Happy birthday PL Imaging!

SPREE Seminar – 15 December 2016

Contents

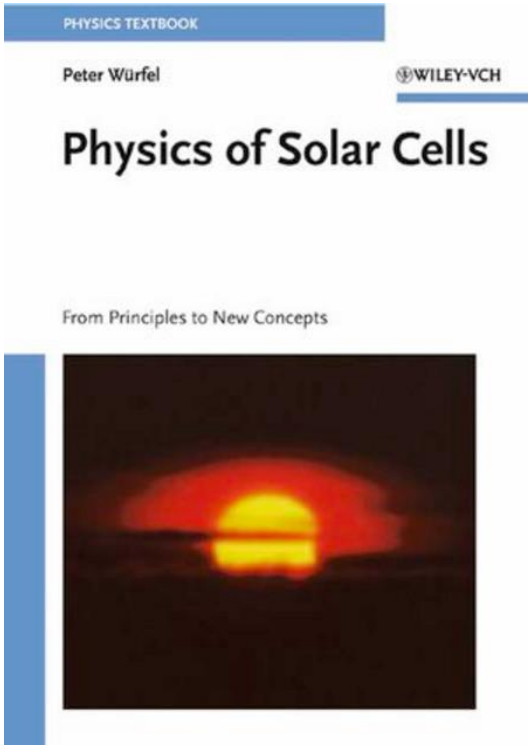
- The importance of good upbringing…
- Born in AUS, a healthy baby!
- Baby step, finding your place in the world.
- Now an adolescent, “knowing it all…”.

  - but yet a lot to learn!

The importance of “good upbringing”.

Prof Peter Würfel

Universität Karlsruhe, Germany



- Lifetime achievements in the “Physics of Solar cells”.
- Early adopter, recognizing the potential of luminescence.
- “Grandfather” of PL imaging!

Some background

- The generalised Planck equation:

$$dr_{sp}(\hbar\omega, T) = \frac{(\hbar\omega)^2 \cdot n^2}{\pi^2 \hbar^3 c_0^2} \cdot \alpha_{BB}(\hbar\omega, T) \cdot \frac{1}{\exp\left(\frac{\hbar\omega - \Delta\eta}{kT}\right) - 1} d(\hbar\omega)$$

Emission spectrum is determined by the absorption properties.

Emission intensity is determined by the separation of the quasi Fermi energies.

W. van Roosbroeck and W. Shockley, Phys.Rev. 94, 1558 (1954).
P. Würfel, J. Phys. C 15, 3967 (1982).

Some background

$$I_{lum} \sim \exp\left(\frac{\Delta\eta - \hbar\omega}{kT}\right) \sim \exp\left(\frac{\Delta\eta}{kT}\right)$$

→ Quantitative information about $\Delta\eta$ from PL intensity!

→ Implied voltage measurements.

$$I_{lum} \sim n \cdot p = \Delta n \cdot (\Delta n + N_{A/D}) = n_i^2 \cdot \exp\left(\frac{\Delta\eta}{kT}\right)$$

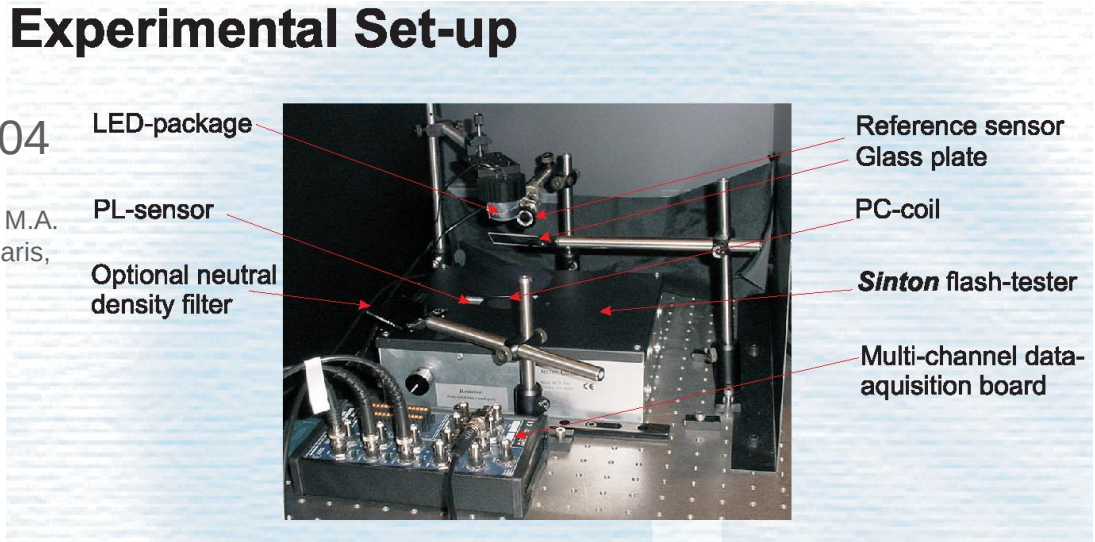
→ Quantitative information about Δn from PL intensity!

→ QSS-PL minority carrier lifetime measurements.

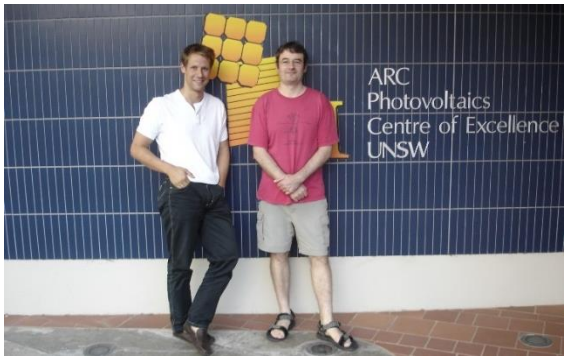
Early days…

First QSS-PL data presented in 2004

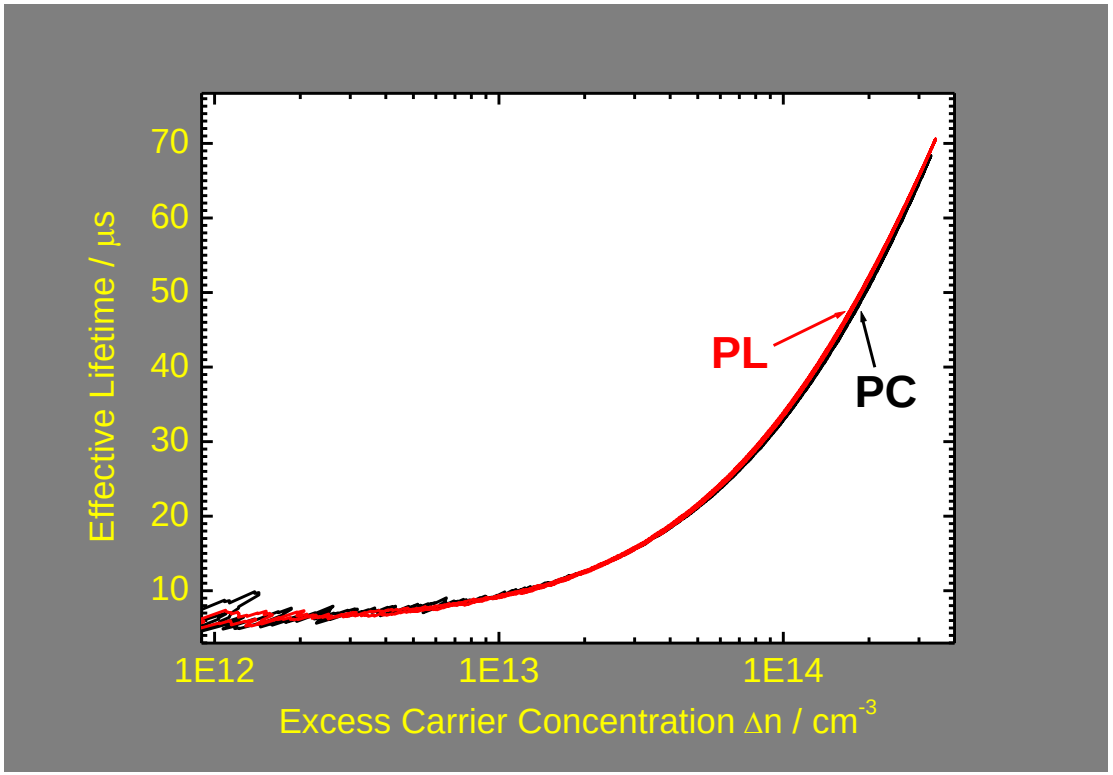
T. Trupke, R.A. Bardos, F. Hudert, P. Würfel, J. Zhao, A. Wang, M.A. Green, 19th European Photovoltaic Solar Energy Conference, Paris, France, June 2004.



- LED based QSS-PL
- >100ms on 1000 Ωcm n-type wafer
- Data controversial (we will see!)
- Ron seemed to like it…

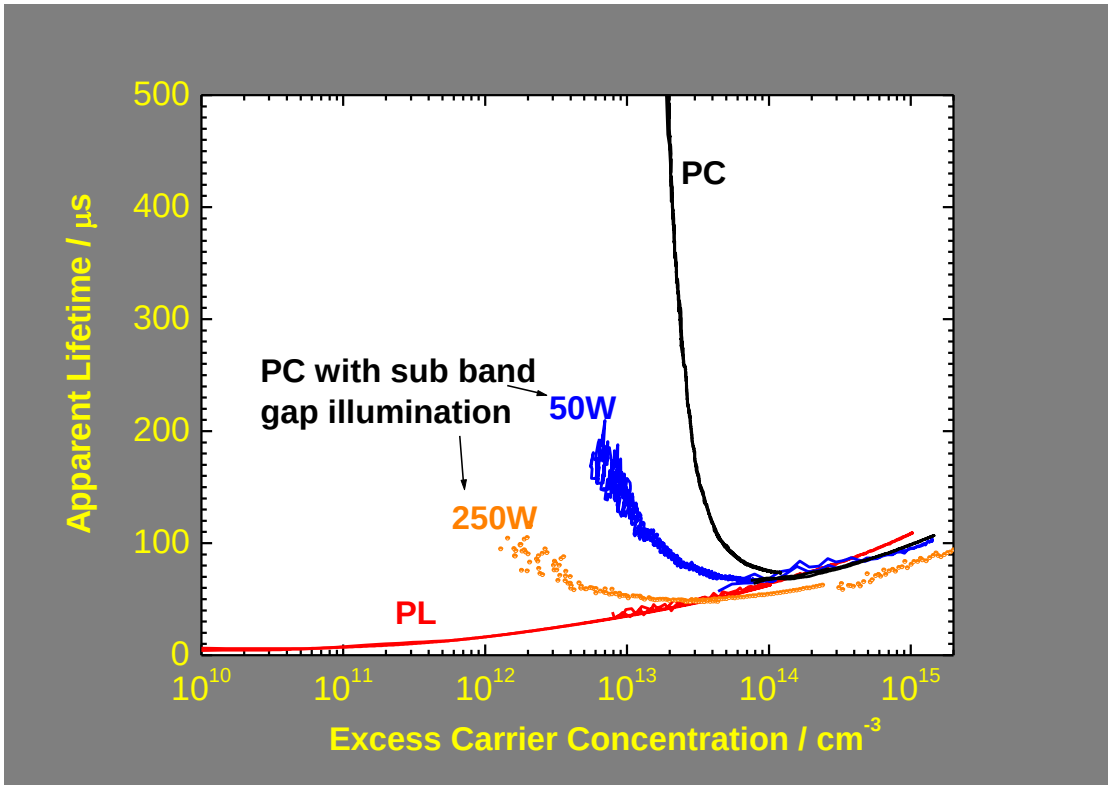


2004: QSS-PL lifetime



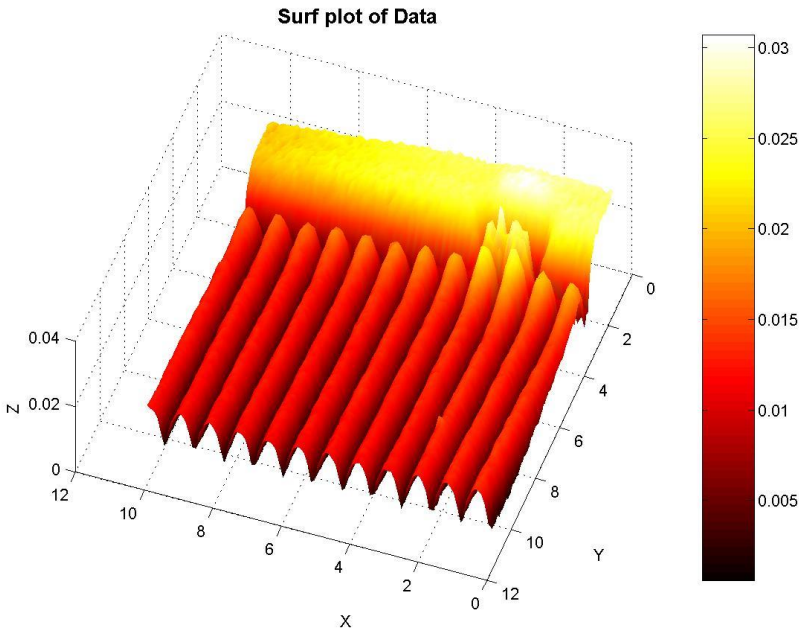
- Excellent agreement between QSS-PL and QSS-PC

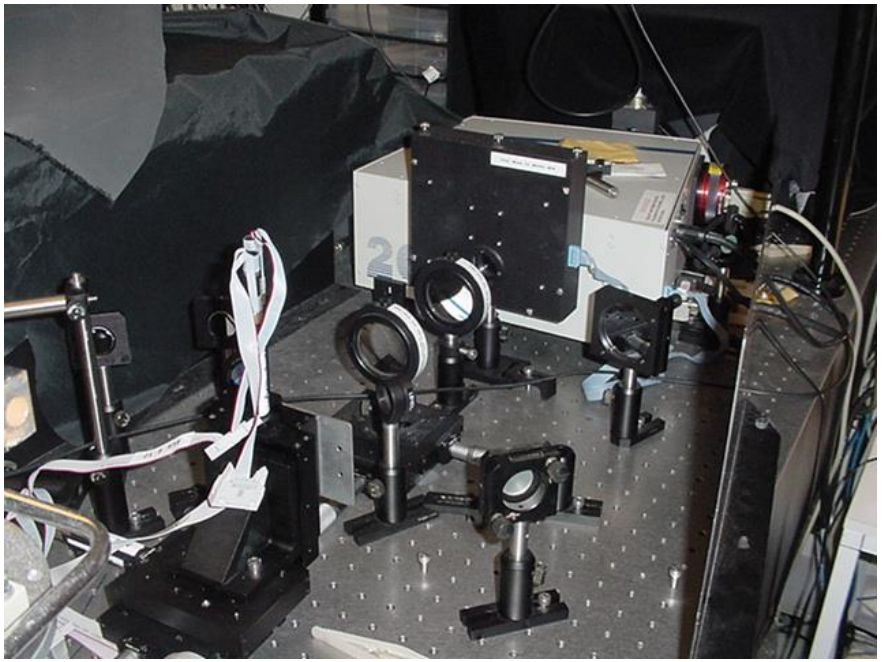
2004: QSS-PL lifetime



- QSS-PL immune to trapping.
- Calibration not trivial.
- QSS-PC still most widely used today.
- Complementary techniques.

2004 – PL mapping





- Scanning spectral PL tool, 50mm x 50mm, micron resolution.
- Slow

→ “Let’s try camera based PL imaging!”

May 2005 – Can we actually afford this?

A weekend email makes all the difference

"Hi Martin,

Rob and I plan to expand our experimental work on QSS-PL to PL imaging.

We would need ~ $ 50,000 to set up a proof of concept system.

TT"

"Hi Thorsten,

that sounds promising, I am happy to support characterisation work at UNSW, pls get the account number from Jenny on Monday. More funding available for this if required.

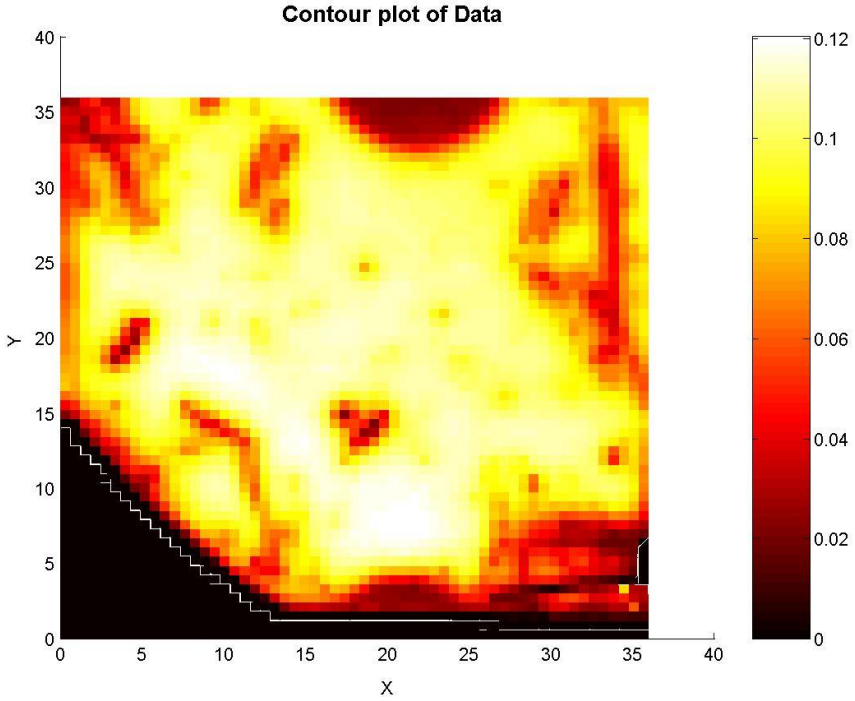
MAG"

Making it happen - quickly!

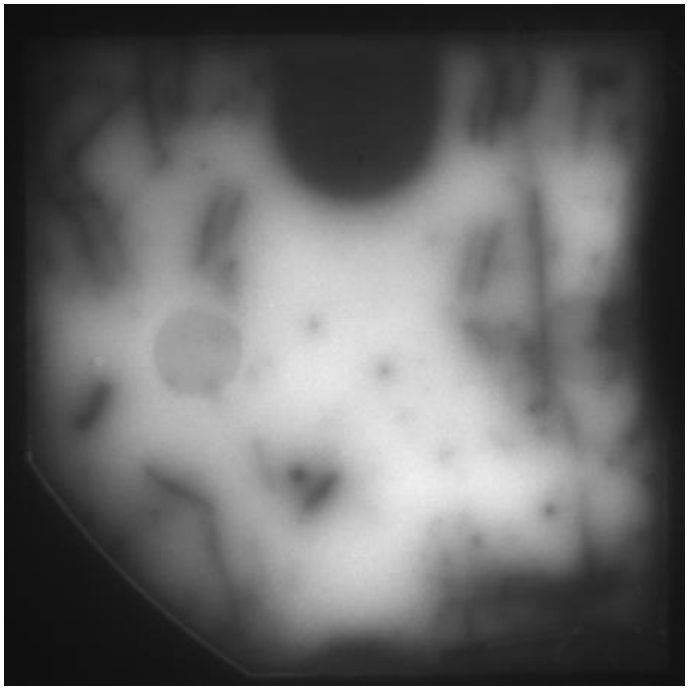
Mid 2005: First PL imaging prototype in EE building, **LG 24**.

- The 100W laser challenge…
- The mapping tool had to go…
- First PL image, a Eureka moment!
- Huge Excitement for months.
- System is still in operation at UNSW.

First PL images



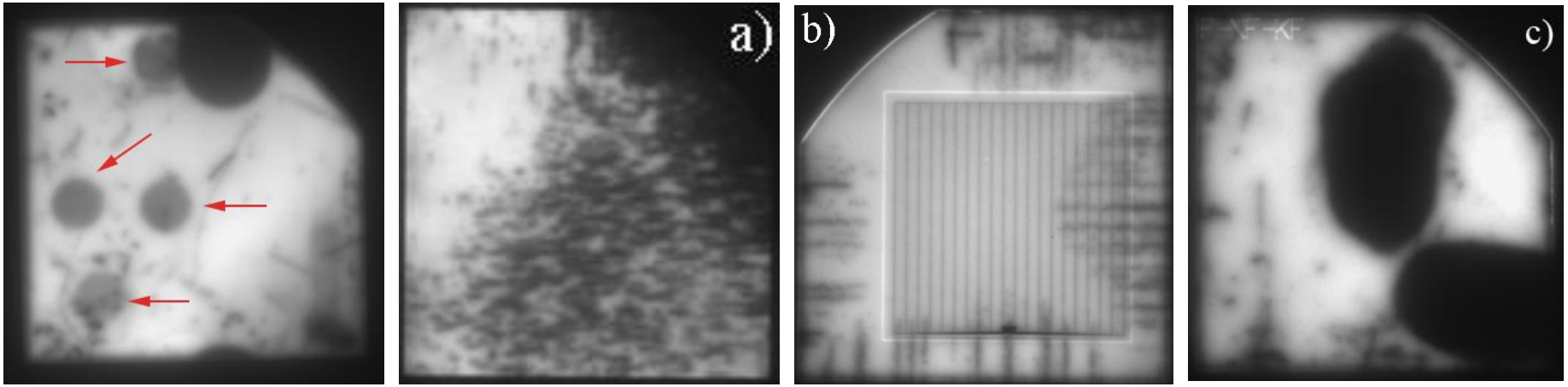
- Up to several hrs
- Typically 1mm per pixel



- 1s
- <100 μm per pixel

Baby steps – learning to walk

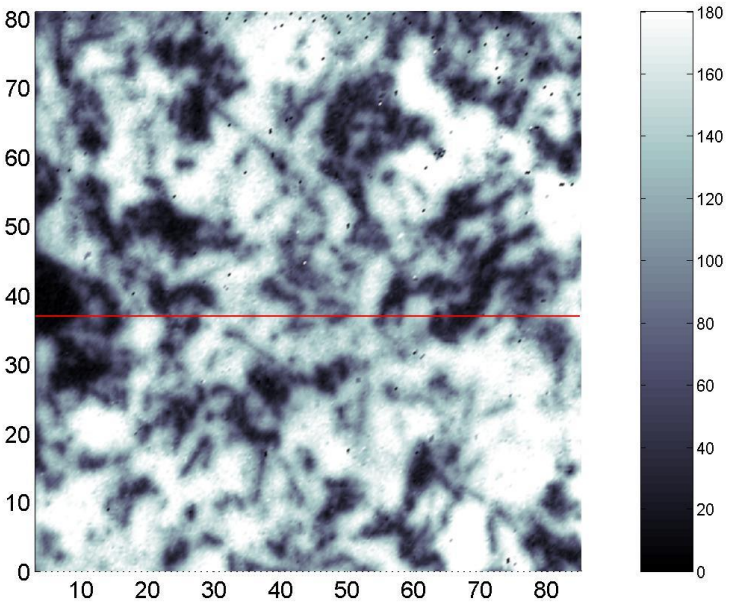
2005: Qualitative PL imaging



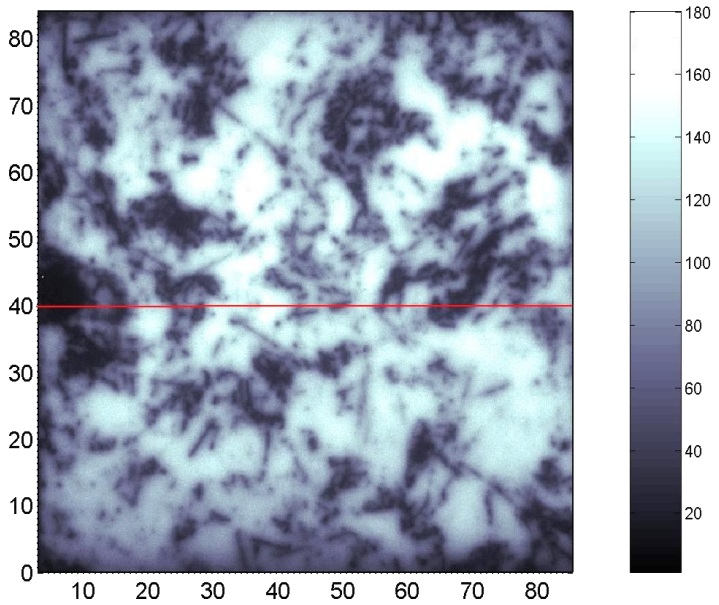
- Wide range of material- and process induced faults detectable
- **Rapid adoption** by the UNSW high efficiency group and the buried contact solar cell group for routine daily process monitoring

Baby steps – learning to walk

2006: Calibrated minority carrier lifetime images



Carrier Density Image (CDI)



PL imaging

- Calibration via QSS-PC best option

T. Trupke, R.A. Bardos, M.C. Schubert and W. Warta, *Photoluminescence imaging of silicon wafers*, Appl.Phys.Lett. **89**, 044107 (2006).

First paper – official birthday!

APPLIED PHYSICS LETTERS **89**, 044107 (2006)

Photoluminescence imaging of silicon wafers

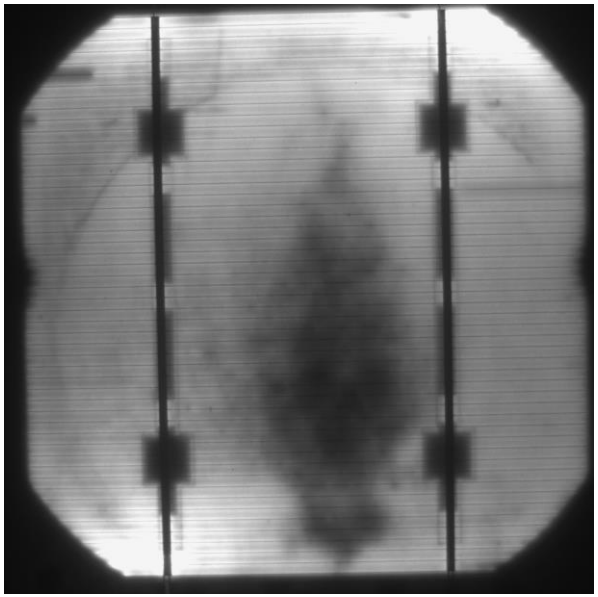
T. Trupke[a)] and R. A. Bardos
Centre of Excellence for Advanced Silicon Photovoltaics and Photonics, University of New South Wales, Sydney 2052, Australia

M. C. Schubert and W. Warta
Fraunhofer Institute for Solar Energy Systems, Heidenhofstrasse 2, D-79110 Freiburg, Germany

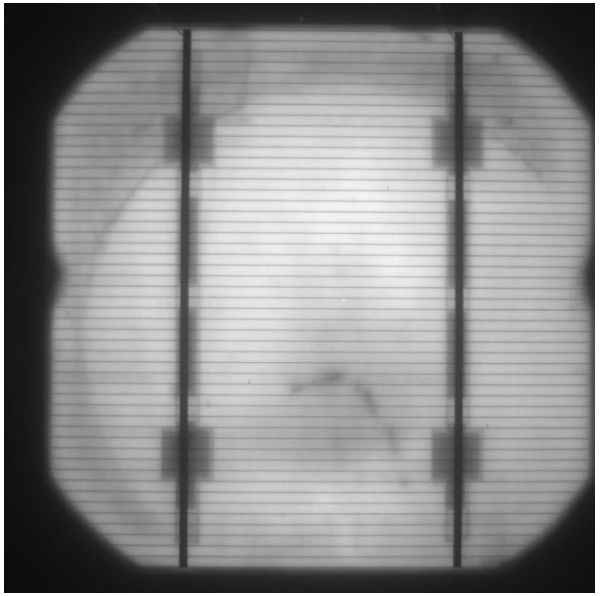
(Received 24 October 2005; accepted 4 June 2006; published online 26 July 2006)

Baby steps – learning to walk

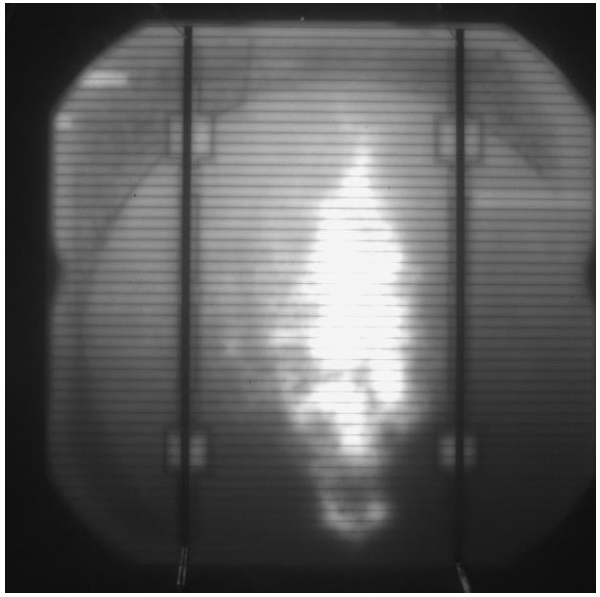
2006: c-Si workshop, Denver



EL image



PL image



PL image with current extraction

- Proposal to use PL for R_s imaging
- But why does this happen…?

Baby steps – learning to walk

Why do Rs variations within a cell show up in luminescence images?

$$I_{lum} \approx \exp\left(\frac{\Delta\eta - \hbar\omega}{kT}\right) \approx \exp\left(\frac{\Delta\eta}{kT}\right)$$

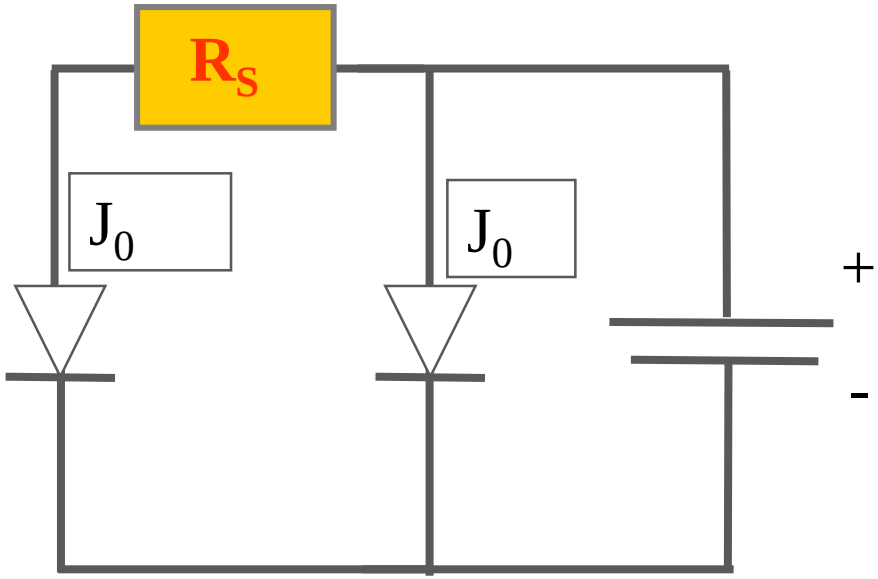
- **EL:** High Rs causes lower junction voltage

  ⇨ Low PL intensity

- **PL:** No current flow, no impact of Rs on junction voltage.

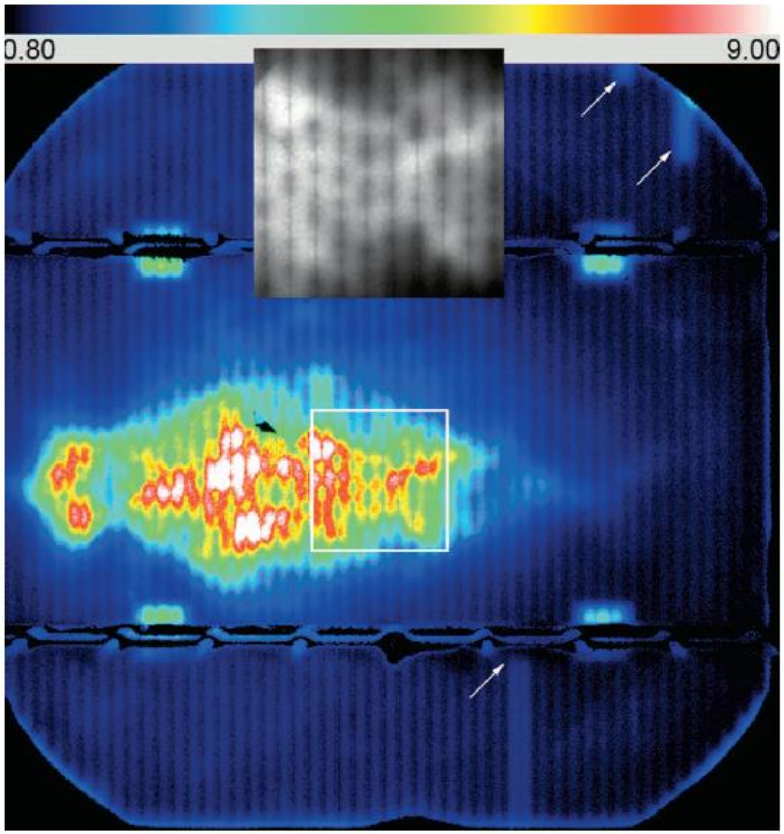
- **PL_{SC}:** High Rs impedes local current extraction

  ⇨ High relative PL intensity



Baby steps – learning to walk

2007: Quantitative Rs imaging



- Rs imaging based on at least two images:
  - Voc
  - MPP
- Good separation of R_s from lifetime
- Quantitative effective local R_s in Ωcm^2
- Several PL/EL based R_S methods followed

- "PL emission at zero voltage!
  What the heck …?"

⇒ "Voltage independent carriers"

T. Trupke, E. Pink, R. A. Bardos, and M. D. Abbott. Appl.Phys.Lett. **90**, 093508 (2007).
H. Kampwerth, T. Trupke, J. Weber, Y. Augarten, Appl.Phys.Lett. **93**. 202102 (2008).

Baby steps – learning to walk

2016: Voltage independent carriers

- Presence of voltage independent carriers follows from the continuity equation:

$$\frac{d^2n[x]}{dx^2} = \frac{n[x]}{L^2} - \frac{\alpha N_\gamma e^{-\alpha x}}{D}$$

$$n = C_a e^{\frac{x}{L}} + C_b e^{-\frac{x}{L}} + C_c e^{-\alpha x}$$

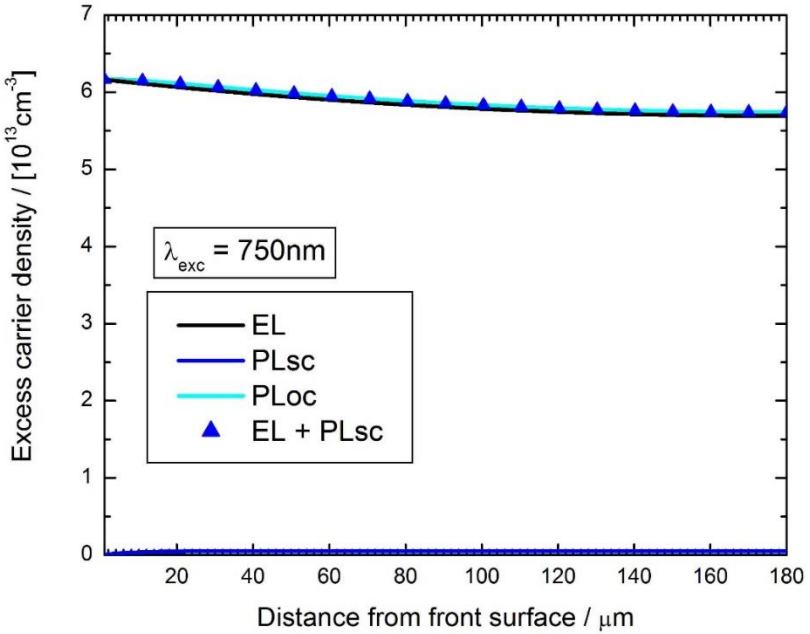
$$n = n_{vd} + n_{vid}$$

- Voltage dependent term: $$n_{vd} = \left(C_{a-vd} e^{\frac{x}{L}} + C_{b-vd} e^{\frac{-x}{L}}\right) e^{\frac{qV}{kT}},$$
- Voltage independent term: $$n_{vid} = \left(C_{a-vid} e^{\frac{x}{L}} + C_{b-vid} e^{\frac{-x}{L}} + C_{c-vid} e^{-\alpha x}\right) N_\gamma$$

Mattias Juhl, manuscript submittted

Baby steps – learning to walk

2016: Voltage independent carriers



Applied voltage in the dark

Illumination with λ_{exc}=1100nm

Illumination with λ_{exc}=1100nm, external SC

⇨ Excess carrier profile under illumination at SC is present at all bias conditions

⇨ First order correction by subtracting PLsc from PL at other bias conditions.

Poster by Mattias Juhl at this workshop!

Growing up

Finding your place in the world

From 2007:

- PL imaging activities at UNSW, ANU, ISE, ISFH, NREL, Uni Konstanz, MPI, ISAS/JAXA…
  - Lifetime imaging and dynamic calibration methods
  - Series resistance imaging
  - Diffusion length imaging on cells
  - J_0, J_{0e} imaging
  - J_{sc} imaging
  - Efficiency imaging
  - Shunt detection and quantification
  - Bulk lifetime imaging on bricks
  - Fe (and other atomic defects) concentration imaging
  - High throughput as-cut wafer imaging
  - …

Growing up

Finding your place in the world

Late 2007:

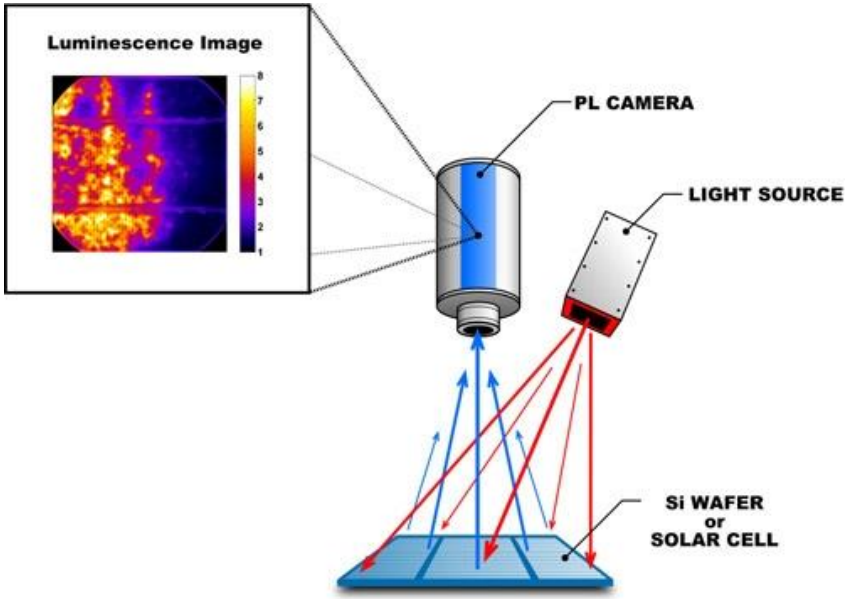
- Interest in PL imaging systems from industry after 2006 presentations (e.g. WCPEC 2006)
- BT imaging founded
  - Jørgen Nyhus from REC, first adopter (UNSW visit in Dec 2007, First PO for R1)!
  - LIS-R1 presented at 2008 EUPVSC, Milan.
  - Commercially availability PL imaging systems enable rapid adoption throughout PV industry.

Growing up

Finding your place in the world

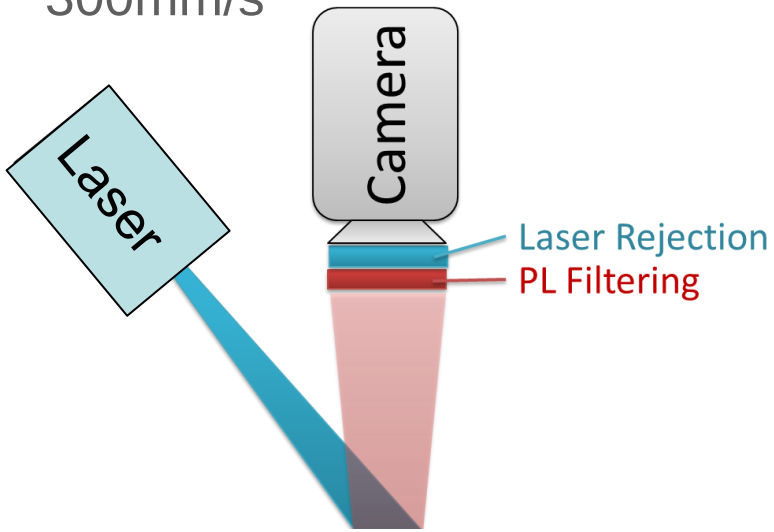
2011: Line scanning PL imaging

Area scanning



Line scanning

- Line illumination
- Measurement on the fly, e.g. 300mm/s

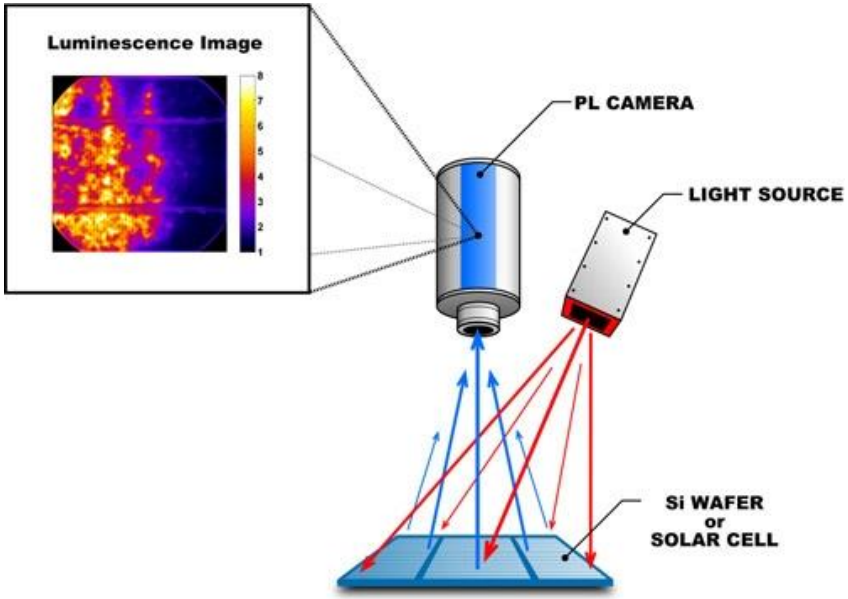


Growing up

Finding your place in the world

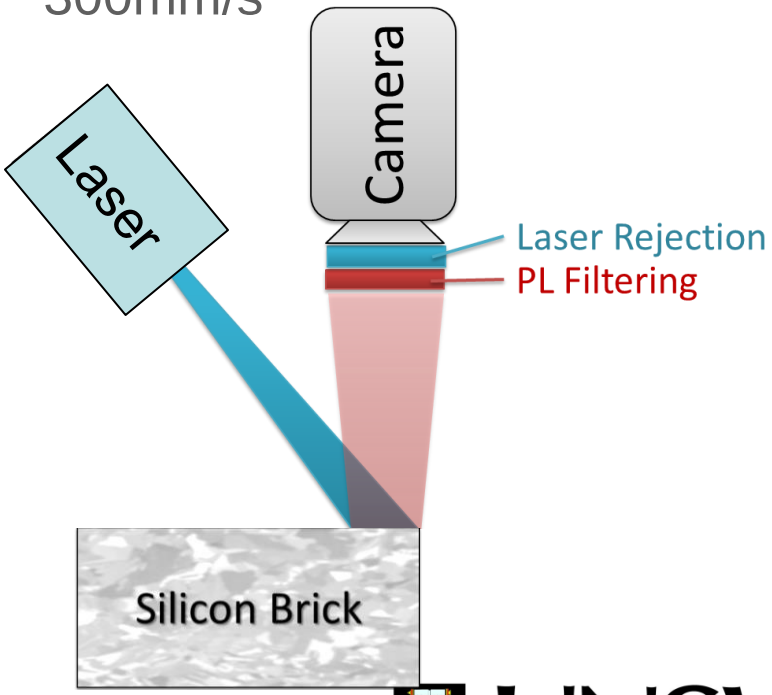
2011: Line scanning PL imaging

Area scanning



Line scanning

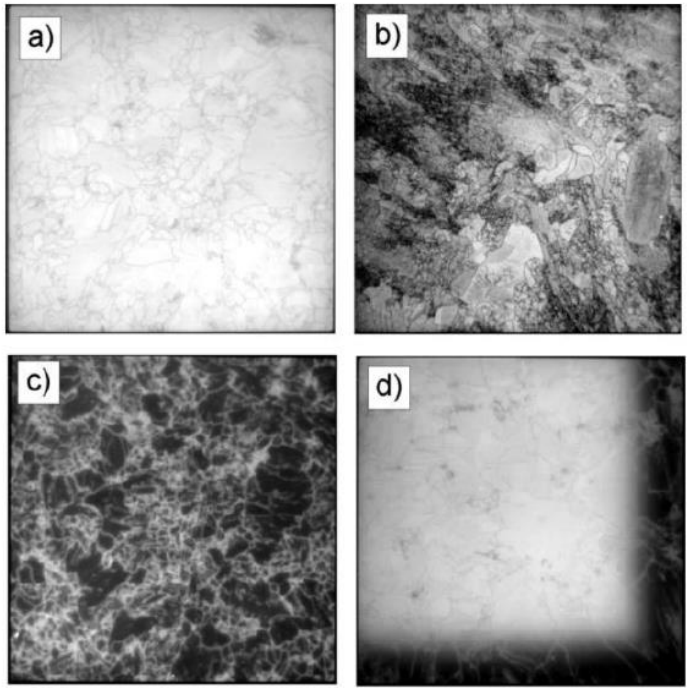
- Line illumination
- Measurement on the fly, e.g. 300mm/s



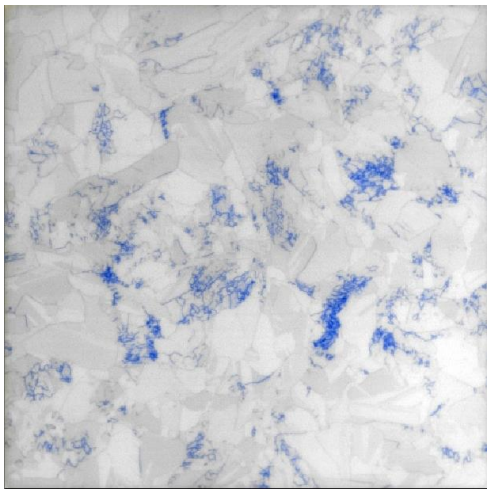
Growing up

Finding your place in the world

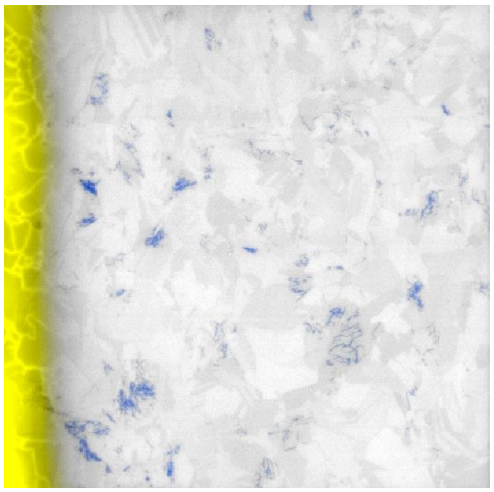
As cut wafer inspection



- Metrics can be extracted from PL images using automatic image processing.



Dislocations

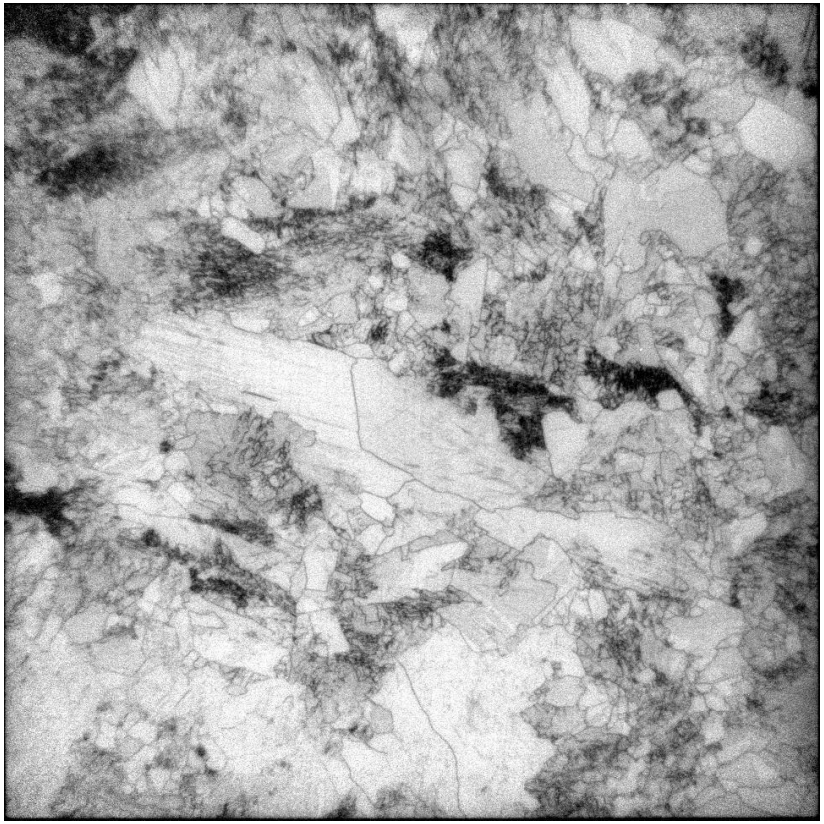


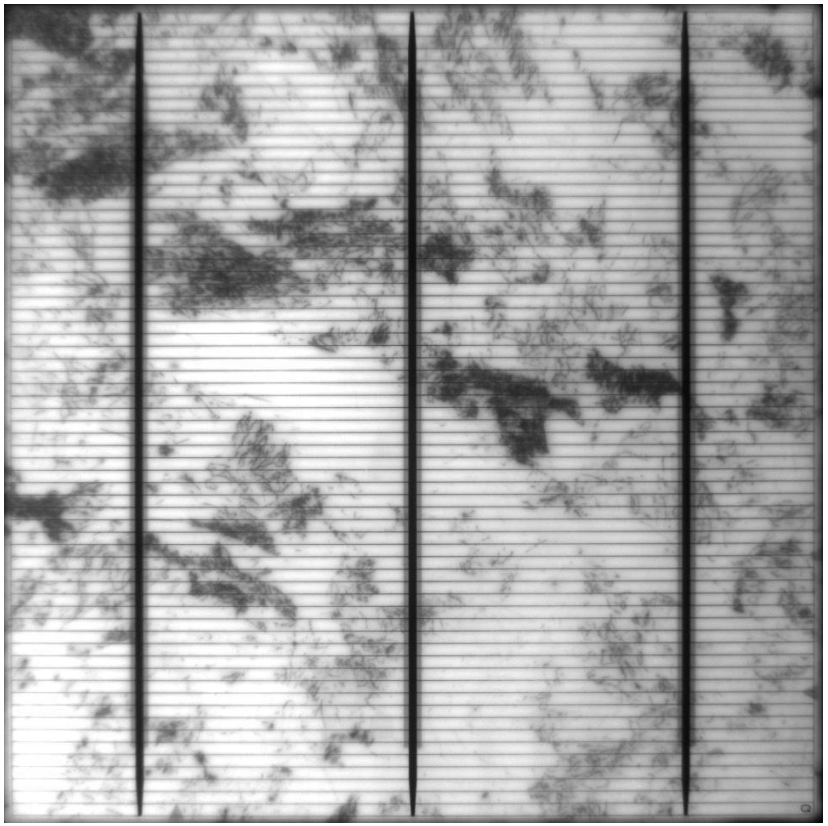
Impure edges

Growing up

Finding your place in the world

As cut wafer inspection

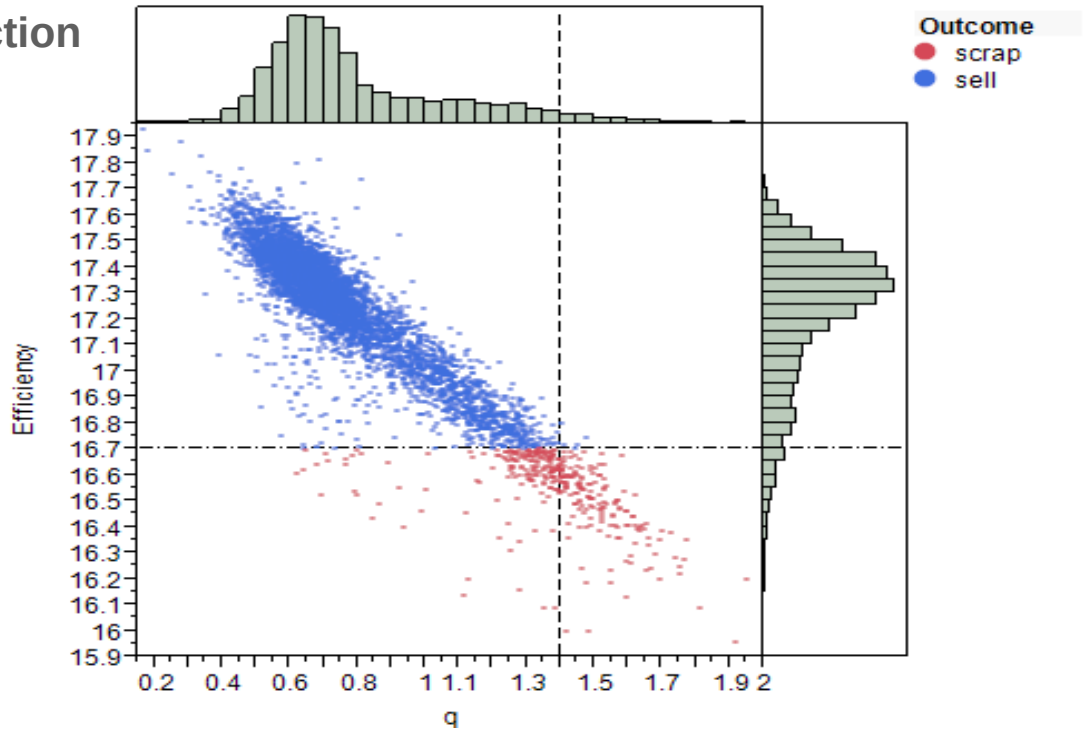




Growing up

Finding your place in the world

As cut wafer inspection

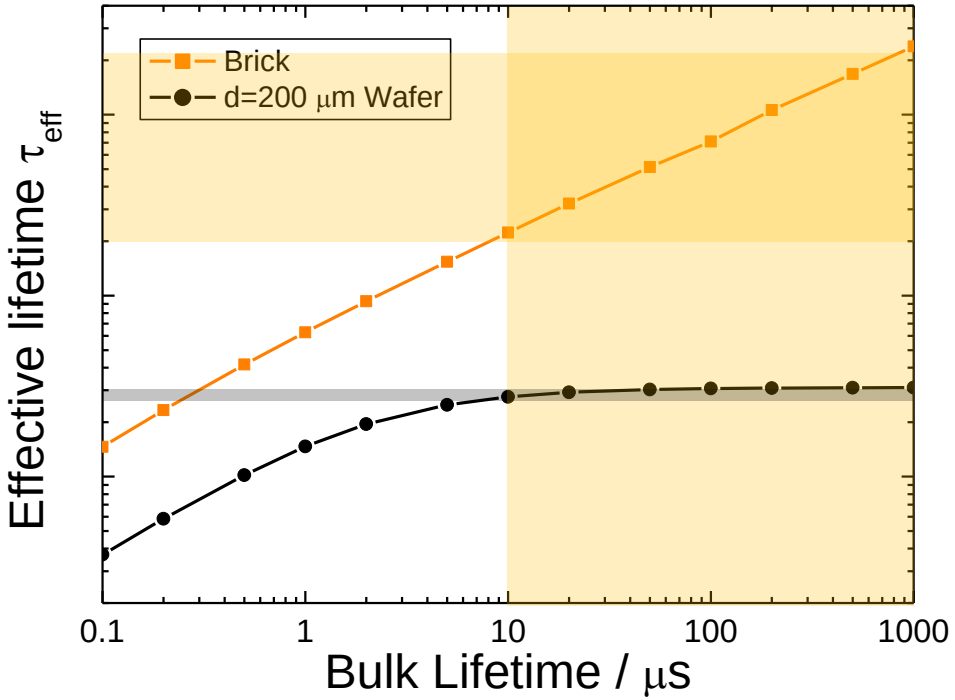


- PL imaging used today for IQC/OQC in production at up to 5,400 wph.
- Correlation of cell efficiency defect density with PL metrics
- Not detectable with sufficient throughput with any other technique.

Growing up

Finding your place in the world

2009: Brick inspection

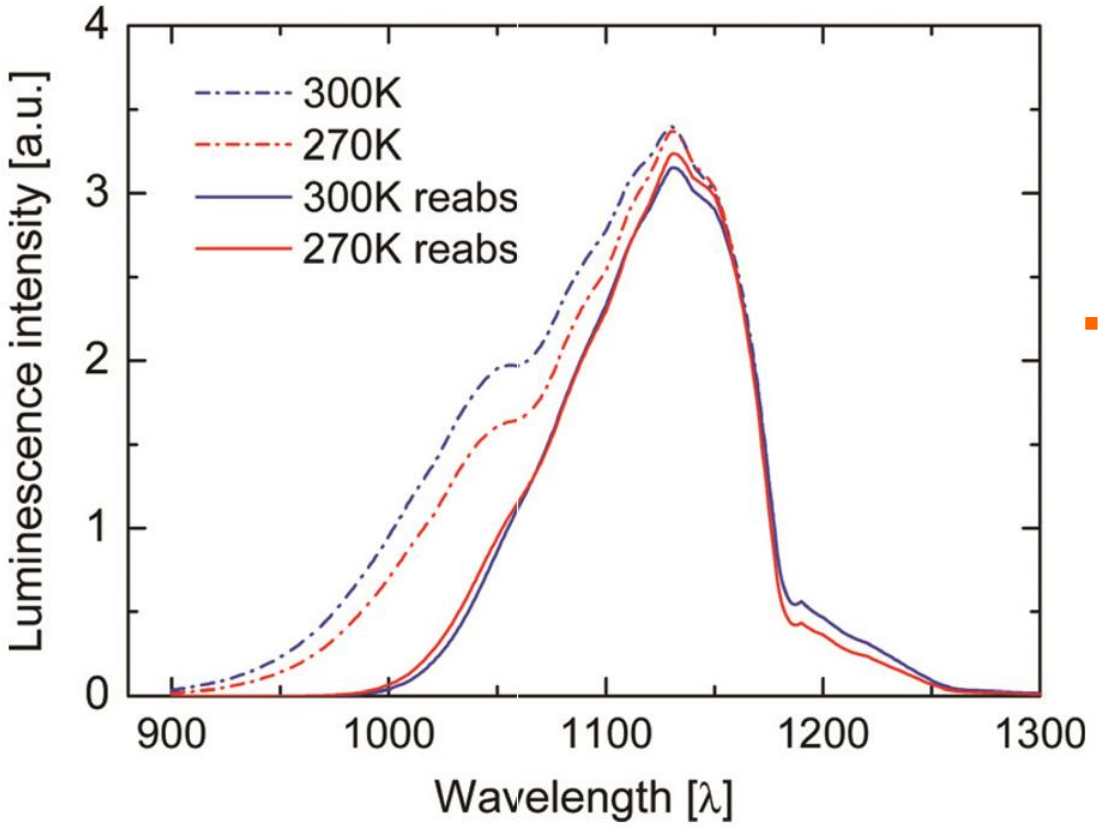


- Bulk lifetime dependence strongly non-linear.
- Virtually no variation for t_b > 10 μs.

Growing up

Finding your place in the world

2007: PL Intensity ratio (PLIR) method



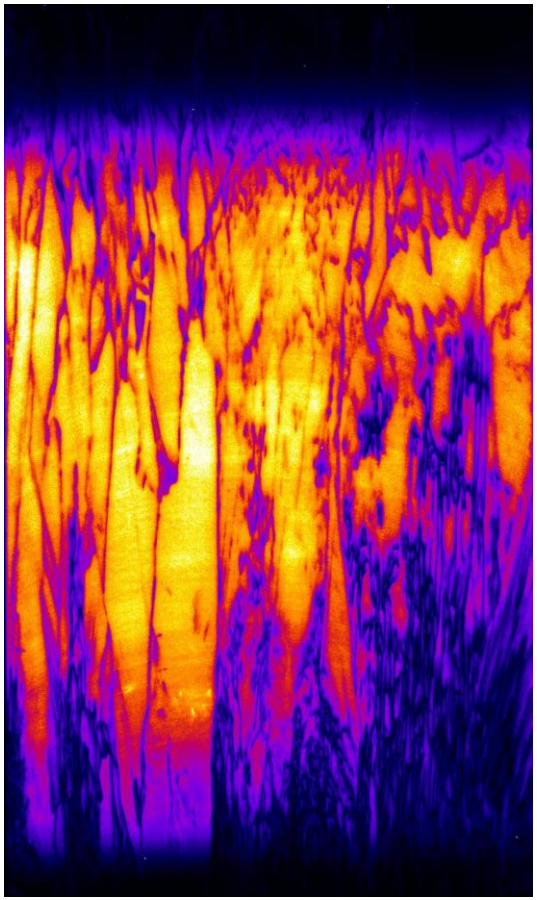
- Emission spectrum changes depending on the depth from the surface!

P. Würfel, T. Trupke, T. Puzzer, E. Schäffer, W. Warta, S.W. Glunz, *Diffusion Lengths of Silicon Solar Cells from Luminescence Images*, J.Appl.Phys. **101**, 123110 (2007).

Growing up

Finding your place in the world

2009: Brick inspection



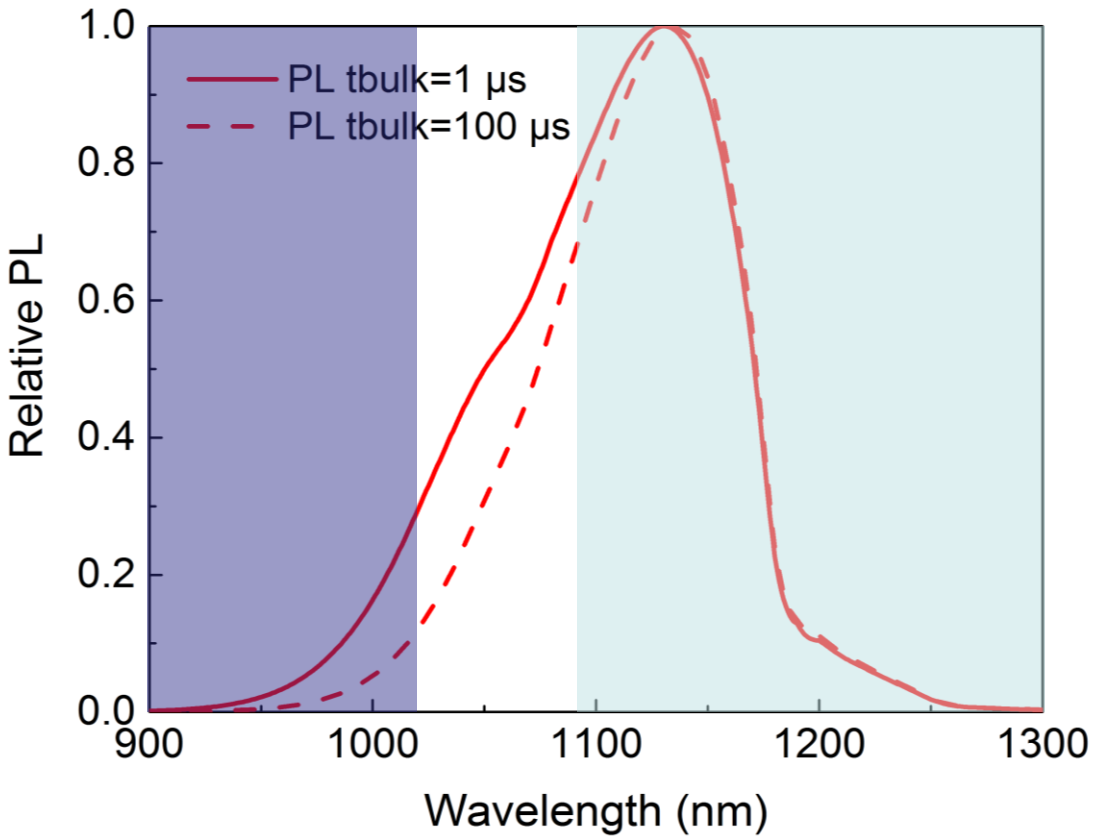
- PL imaging on bricks
- How to quantify?

$$I_{lum} \sim n \cdot p \approx \Delta n \cdot N_{D/A} = \tau_{eff} \cdot N_{D/A}$$

Growing up

Finding your place in the world

2011: Bulk lifetime imaging from PLIR



1st PL image measured with a SP filter

2nd PL image measured with a LP filter

$$PLIR = \frac{I_{PL,\,SP}}{I_{PL,\,LP}}$$

- Absolute lifetime from first principles.
- Background doping cancels in PLIR!

B. Mitchell, T. Trupke, J. W. Weber, and J. Nyhus, *J. Appl. Phys.* **109**, 083111 (2011).

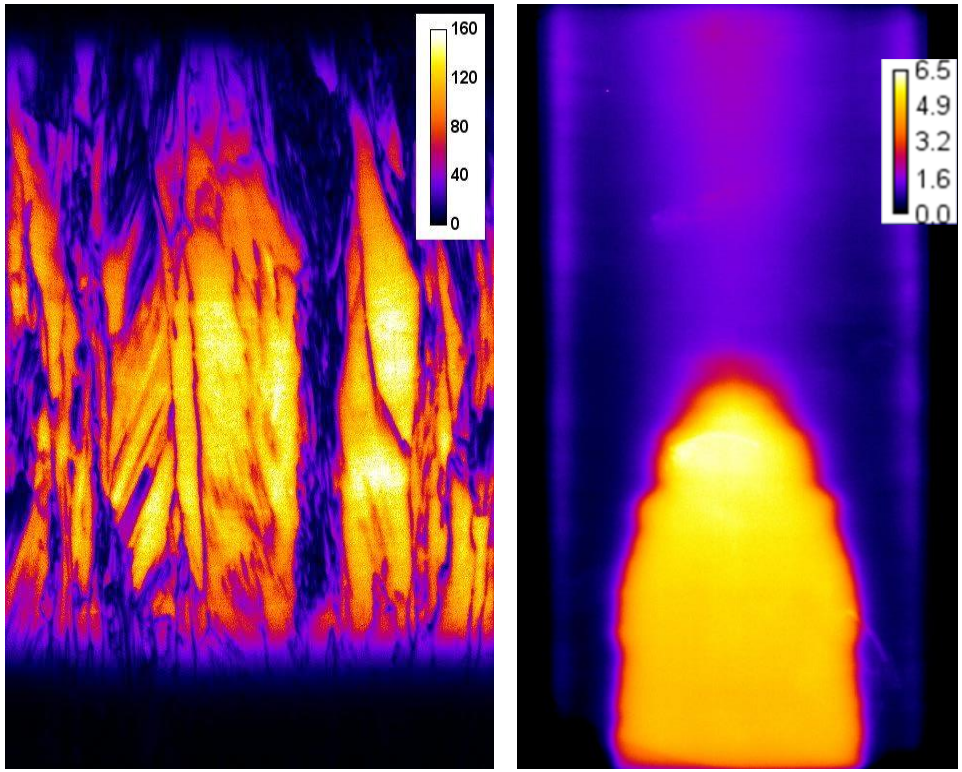
Growing up

Finding your place in the world

2011: Bulk lifetime imaging from PLIR

p-type multi:

$0.2\ \mu s < \tau_b$



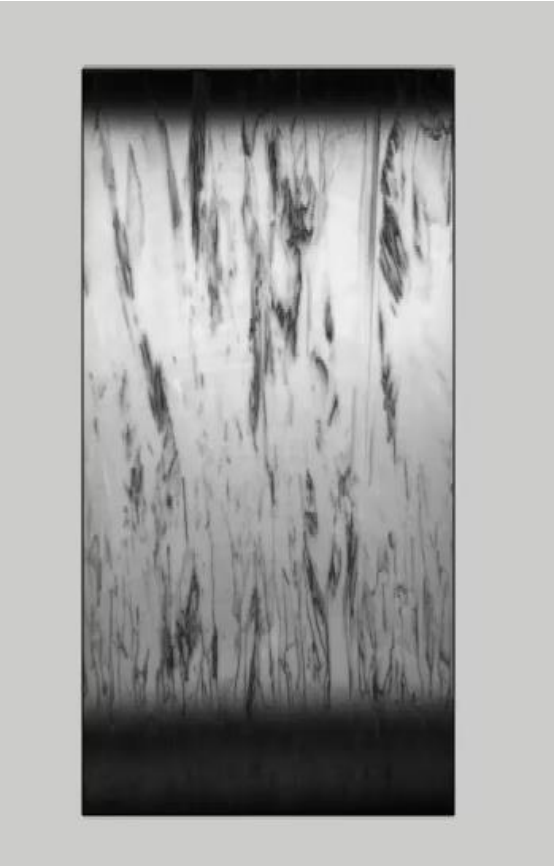
n-type Cz:

Measured τ_b up to 7 ms

- Background doping variations cancel out in PLIR
- Bulk lifetime as quality specification for wafers
- Cutting guide

Bulk lifetime on bricks and thick wafers

2011

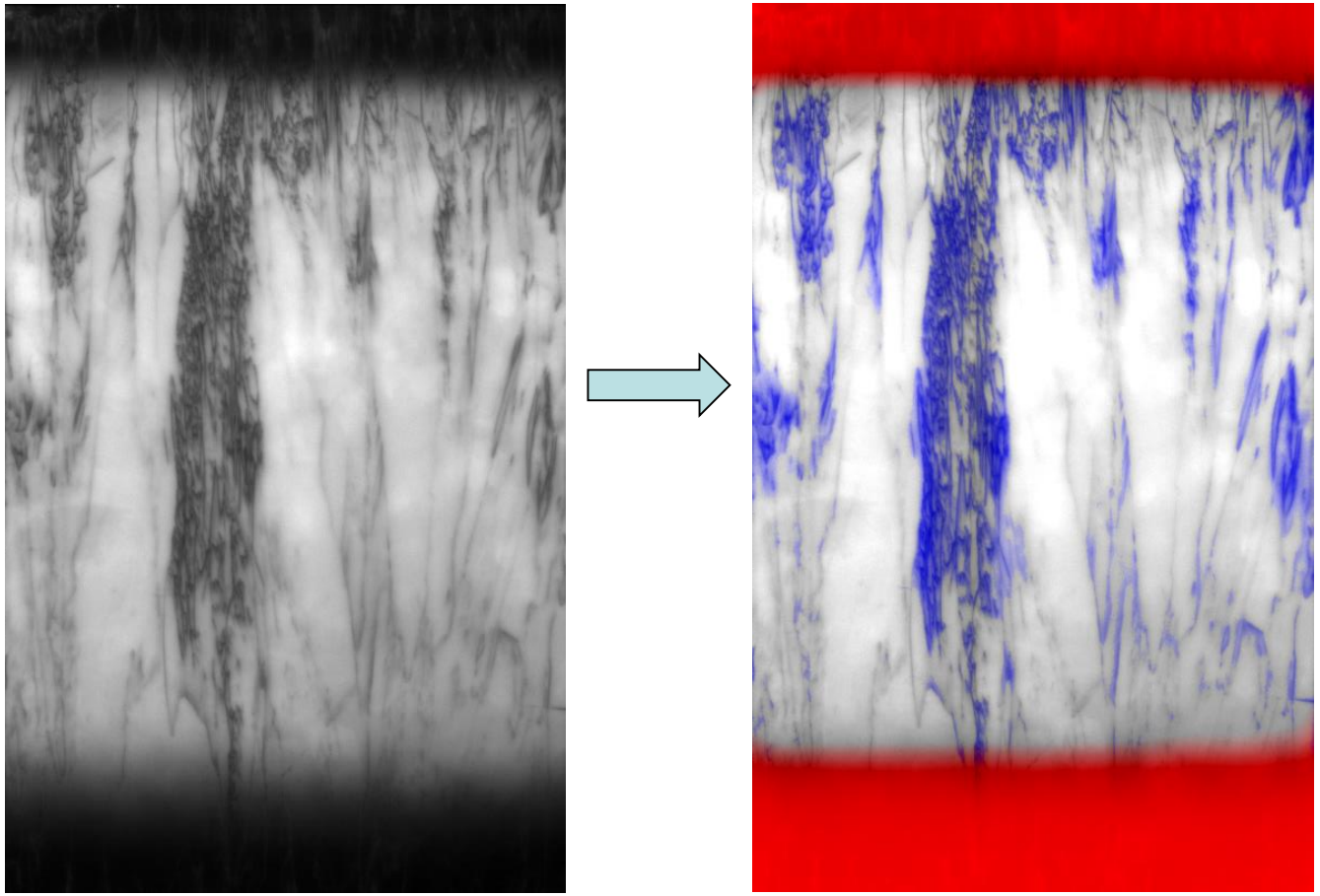


2015

- Structural defect analysis

D. Chung, B. Mitchell, J.W. Weber and T. Trupke, MRS Spring meeting 2016, Phoenix, USA, March 2016

Bulk lifetime on bricks and thick wafers

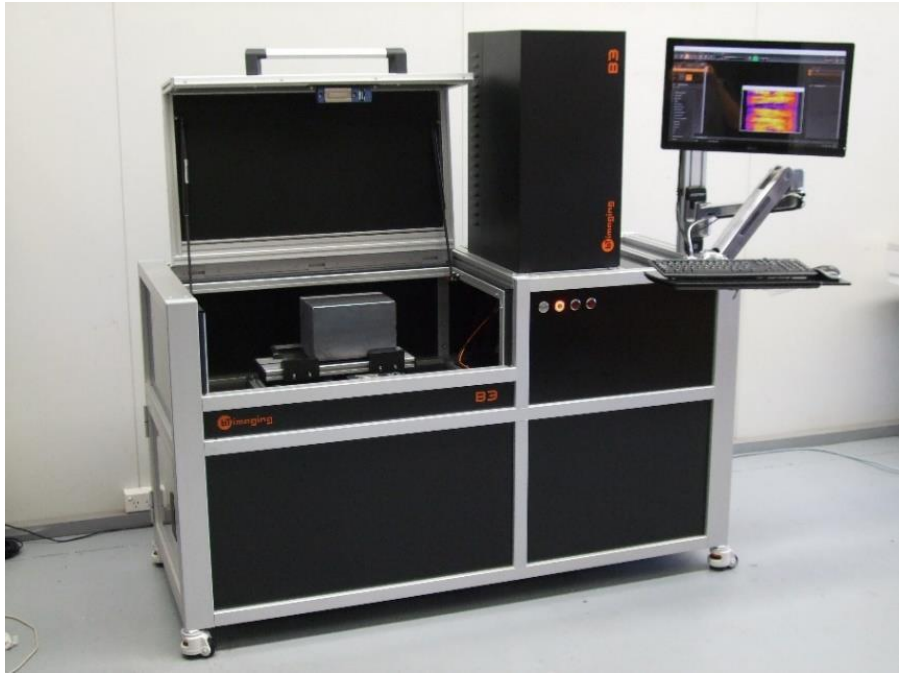


- Automatic defect analysis

Growing up

Finding your place in the world

2016: Bulk lifetime using **line scan PL imaging**



- Now in production
- Cutting guide
- Bulk lifetime and defect distribution for process development and process monitoring.

Now a teenager

Still a lot to learn…

LG25 in the TETB building

New playground for the PL group…

ARENA

Australian Government

Australian Renewable Energy Agency

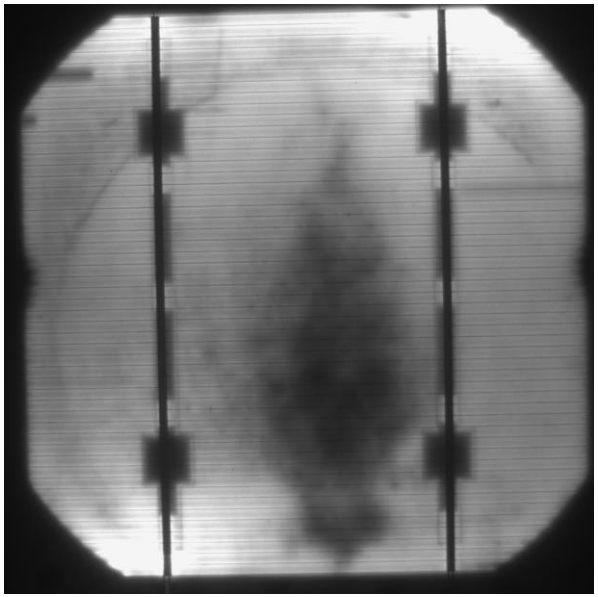
bT imaging INSPECTION SYSTEMS

UNSW THE UNIVERSITY OF NEW SOUTH WALES

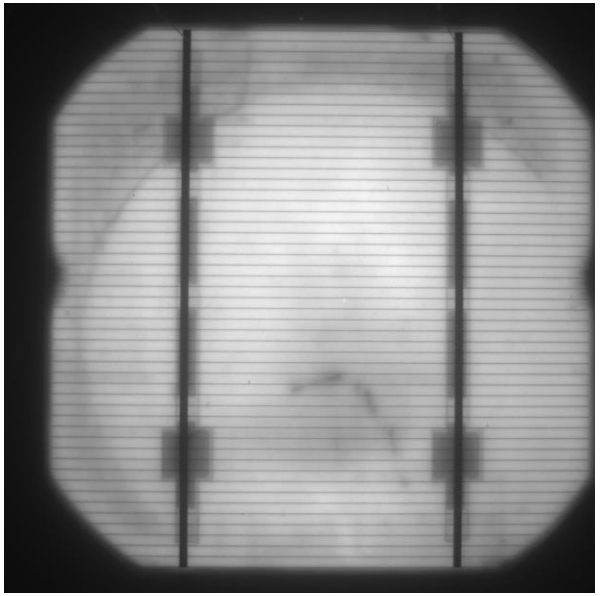
Now a teenager

Still a lot to learn…

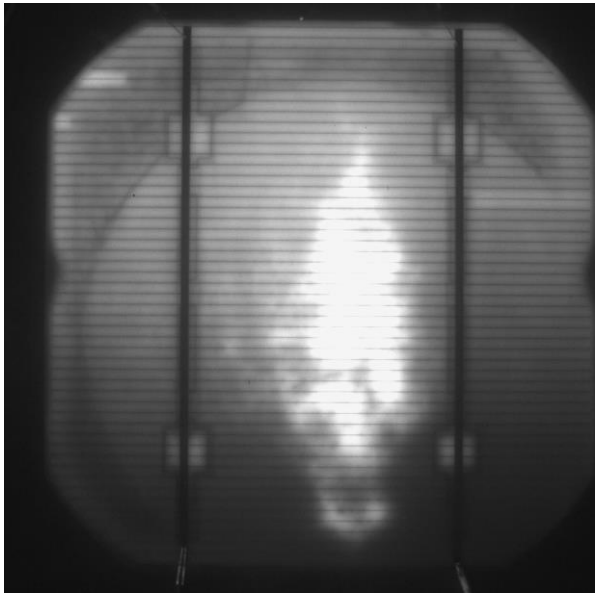
2006: c-Si workshop, Denver



EL image



PL image



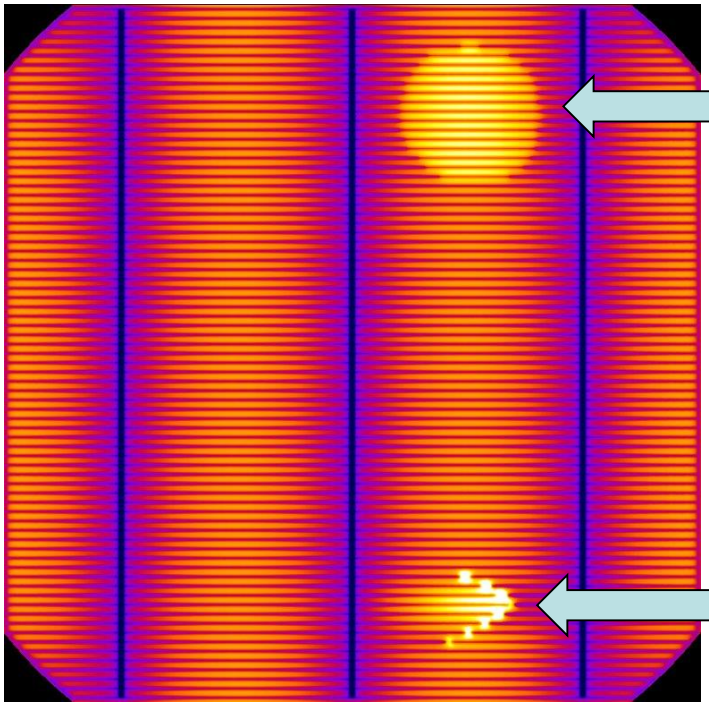
PL image with current extraction

- Proposal to use PL for R_s imaging
- But why does this happen…?

Now a teenager

Still a lot to learn…

Solar cell with local Rs issues



Enhanced contact resistance

Some broken fingers

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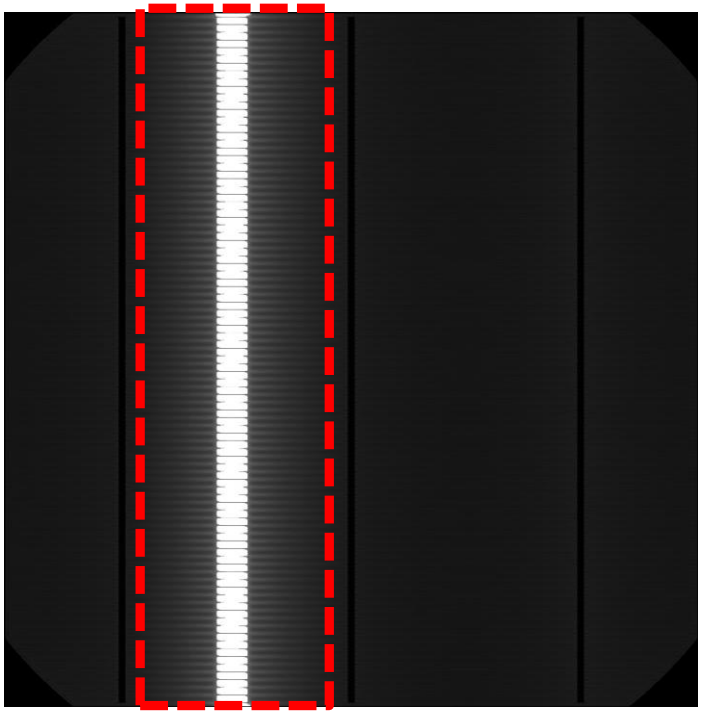
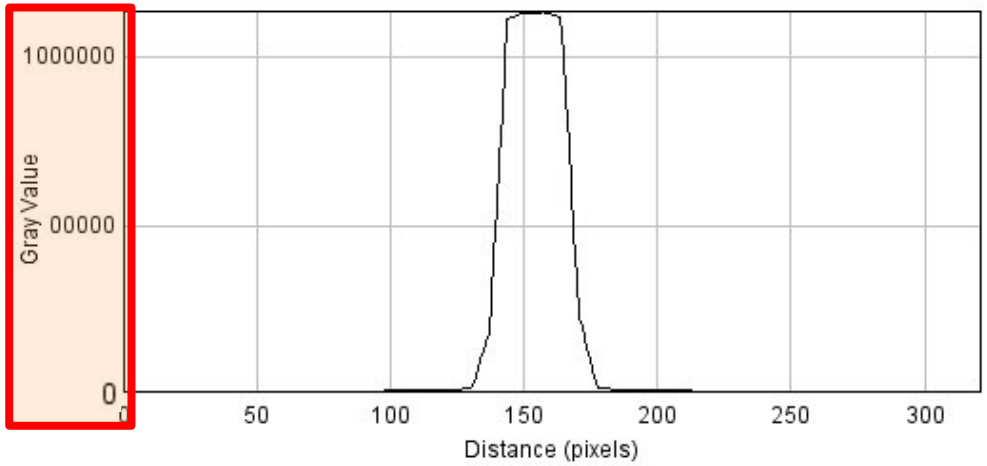
Still a lot to learn…

Line can PL imaging on cells





High illumination intensity:

High PL contrast between illuminated and non illuminated areas

Griddler[1] simulation

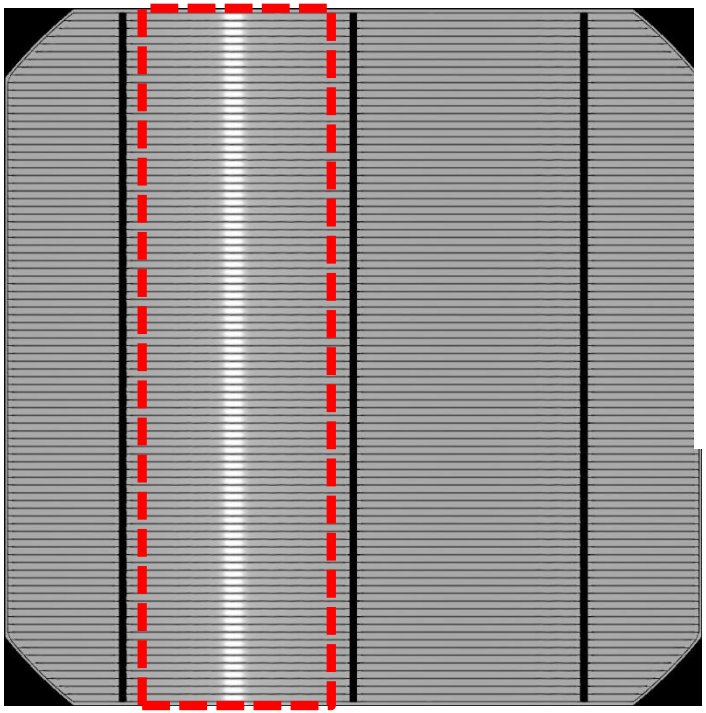
[1] J. Wong, *Griddler: Intelligent Computer Aided Design of Complex Solar Cell Metallization Patterns*, 39th IEEE Photovoltaic Specialists Conference, Tampa, USA (2013).

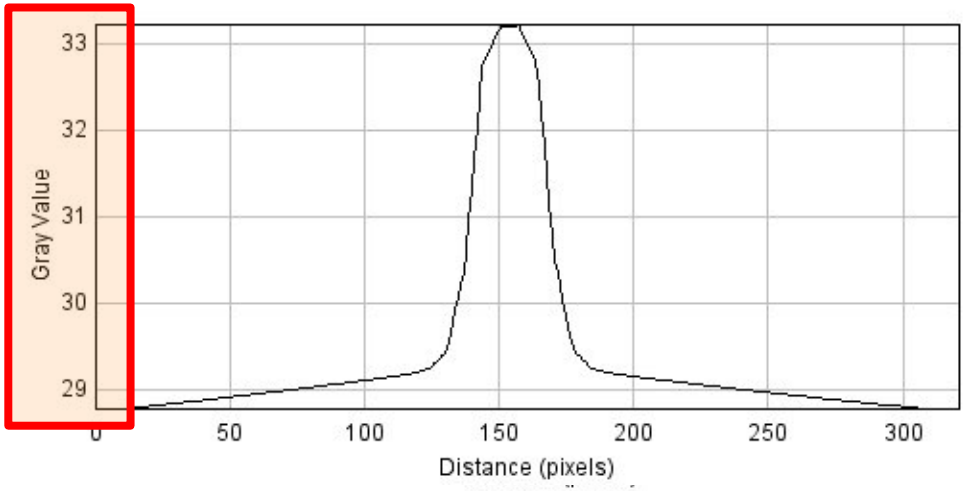
All Griddler simulations by Iskra Zafirovska

Now a teenager

Still a lot to learn…

Line scan PL imaging on cells





Low illumination intensity:

Very efficient lateral current spreading

Griddler[1] simulation

[1] J. Wong, *Griddler: Intelligent Computer Aided Design of Complex Solar Cell Metallization Patterns*, 39th IEEE Photovoltaic Specialists Conference, Tampa, USA (2013).

All Griddler simulations by Iskra Zafirovska

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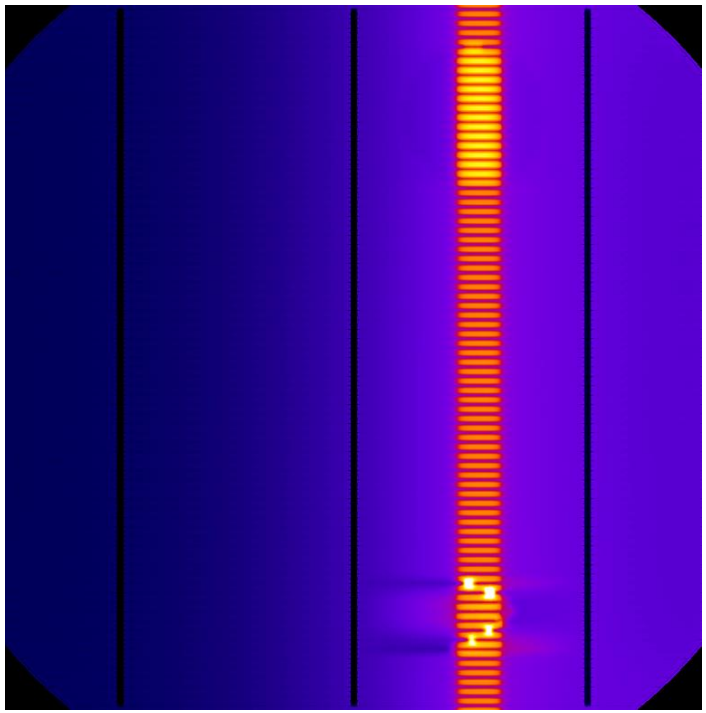
Still a lot to learn…

Line can PL imaging on cells



Griddler simulation:

Line scanning PL image of c-Si solar cell with local Rs problems!

Note: this simulations represents just one snapshot in time from the line scanning PL imaging acquisition series.

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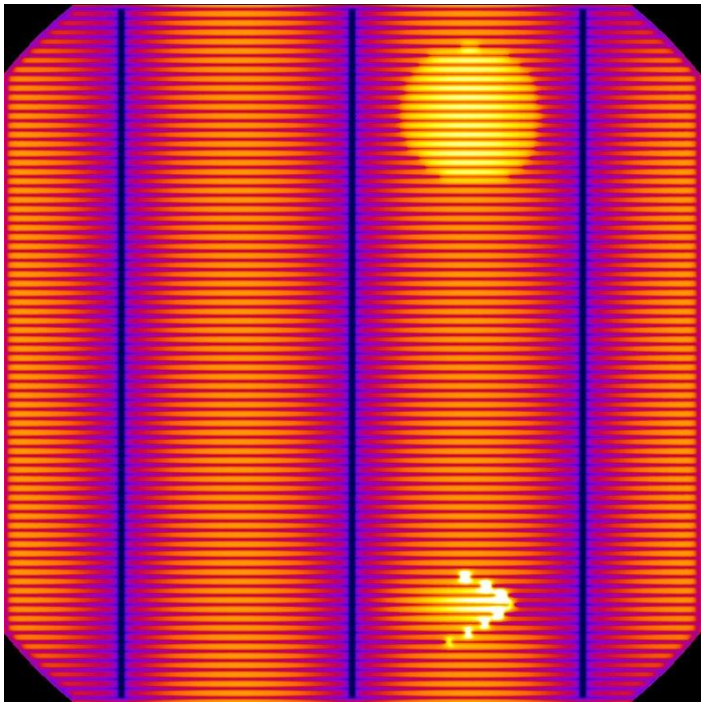
Still a lot to learn…

Line can PL imaging on cells



Griddler simulation:

- Line scanning PL image of c-Si solar cell with local Rs problems!
- Similar contrast as in conventional PL images with current extraction.

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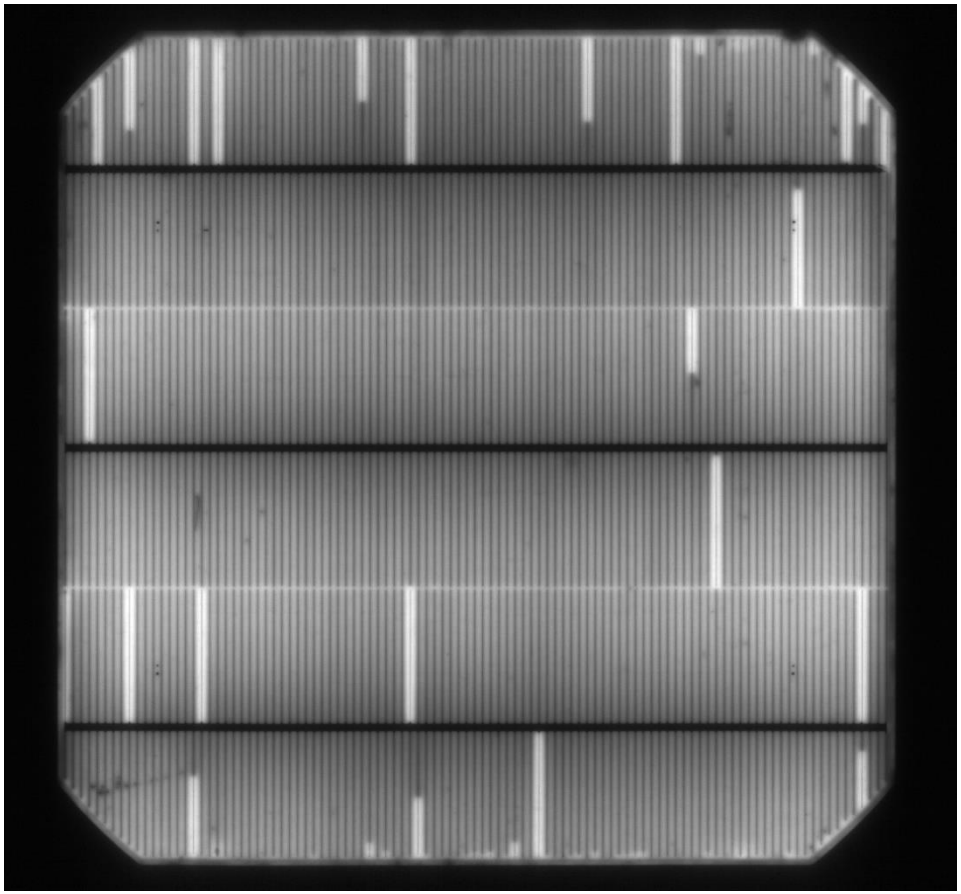
Still a lot to learn…

Line can PL imaging on cells



- **Lowest** illumination
- Busbars parallel to motion

- Strongest Rs effects

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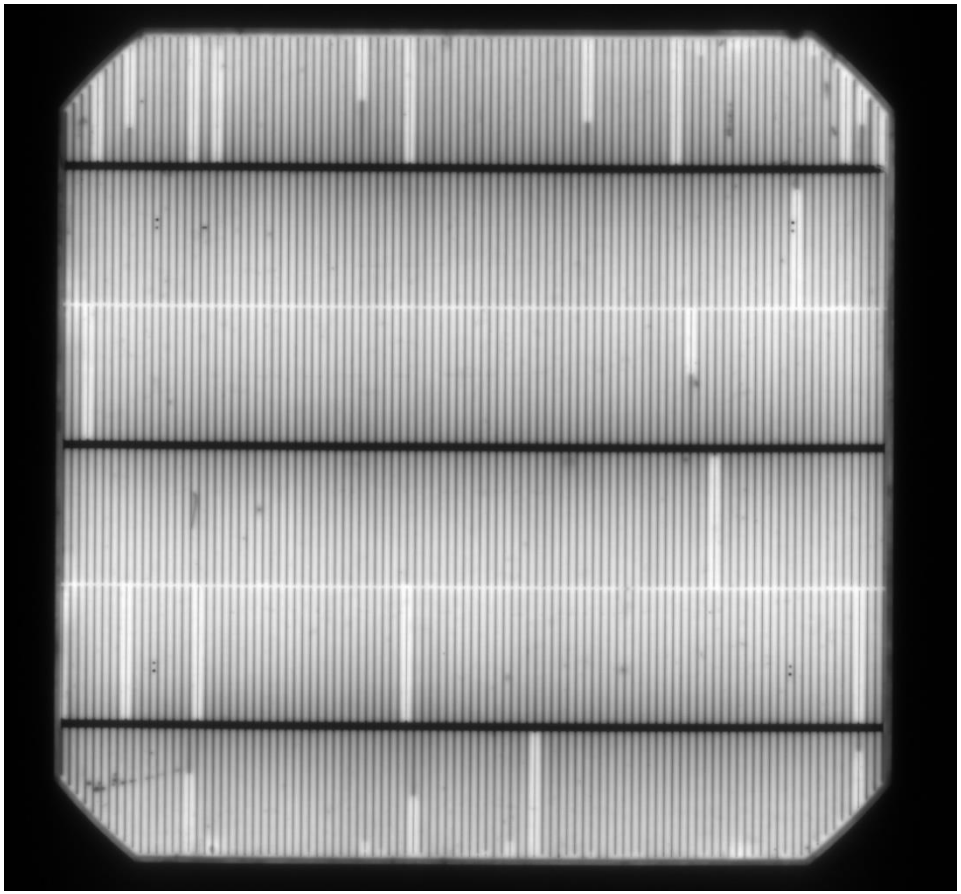
Still a lot to learn…

Line can PL imaging on cells



- **Medium** illumination
- Weaker contrast due to Rs effects

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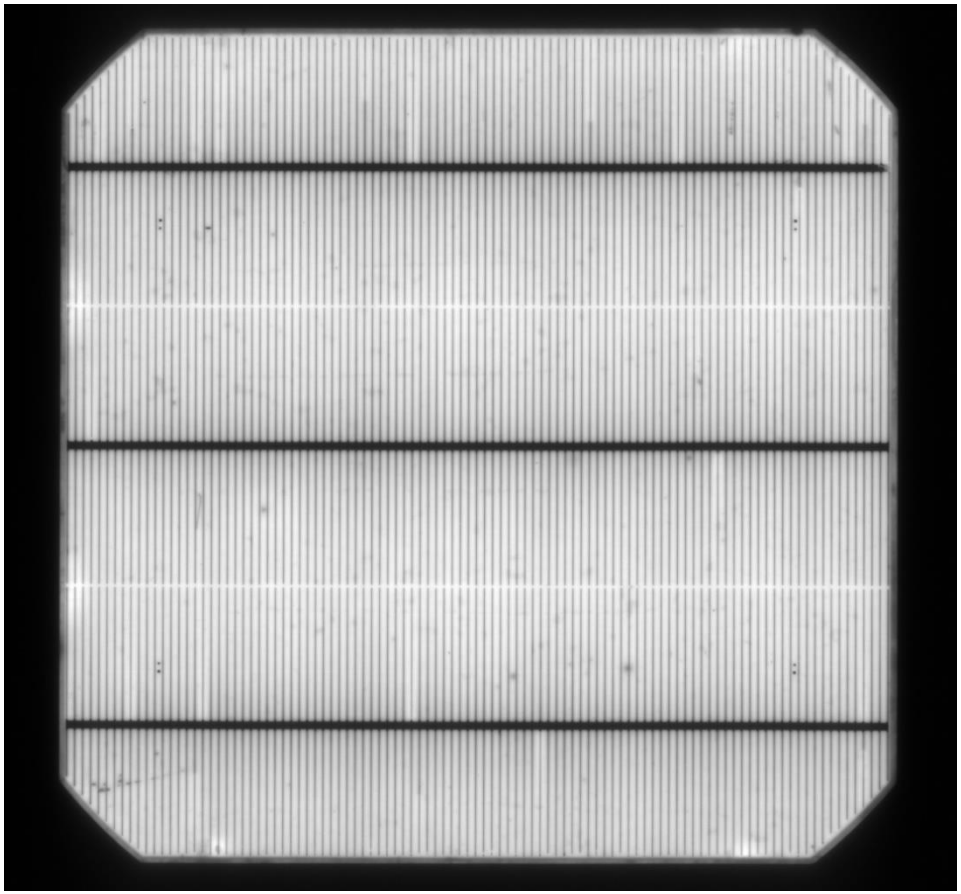
Still a lot to learn…

Line can PL imaging on cells



- **Highest** illumination
- Weak Rs effects

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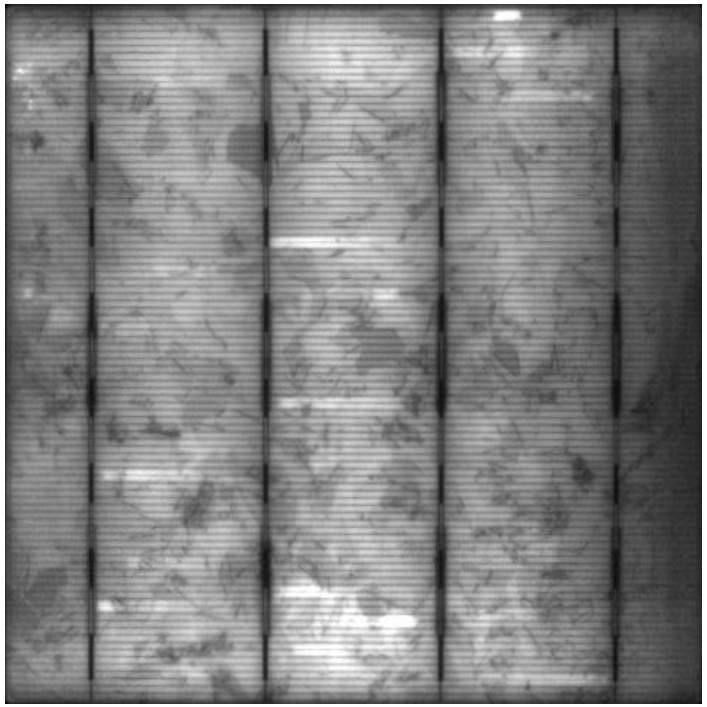
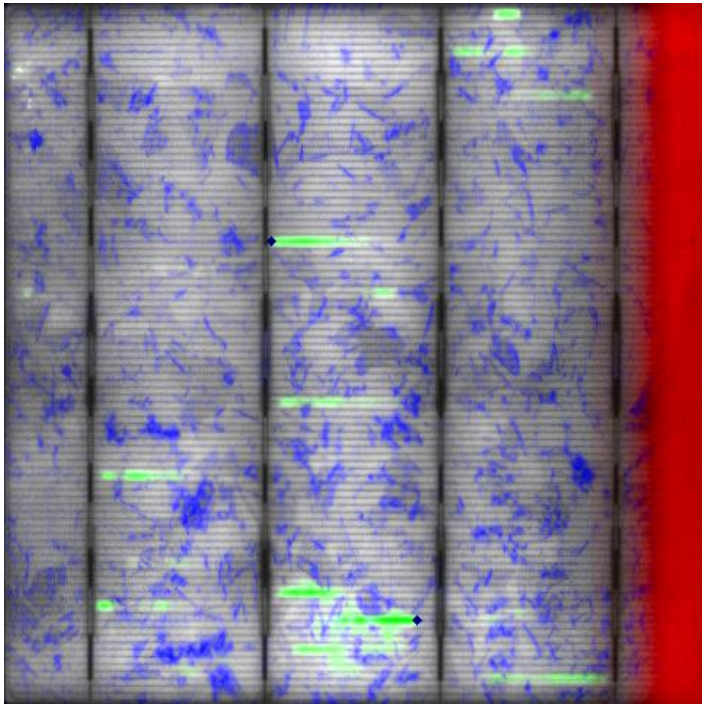
Still a lot to learn…

Line can PL imaging on cells



Inline PL image



Automatic Image algorithms

iLS-C3 PL module

- Contrast inversion facilitates image processing

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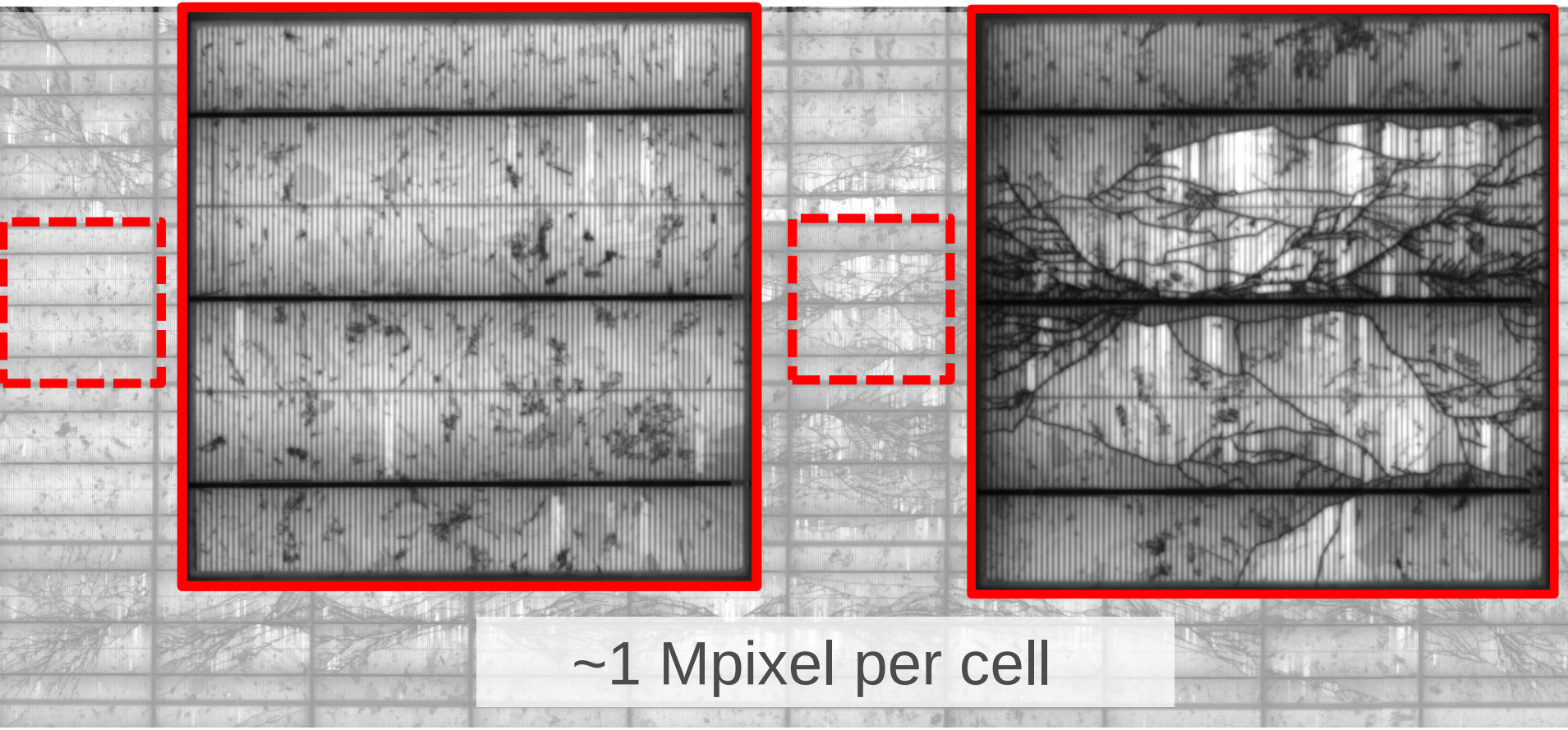
Still a lot to learn…

PL imaging on modules



~1 Mpixel per cell

I.Zafirovska, J.Weber, O.Kunz, T.Trupke, *Module inspection using line scanning photoluminescence imaging*, presented at EU PVSEC, Munich, June 2016.

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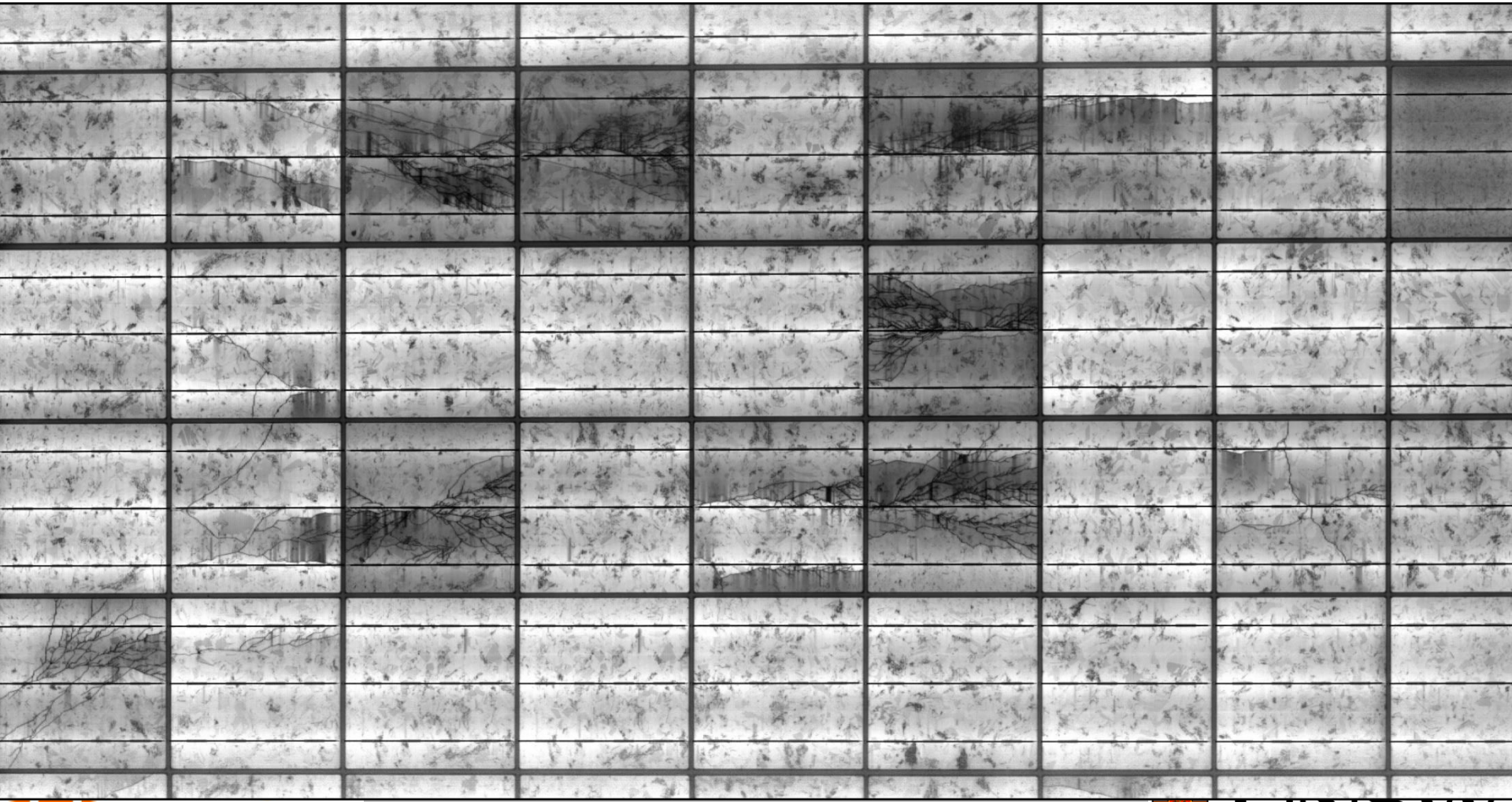
Still a lot to learn…

EL image

Prototype of line scanning PL imaging system



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Still a lot to learn…

PL image

Prototype of line scanning PL imaging system

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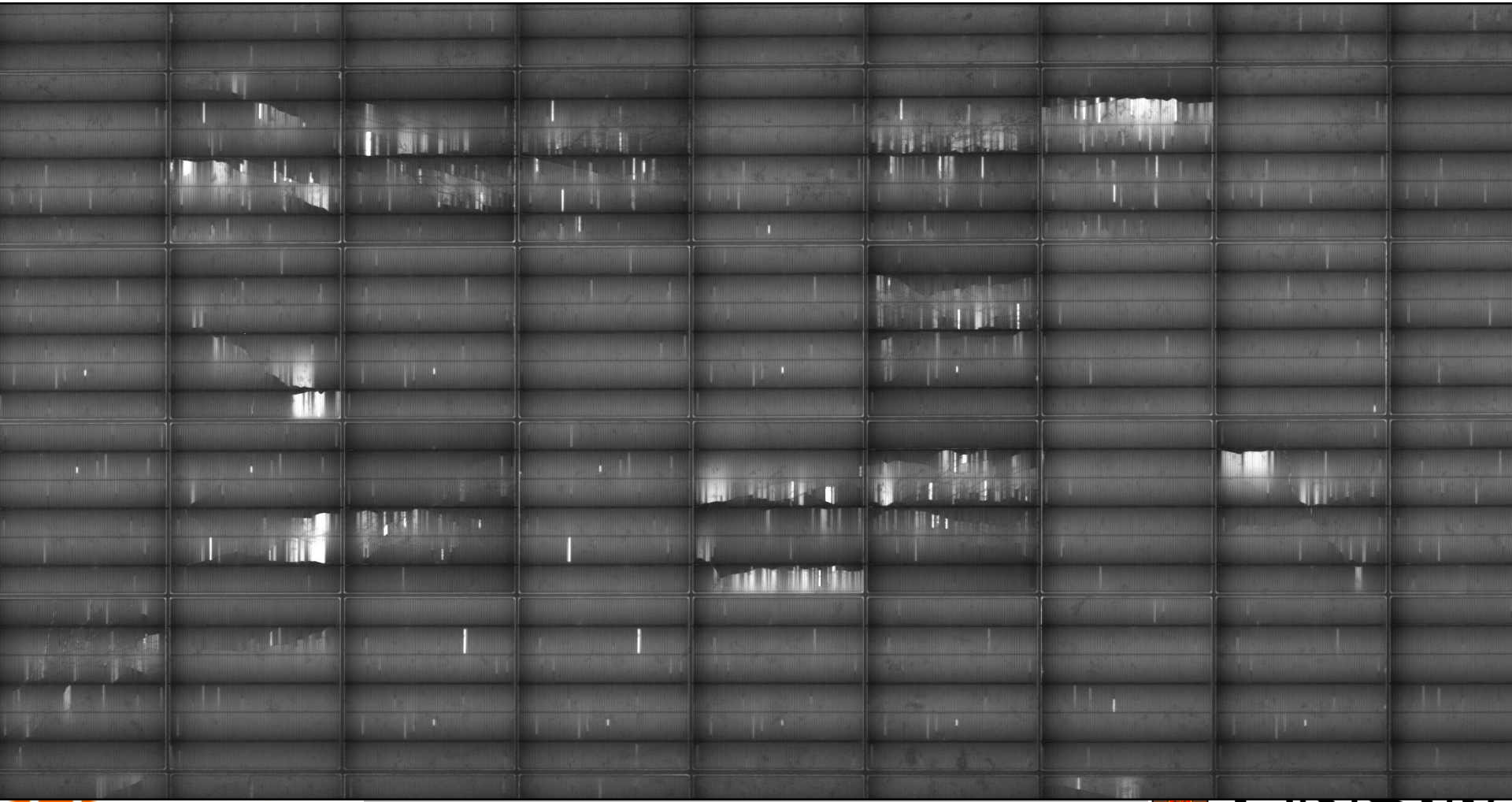
Still a lot to learn…

Processed image

Prototype of line scanning PL imaging system



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Still a lot to learn…

Line can PL imaging on modules

- Advanced quality control for modules
  - Superior image quality
  - Fast
  - Contactless – on the fly acquisition
  - Quantitative analysis
    - Cracks
    - Finger breaks
    - Defect analysis
    - …
  - PL images under various operating conditions
  - Outdoor PL imaging

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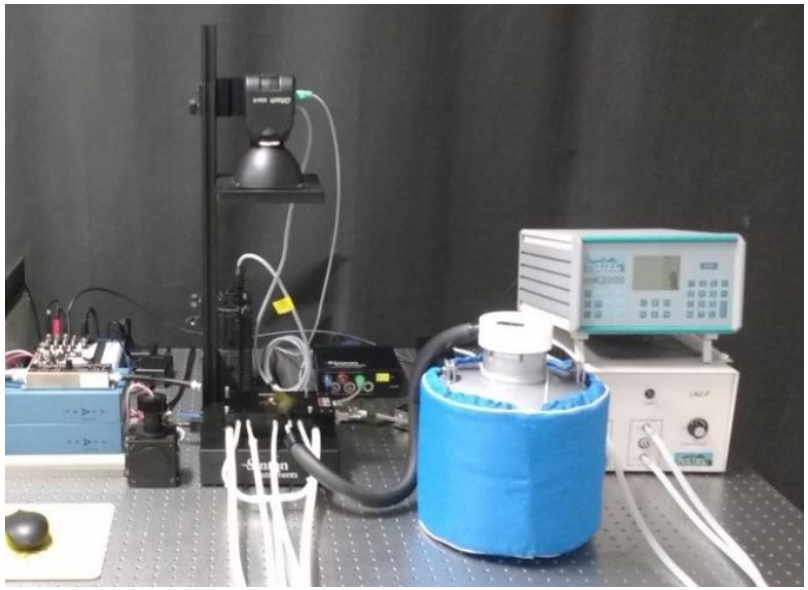
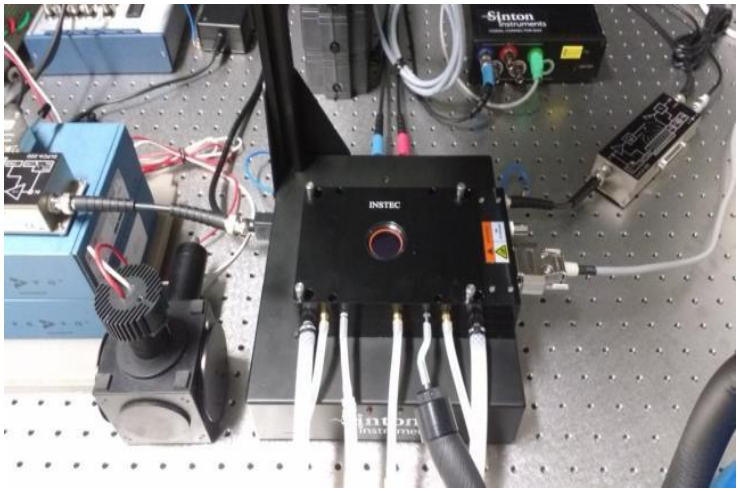
Still a lot to learn…

The mother of lifetime systems: TIDLS



- -200 C to 400 C
- PL and PC detectors
- Various illumination sources
- Front and rear detection
- Corona charger

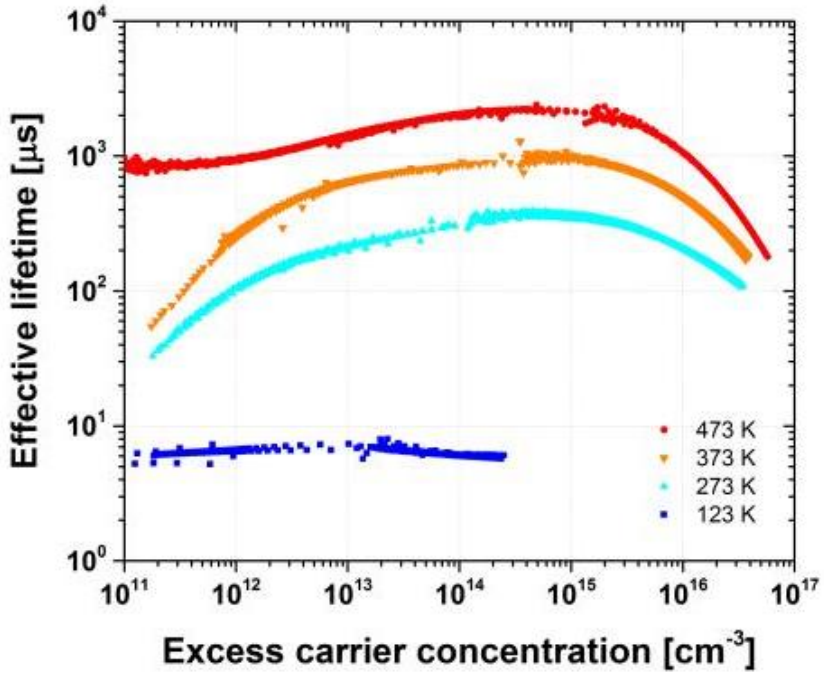


Courtesy of Ziv Hameiri

Now a teenager

Still a lot to learn…

Temperature dependent lifetime



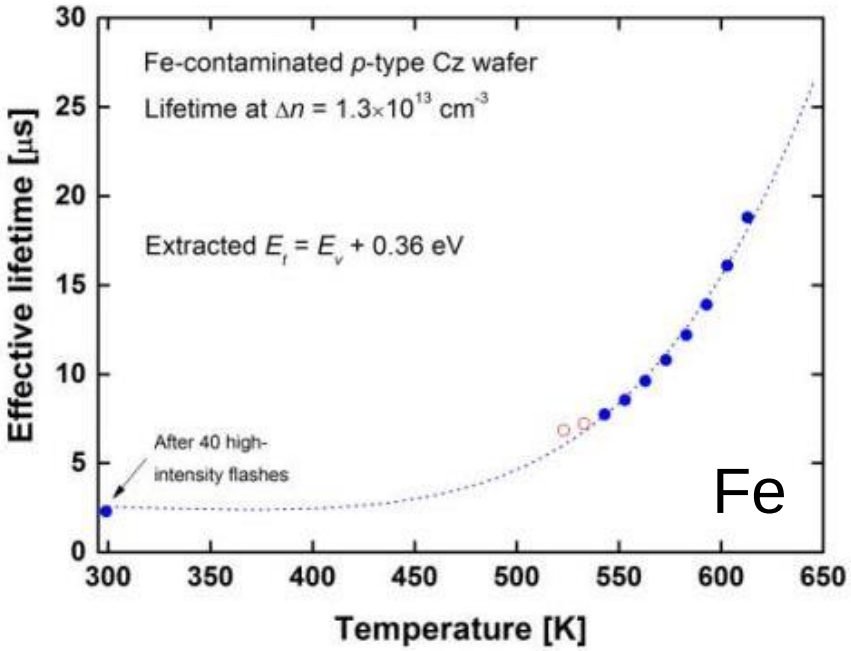
- Advanced defect characterisation using TIDLS
- Based on PL and/or PC data

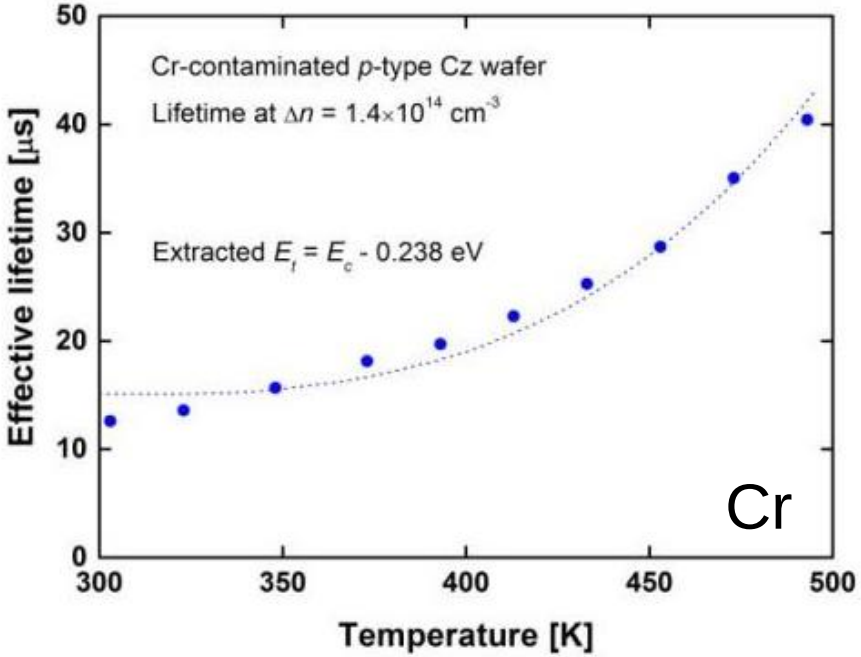
Courtesy of Mallory Jensen

Now a teenager

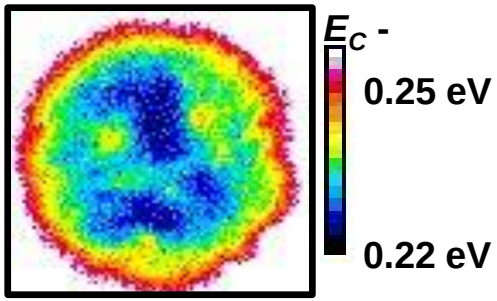
Still a lot to learn…

Temperature dependent PL imaging





Defect energy level map of a 1” Cr-contaminated n-type wafer



Courtesy of Ziv Hameiri

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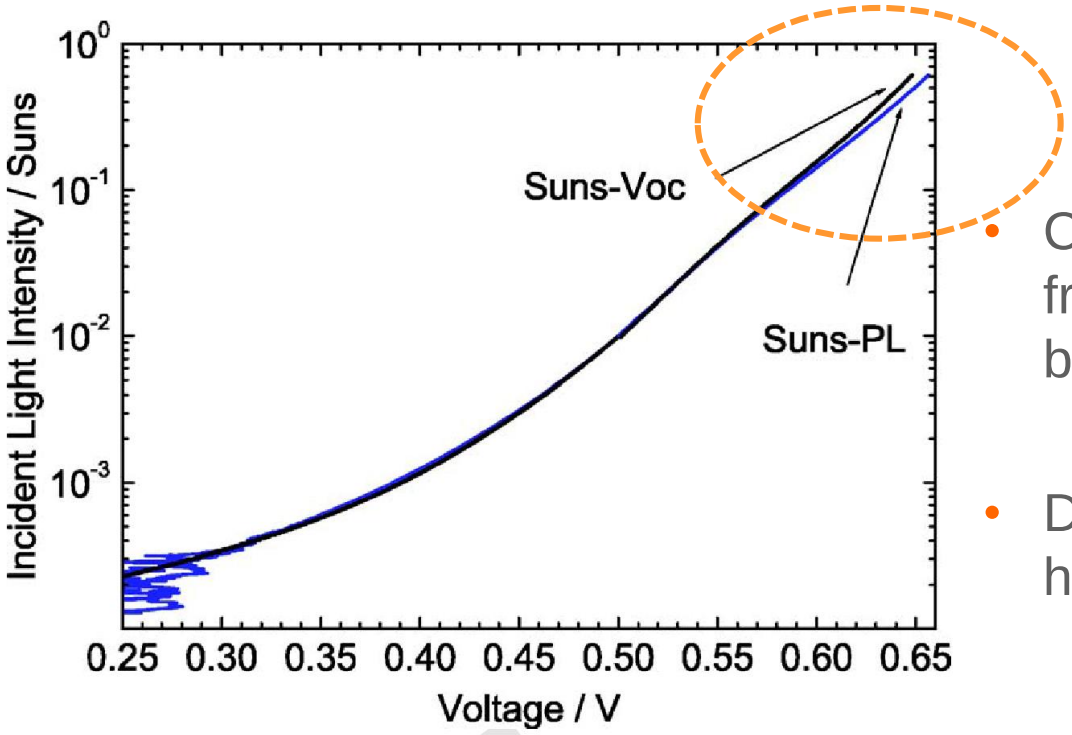
Still a lot to learn…

Front detection PL, application to fully metalised cells



- Contactless implied IV curves from PL demonstrated on bifacial cells in 2005.
- Deviations from Suns-Voc at high illumination intensity.

T. Trupke, R.A. Bardos, M.D. Abbott and J.E. Cotter, Appl.Phys.Lett. **87**, 093503 (2005).

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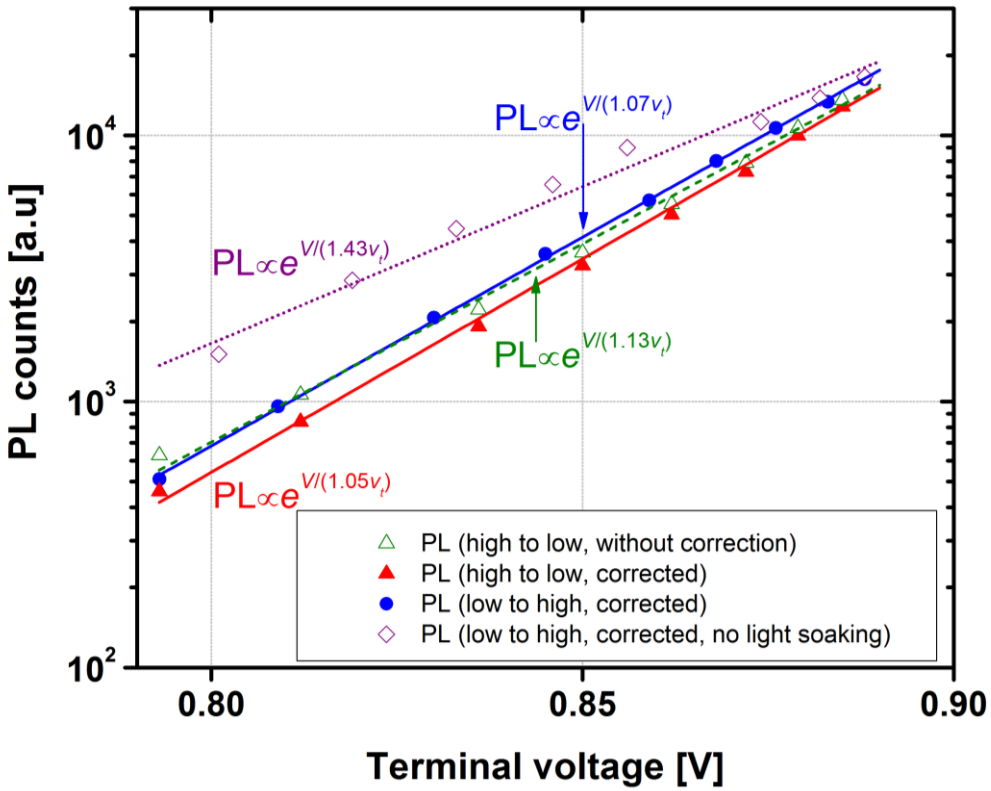
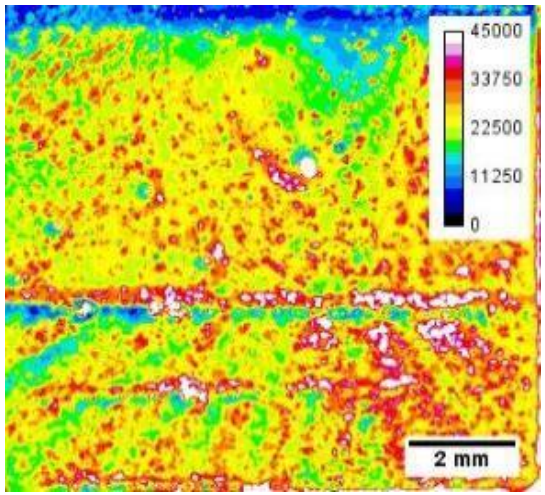
Still a lot to learn…

PL imaging on Perovskites





Ziv Hameiri, Arman M. Soufiani et al., *Photoluminescence and electroluminescence imaging of perovskite solar cells*, Prog.Photov. **23**, 1697 (2015).

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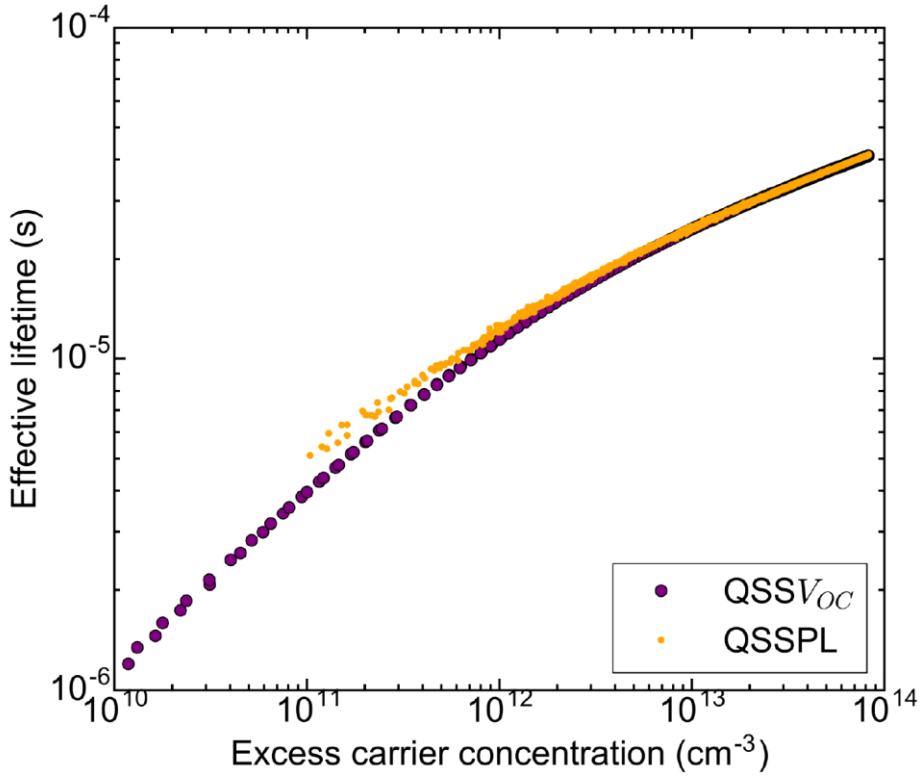
Still a lot to learn…

Front detection PL, application to fully metalized cells



- Injection dependent lifetime on fully metalized cells.

Courtesy of Robert Dumbrell, PhD candidate at UNSW

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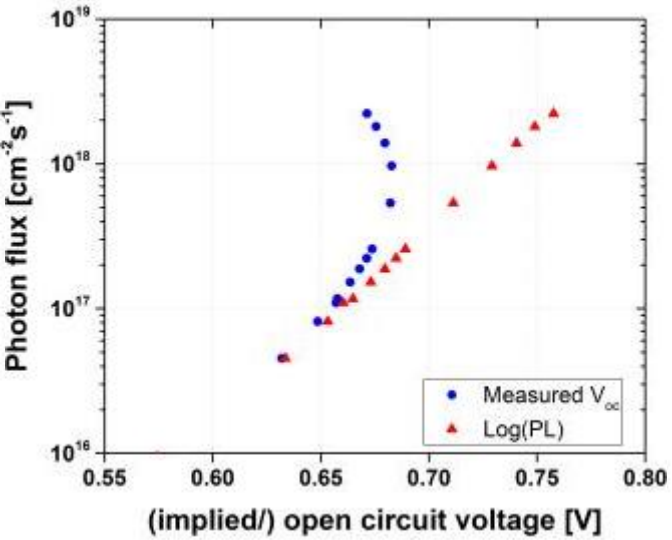
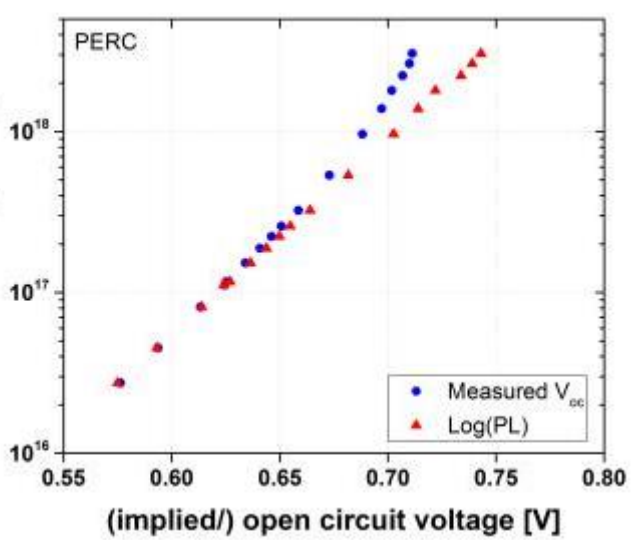
Still a lot to learn…

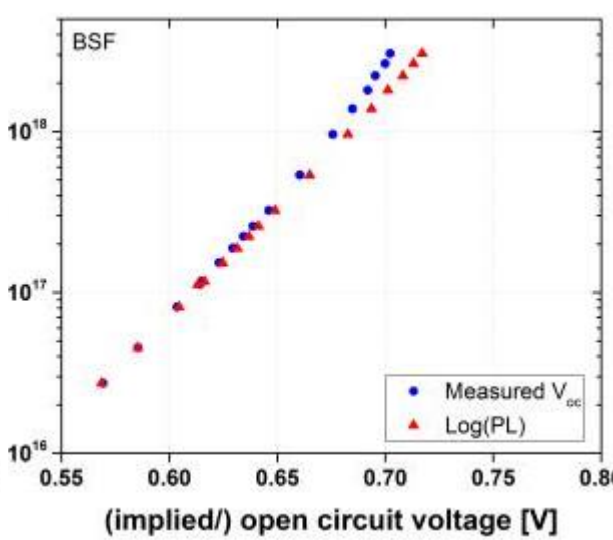
Front detection PL, application to fully metalized cells



LFC cell



PERC



Standard BSF cell

- Suns-PL using front detection PL system

Courtesy of Robert Dumbrell, PhD candidate at UNSW

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Still a lot to learn…

PL imaging with non-uniform illumination

Why is this PL image so crisp…?

Crisp Cake Conundrum…

- PL imaging system using Digital mirror device (DMD) for illumination
- Enables PL imaging with arbitrary non-uniform illumination
- Opens a new applications space!

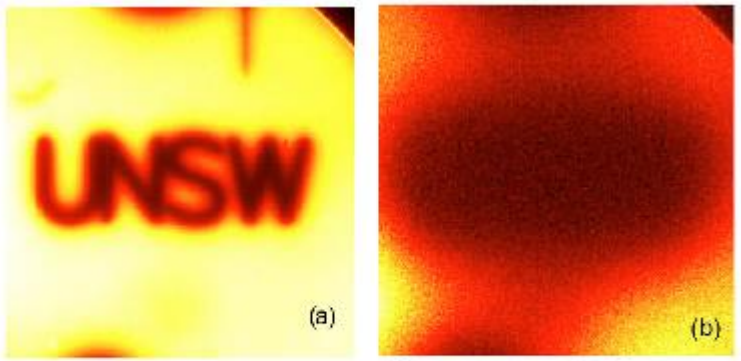

FIG. 4. (Color online) PL image (3.4×3.4 cm^2) of a monocrystalline silicon wafer which has locally been damaged by a laser, measured with (a) 13×10^{17} cm^{-2} s^{-1} (~5 Suns) and (b) 2.5×10^{16} cm^{-2} s^{-1} (0.1 Suns).

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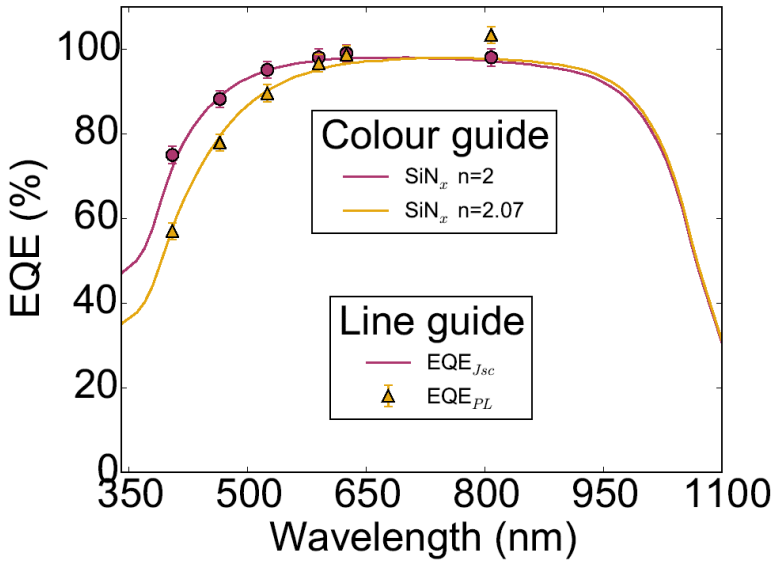
Still a lot to learn…

PL imaging with variable illumination wavelengths

- PL imaging with LED illumination with 11 different illumination wavelengths.



Courtesy of Appu Paduthol, PhD candidate at UNSW

Acknowledgement

- 10 years of development: PL imaging has come a long way.
- Long way to go!
- Thanks to the outstanding teams at UNSW and BTi, various industry partners and collaborators.
- UNSW team happy to collaborate!

Thanks to ARENA for funding 2014/RND009

Thanks for listening…