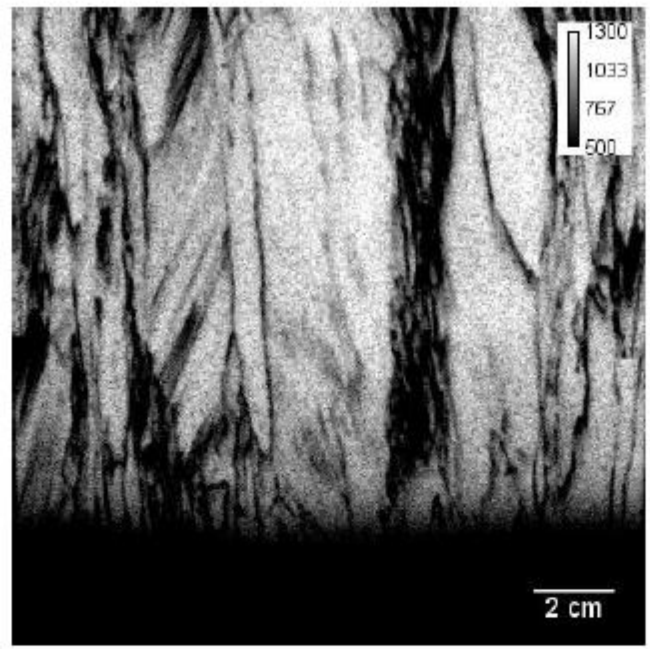




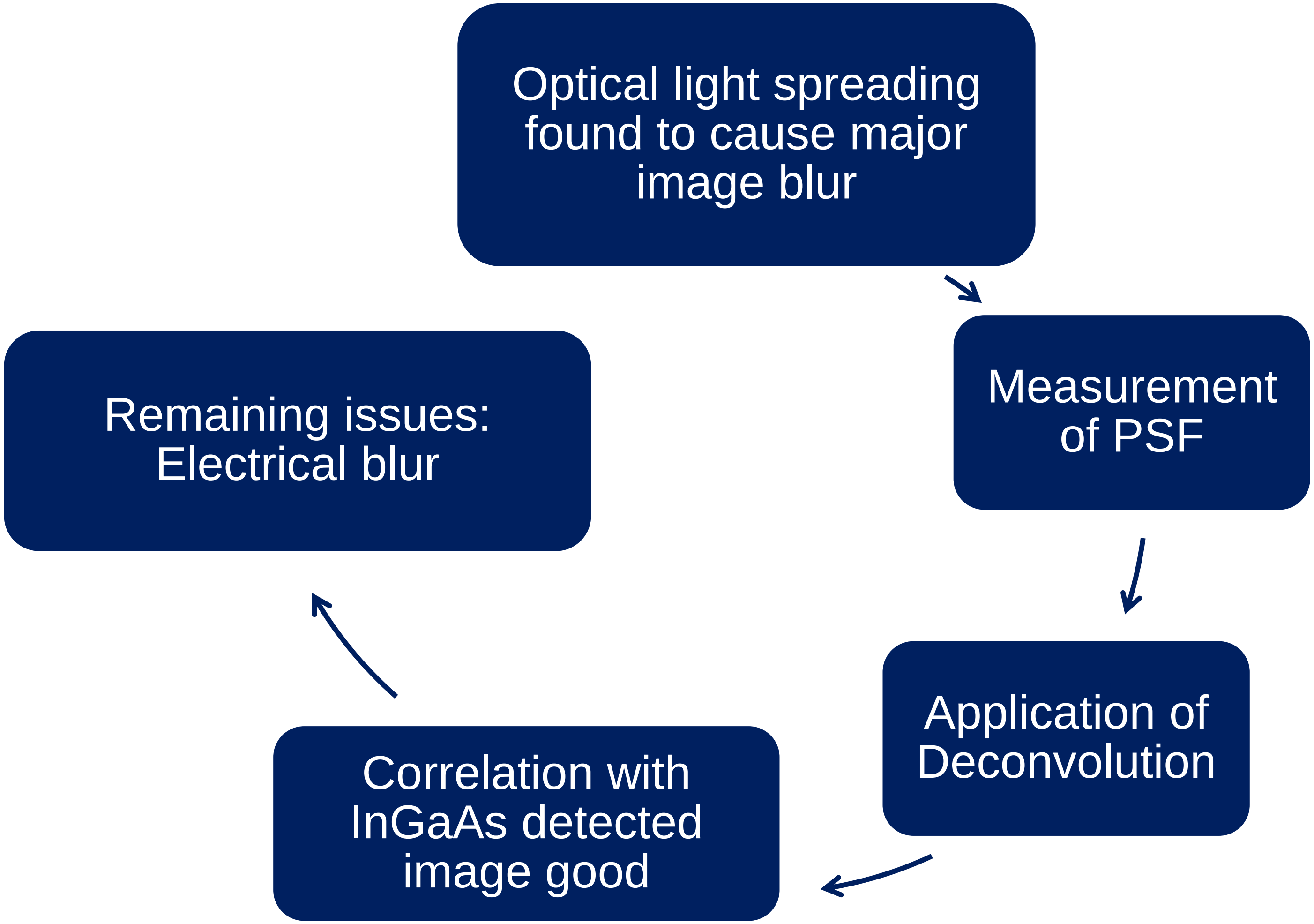
Alternative InGaAs detected PLIR?







What have we learned more?



Quantifying physical limitations

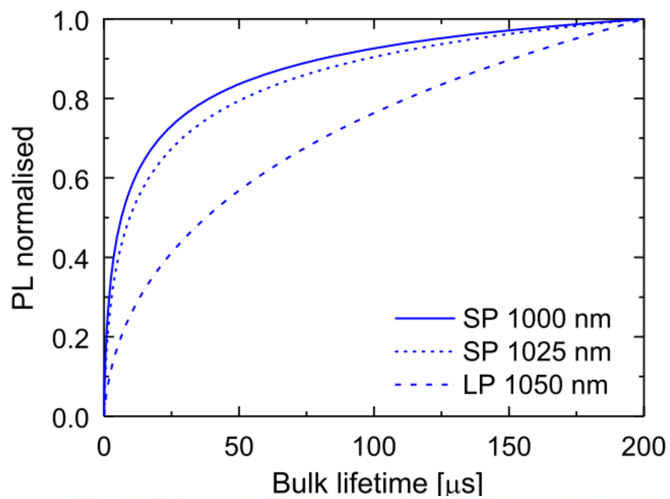
Solar Energy Materials & Solar Cells 107 (2012) 75–80

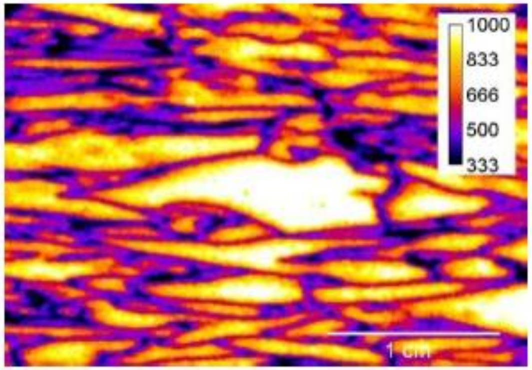
Quantifying the effect of minority carrier diffusion and free carrier absorption on photoluminescence bulk lifetime imaging of silicon bricks

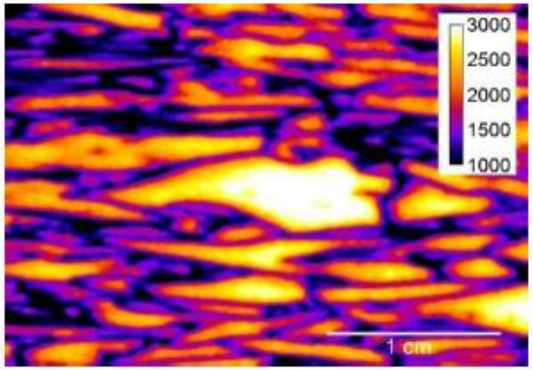
Bernhard Mitchell [a,*], Johannes Greulich [b], Thorsten Trupke [a,c]

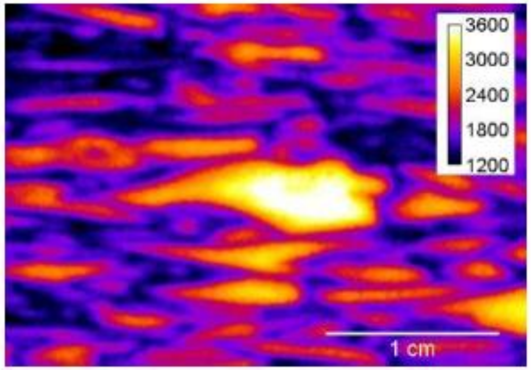
[a] *School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, NSW 2052, Australia*
[b] *Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstr. 2, 79110 Freiburg, Germany*
[c] *BT Imaging, 1 Blackburn St, Surry Hills, NSW 2010, Australia*

Image contrast and minority carrier diffusion







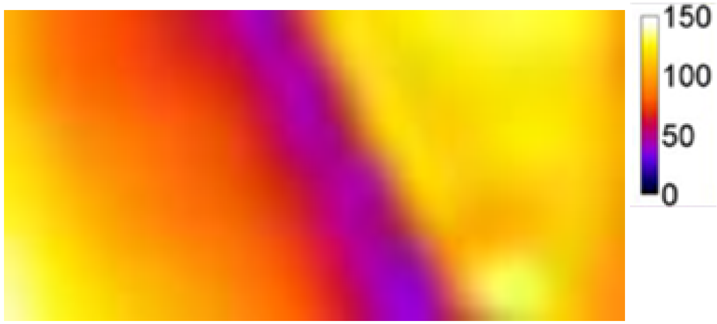


SP 1000 nm filtered

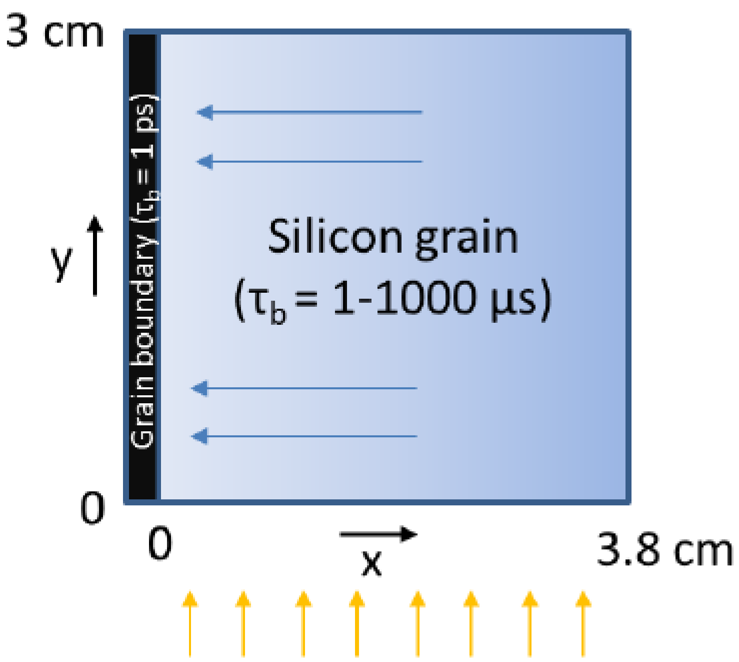
SP 1025 nm filtered

LP 1050 nm filtered

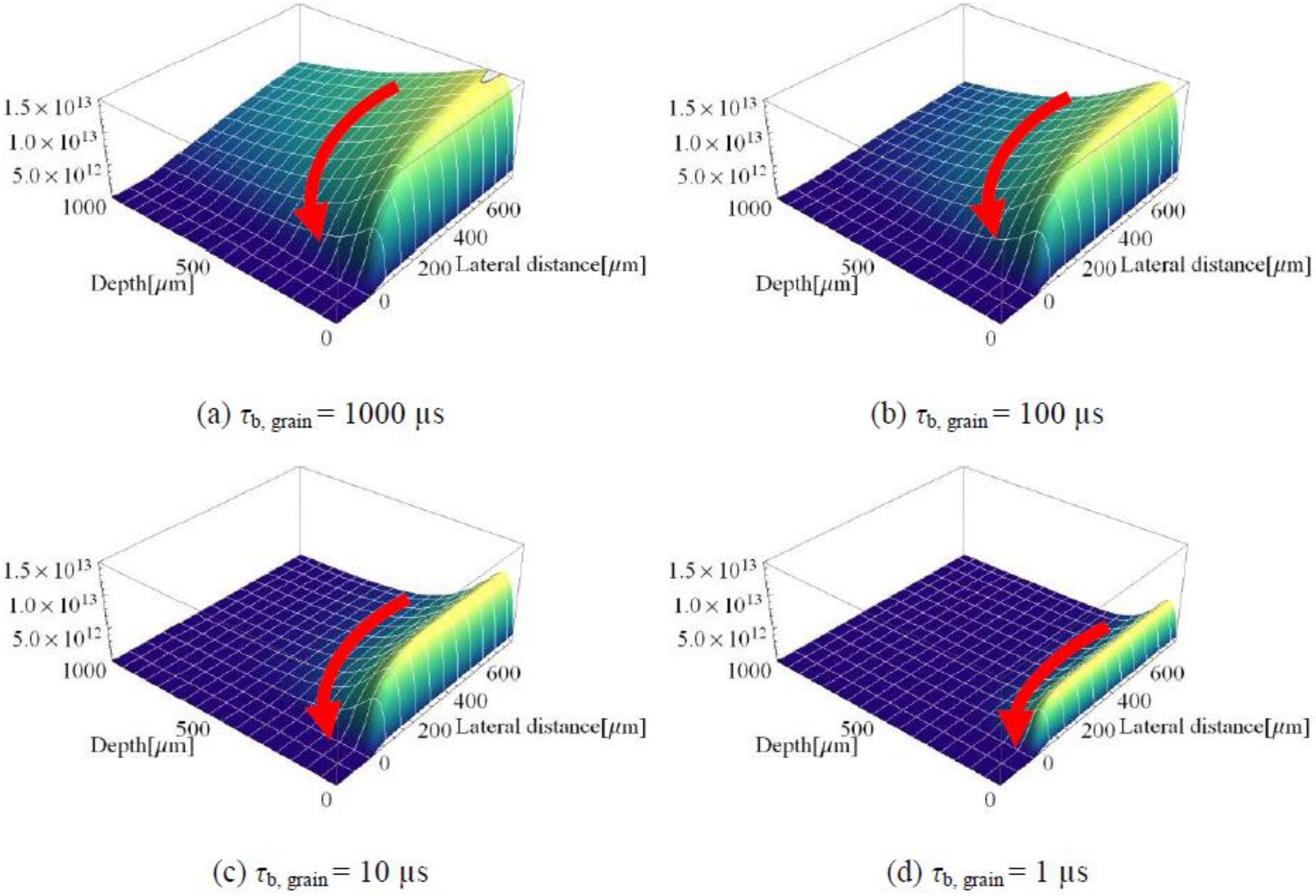
Study: Grain / Grain boundary interface



Measured bulk lifetime contrast at GB [μs]



Electrical simulation: 2D excess carrier densities



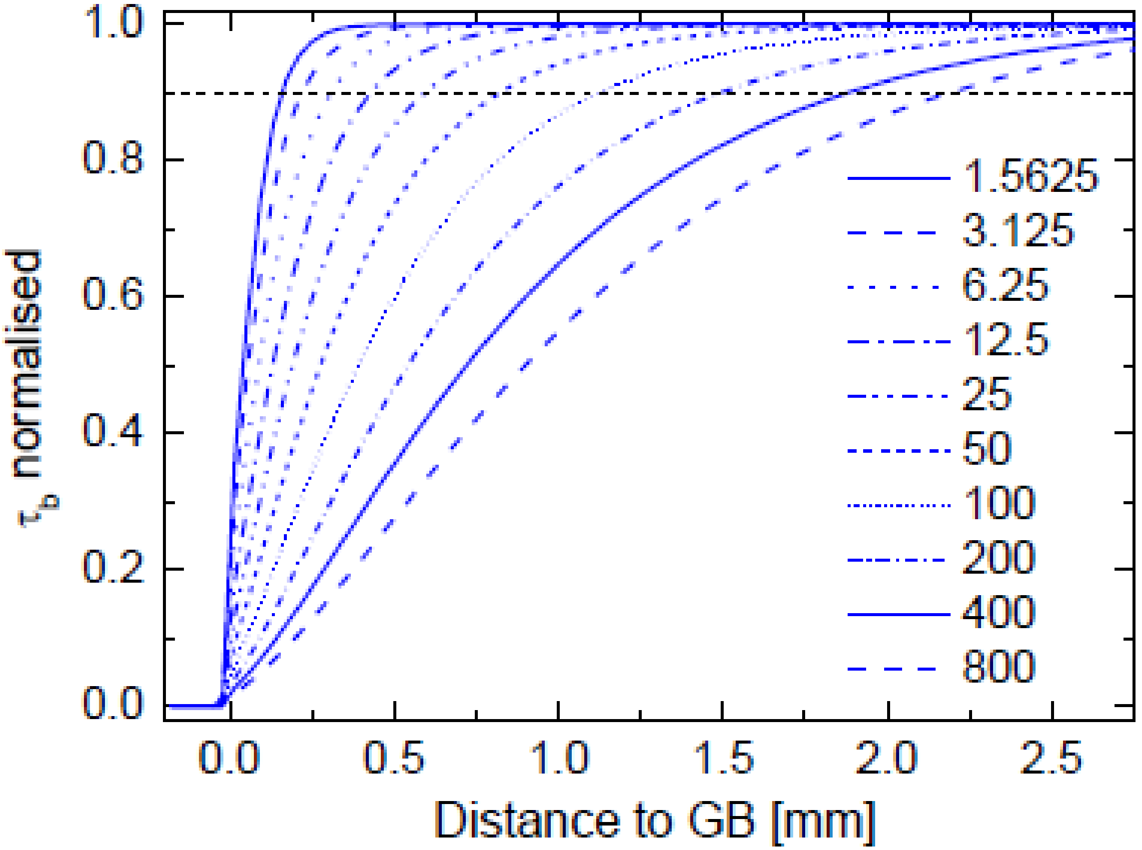
(a) $\tau_{b,\ grain} = 1000\ \mu s$

(b) $\tau_{b,\ grain} = 100\ \mu s$

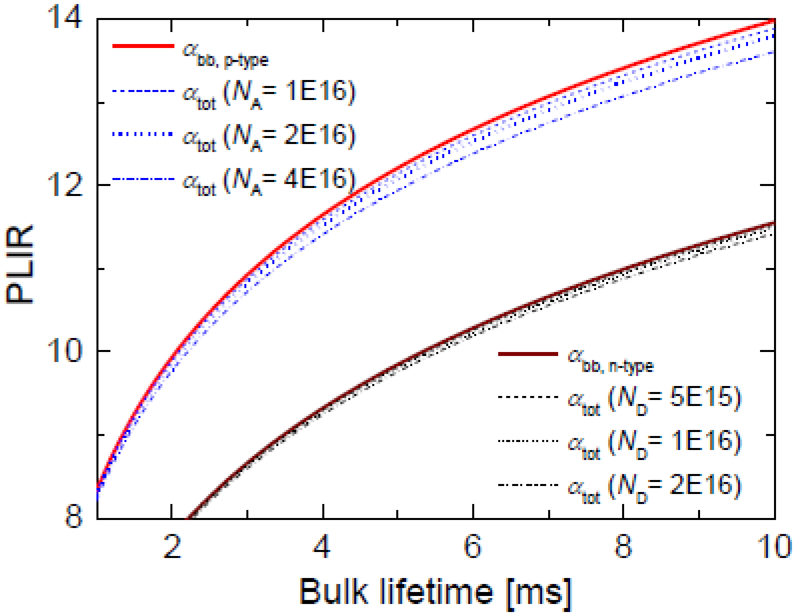
(c) $\tau_{b,\ grain} = 10\ \mu s$

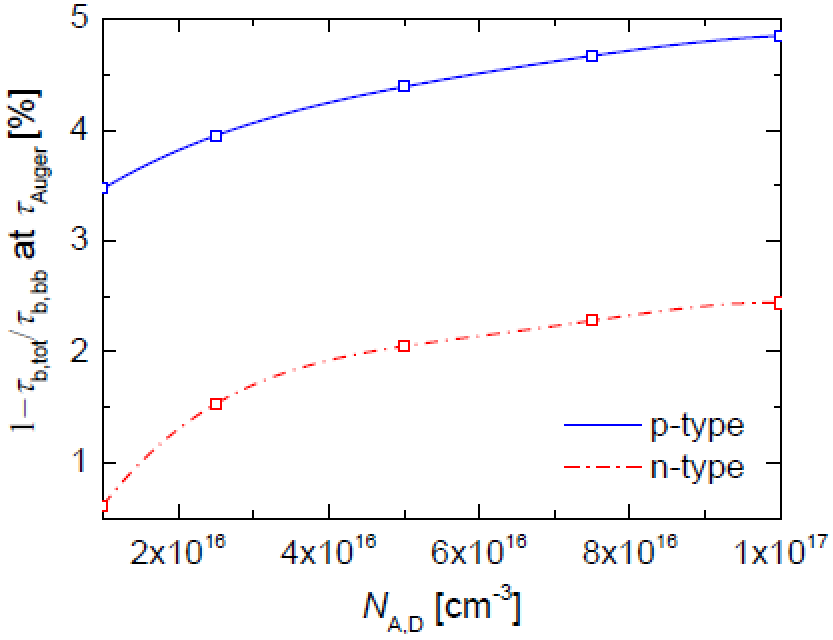
(d) $\tau_{b,\ grain} = 1\ \mu s$

Lateral effect of diffusion on PLIR detected bulk lifetime

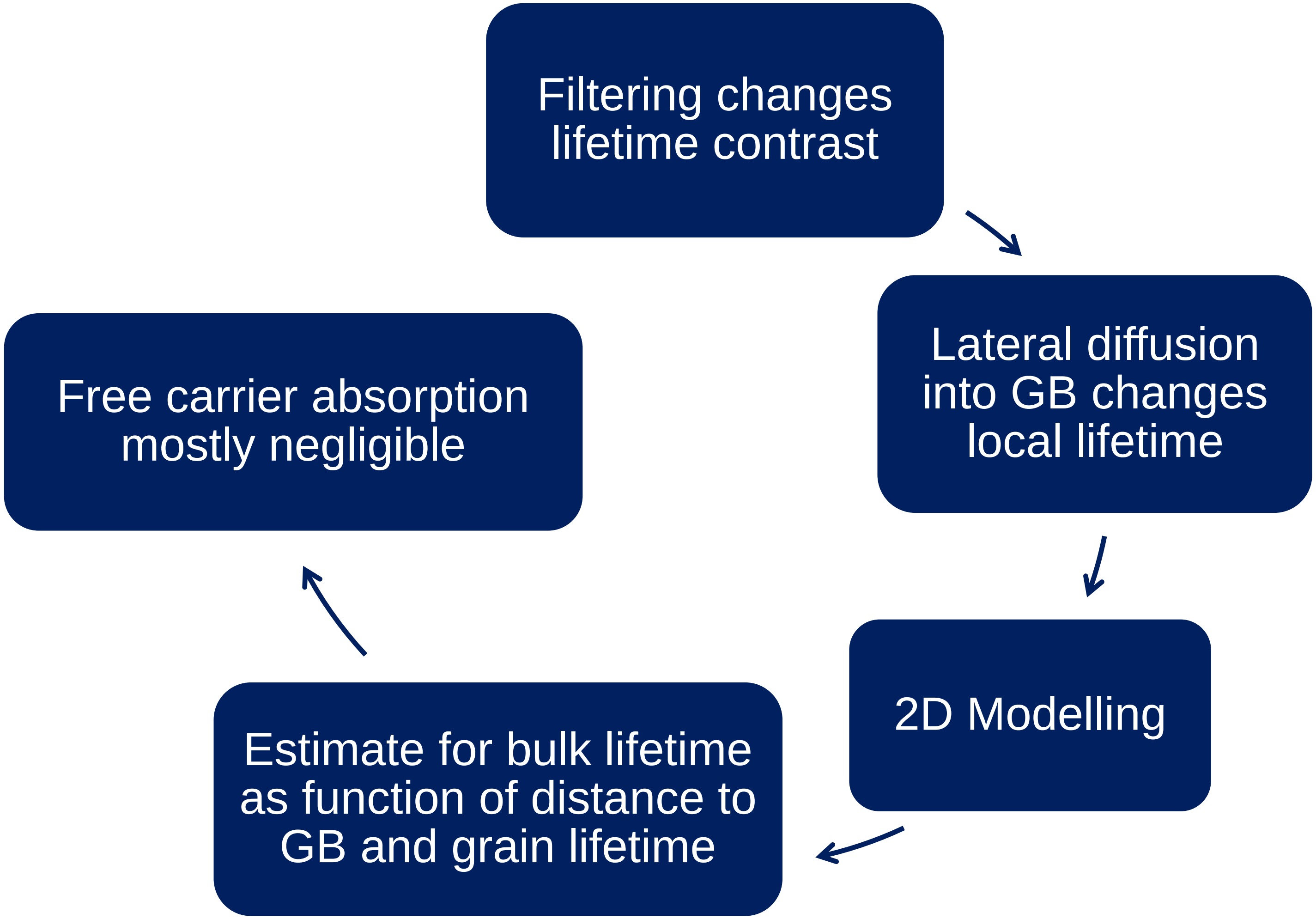


Effect of free carrier absorption





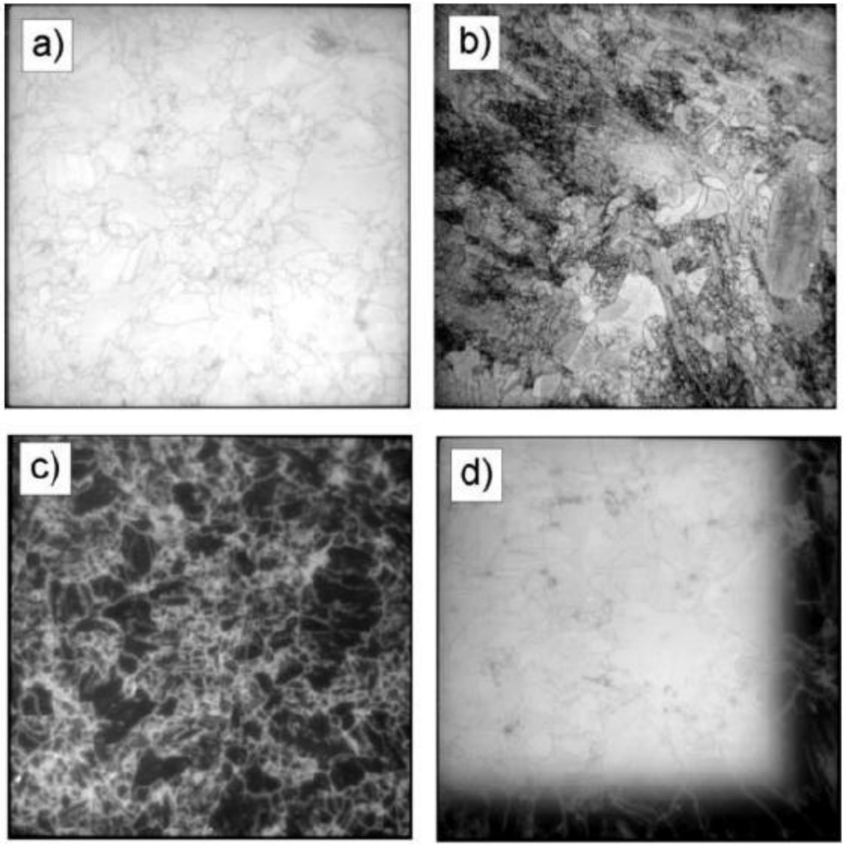
Further conclusions



Outlook brick characterisation

- Impurity analyses on brick level
- Full spectrum analyses
- Efficiency predictions?
- Inline measurements

Inline inspection and sorting of as-cut wafers

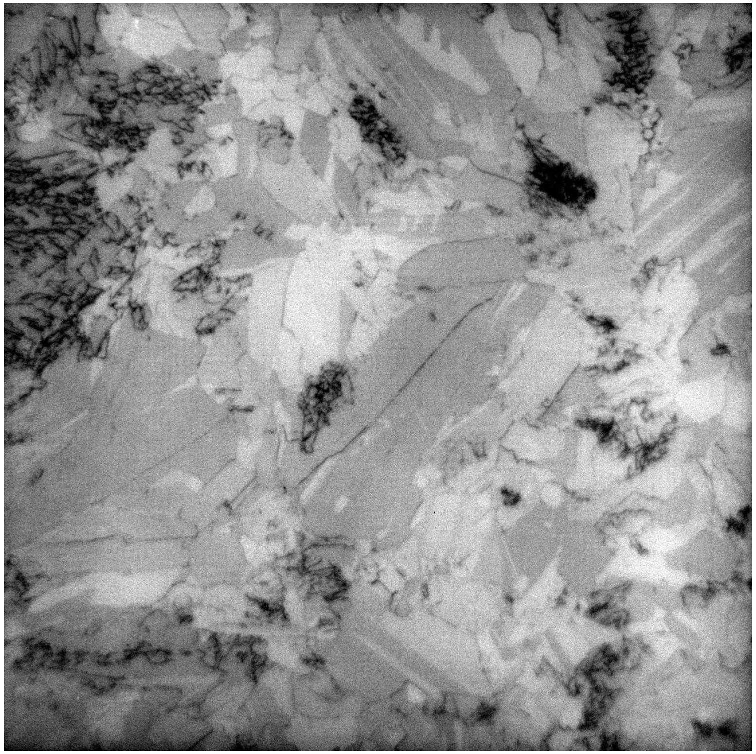


As cut wafer vary vastly in impurity and dislocation concentration!

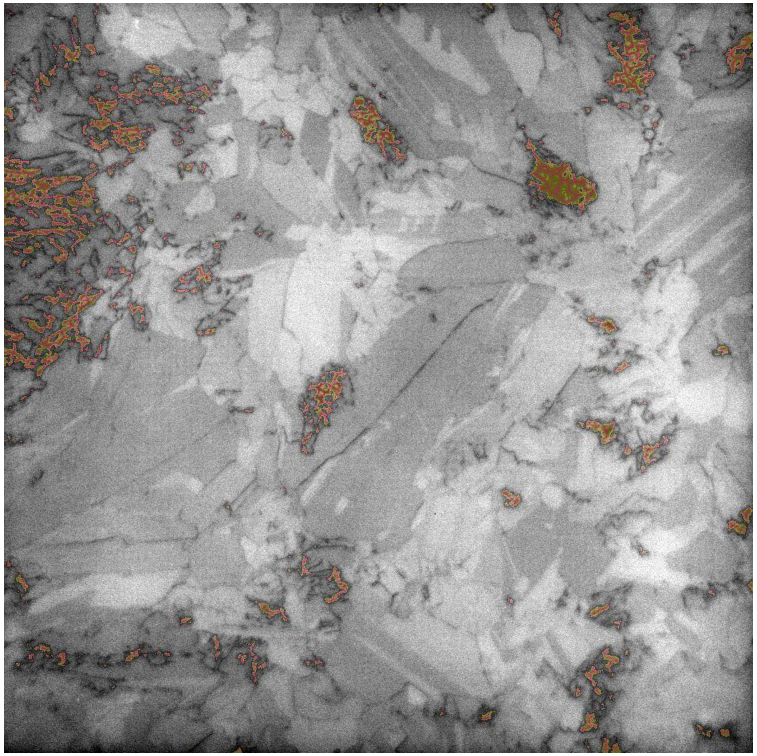
Inspection and classification at inline speed now possible!

Dislocation Defect Classification: mc-Si & cast mono

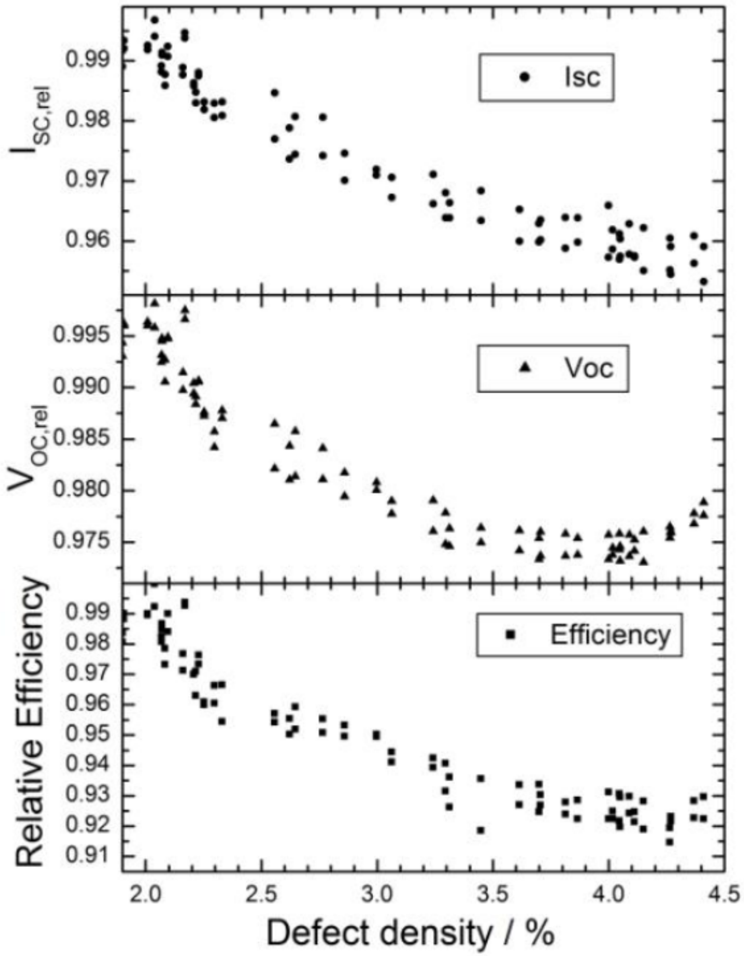
PL Image



Processed Image



Correlation between defect metrics and cell performance

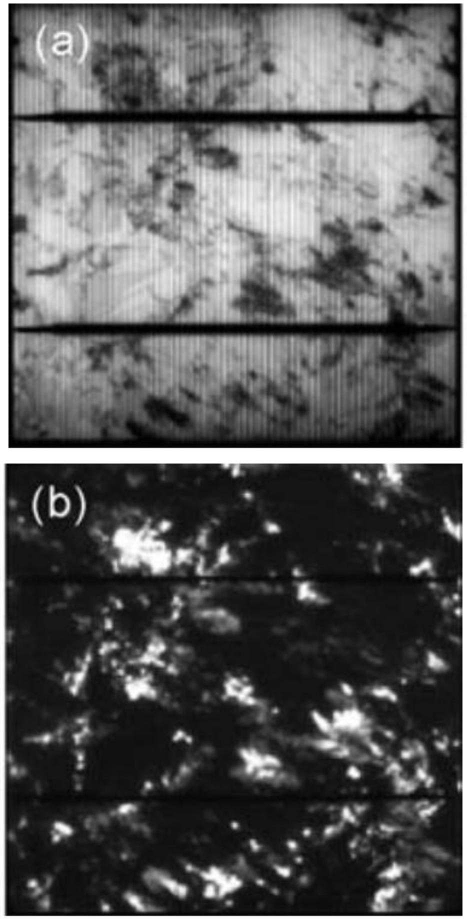


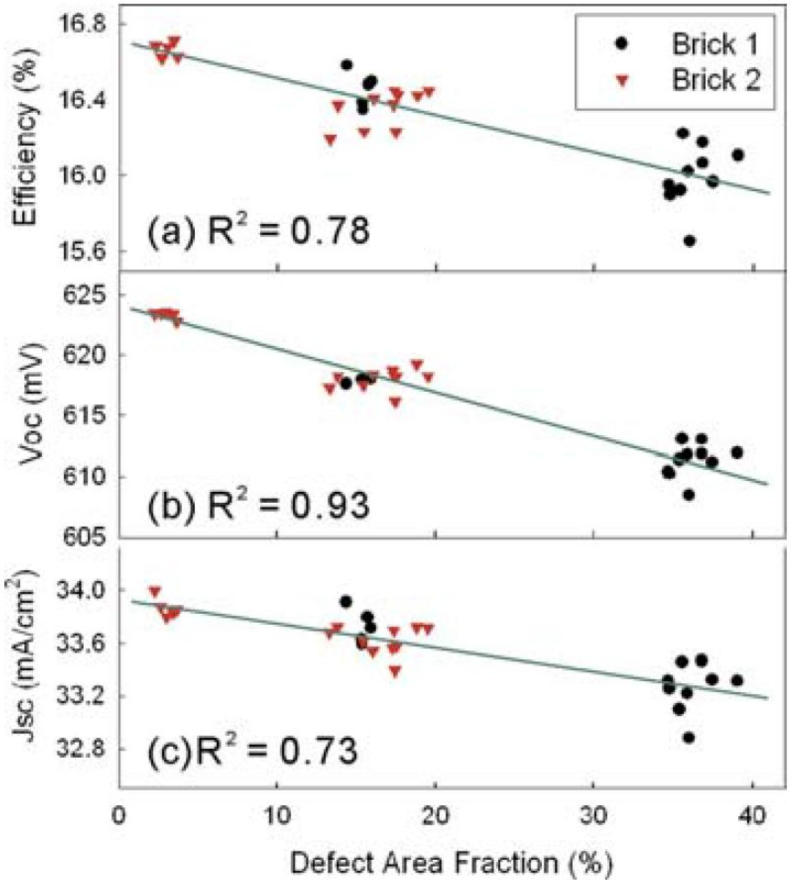
➔ Strong correlation of IV data with PL defect metric!

➔ No lifetime data used for correlation!

W. McMillan, T. Trupke, J. Weber, M. Wagner, U. Mareck, Y.C. Chou, and J. Wong, "In-line monitoring of electrical wafer quality using photoluminescence imaging," *Proceedings of 25th EPVSC, Valencia, Spain, September*, 2010.

Defect band imaging





[22] F. Yan et al., "Defect-band photoluminescence imaging on multi-crystalline silicon wafers," *physica status solidi (RRL) - Rapid Research Letters*, vol. 6, no. 5, pp. 190-192, May 2012.

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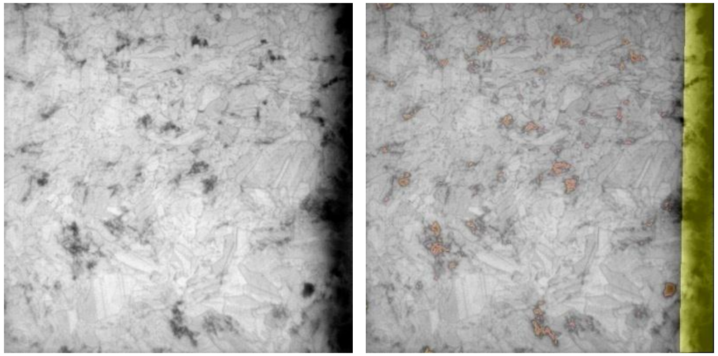
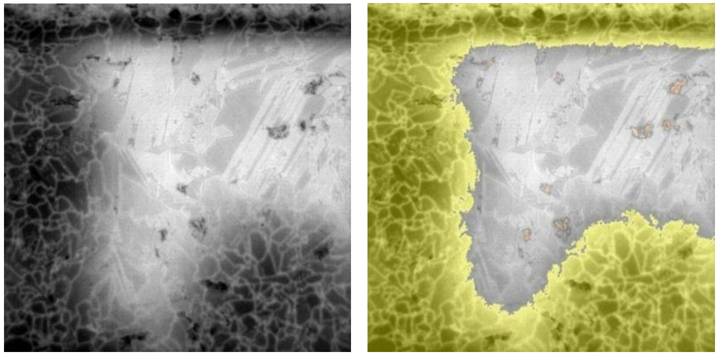
Impurity Signatures

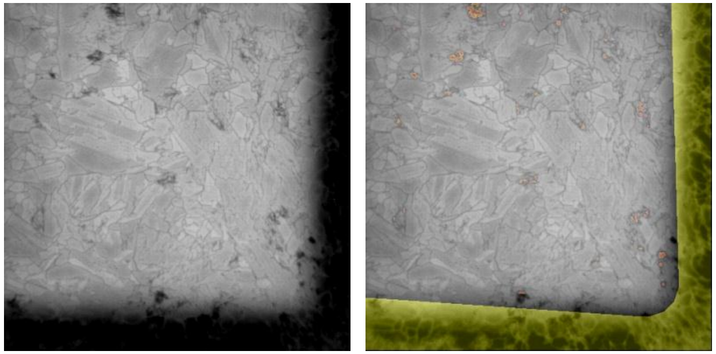
Ingot Edge



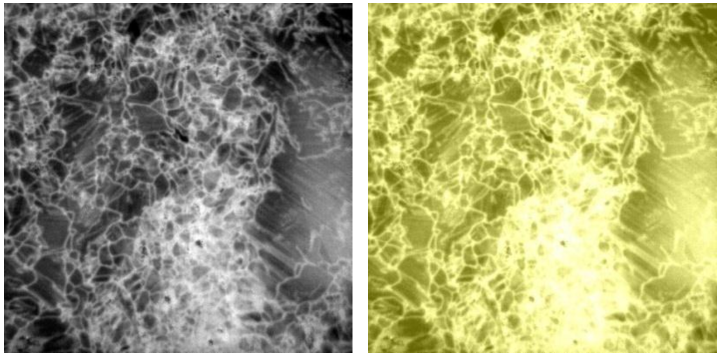
Transition



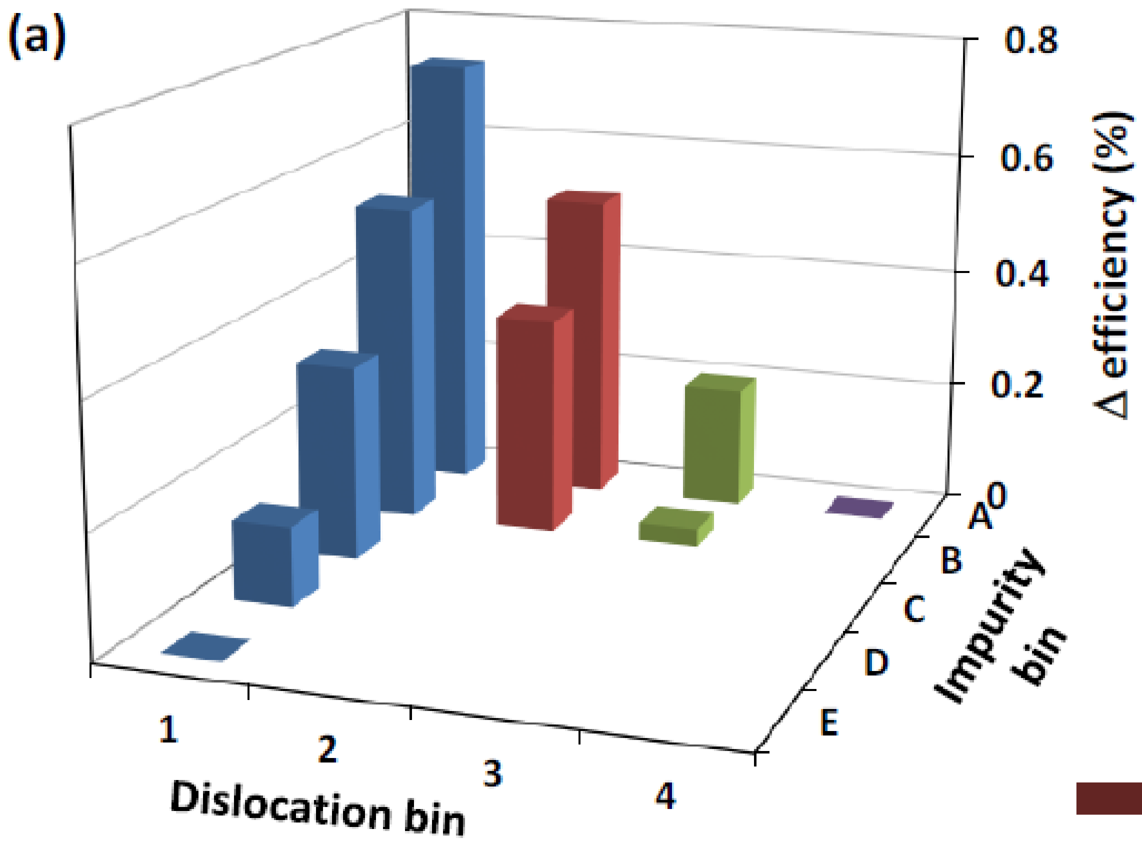
Ingot Corner



Fully Impure (top/bottom)



Impurity Signatures



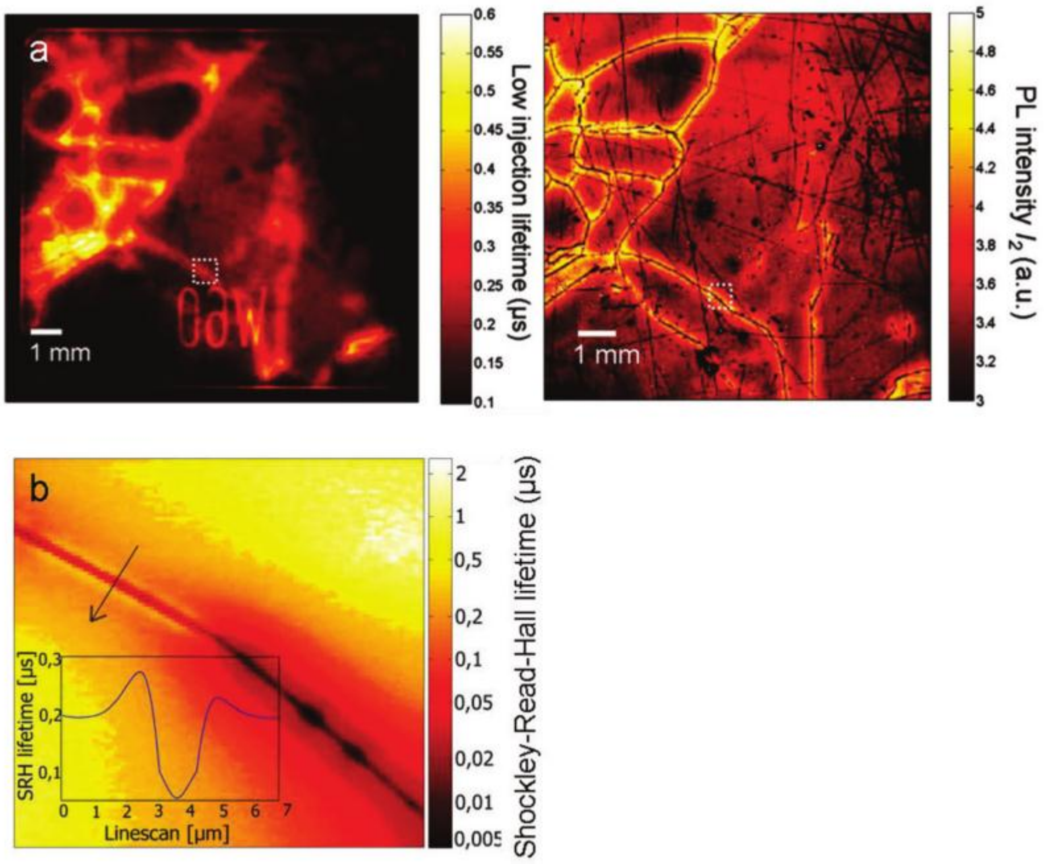
Dependence on dislocation density, weaker than usual.

Strong dependence on impurity fraction!

→ Poor gettering!

Characterisation of Advanced Cell Concepts with Sub-Micron Resolution

Micro PL spectroscopy



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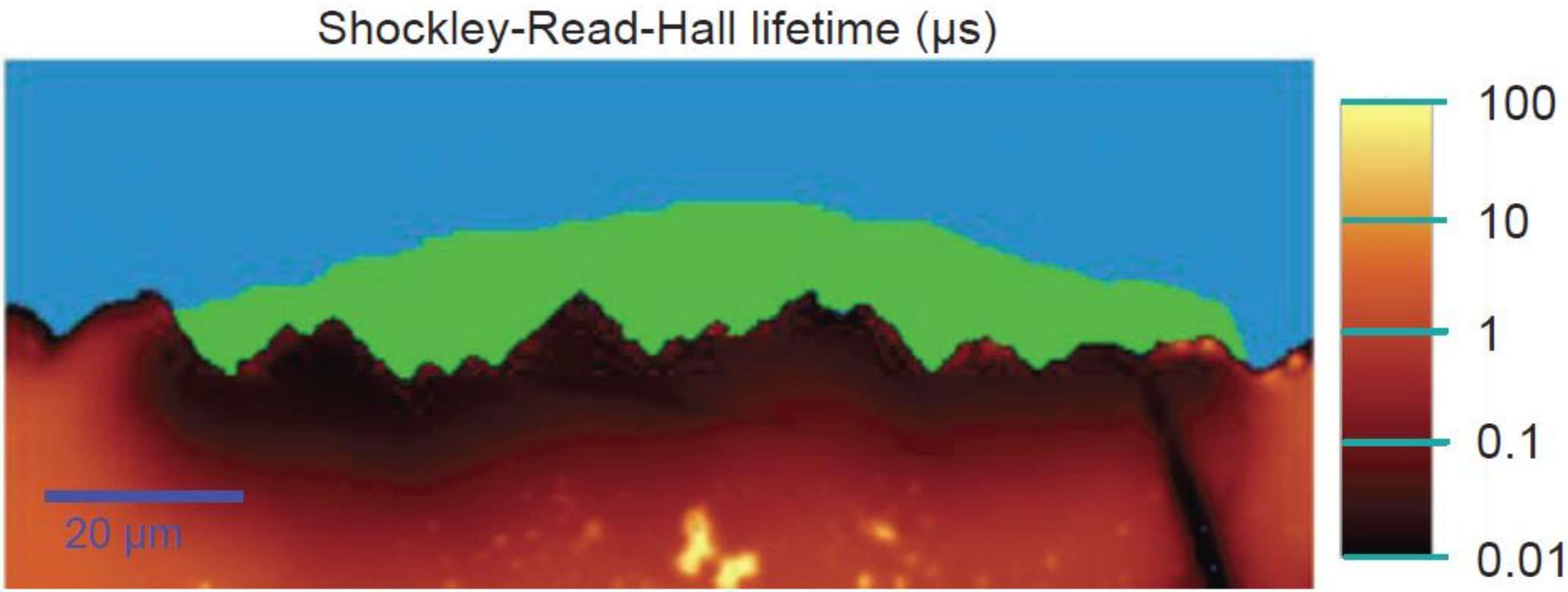
Nickel plated front contacts



Contact was tempered at 500C for 10 min

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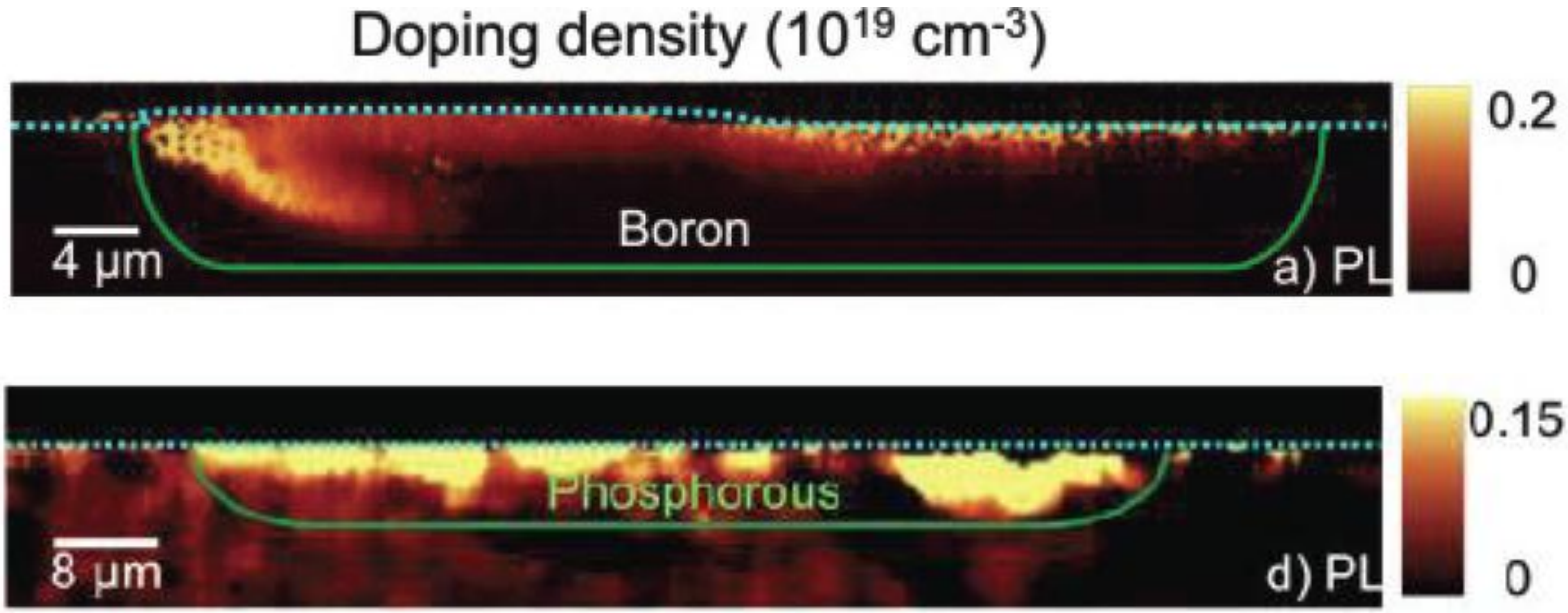
Laser doped back surface field



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Conclusions & Outlook

- PL Imaging with increasing number of quantitative applications
- Quantitative brick imaging could become a valuable early stage characterisation and prediction tool
- Qualitative images contain more than just effective lifetime imaging (as-cut sorting, gettering efficiency, efficiency prediction)
- Microscopic PL candidate for research application (local doping structures, local recombination activity, defects)

➢ PL keeps playing a strong role as an ideal characterisation tool for solar cell materials and devices