Advanced inline characterization of crystalline silicon solar cells

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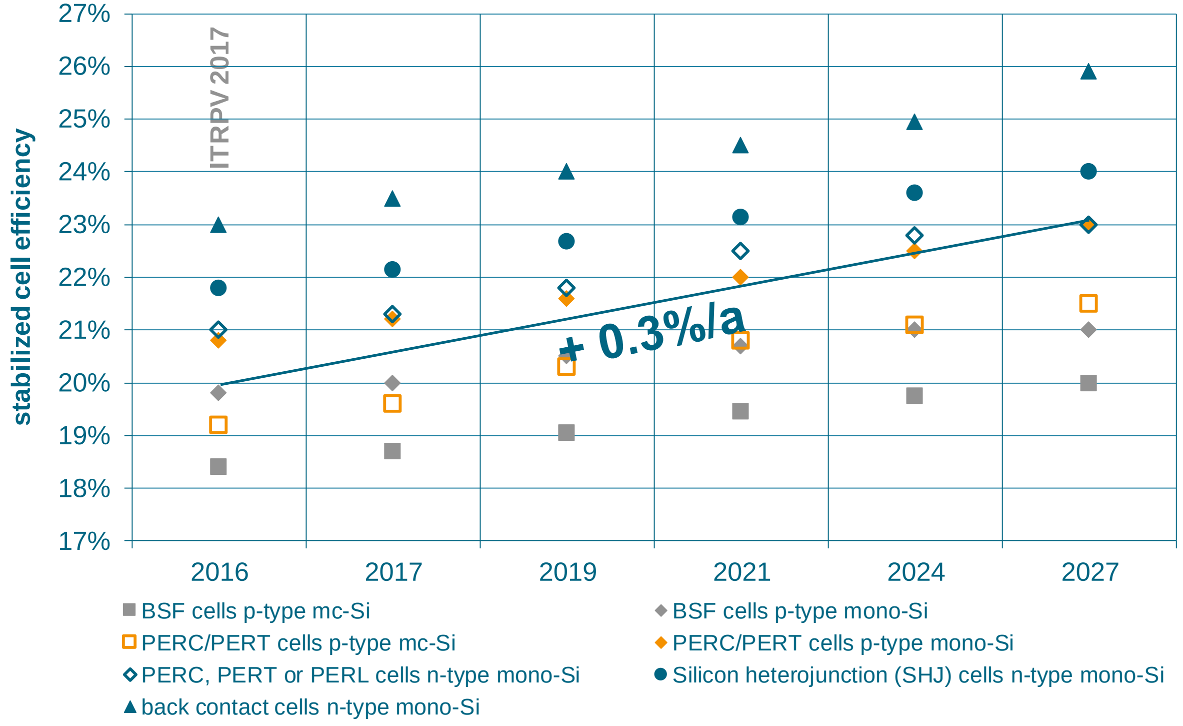
PV-Seminar at UNSW

Sydney, March 24th 2017

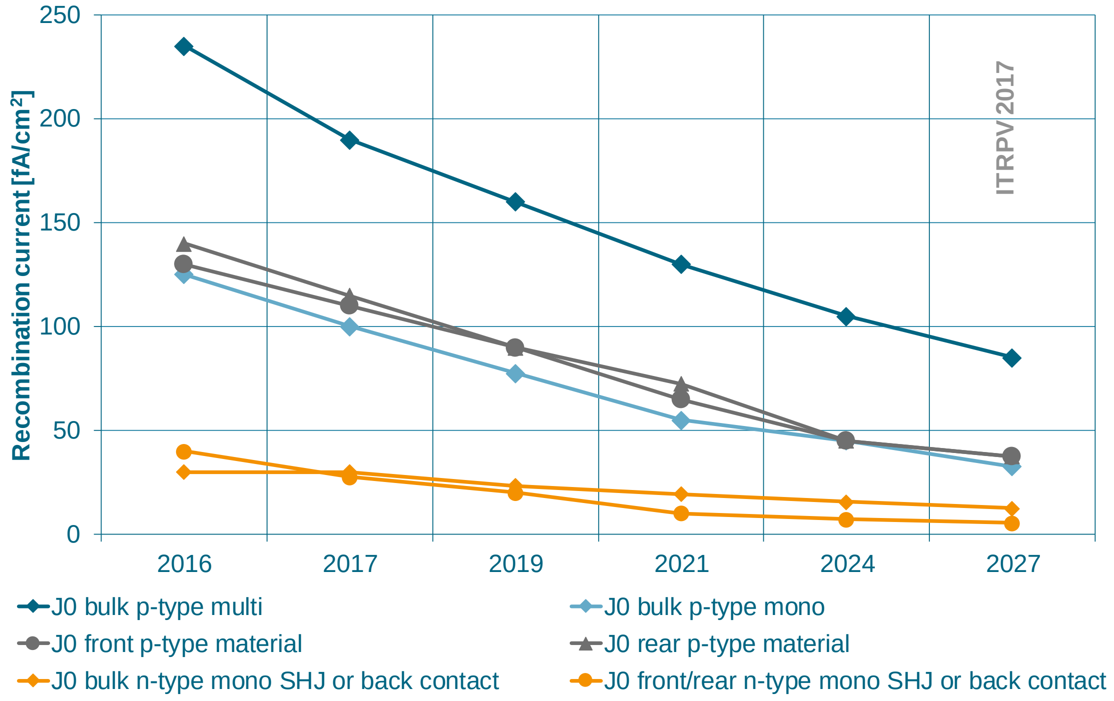
Challenges in process and quality control

.h.a.l.m.

Stabilized cell efficiencies (ITRPV 2017)



Recombination current densities (ITRPV 2017)



Increasing capacitance effects

Increasing material/process sensitivity

Challenges in process and quality control

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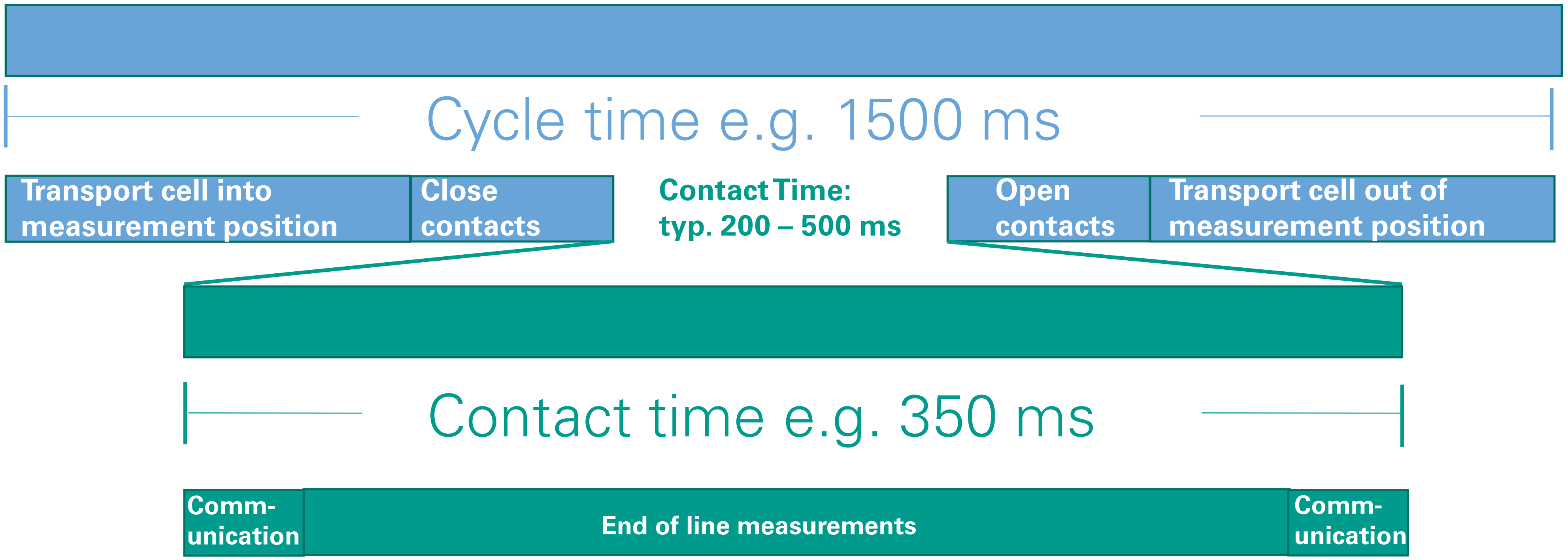

All measurements for quality and process control in cell testing **must be performed within contact time**

Outline

.h.a.l.m.

- How to deal with **capacitance effects**?
- **Defect detection** by EL -imaging
- **Hotspot detection** by IR thermography
- **Control of metallization process** by grid resistance measurement
- **Detection of recombination losses** by inline spectral response
- How to measure **bifacial cells**?
- Contacting of **busbarless cells**
- **Conclusion**

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Background – where does solar cell capacity come from

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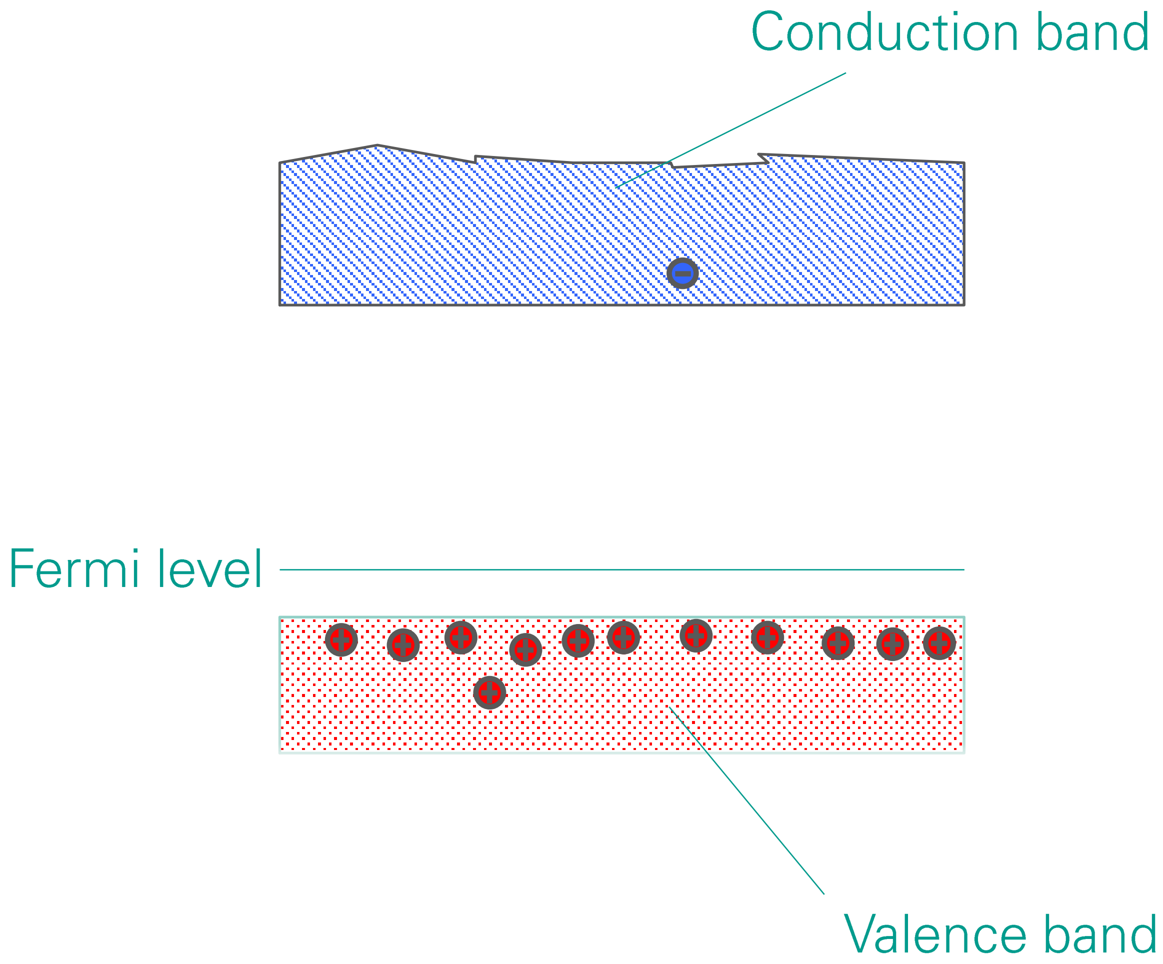

- P-doped silicon in equilibrium
- Excited charge carriers in conduction band (fermi distribution)

Background – where does solar cell capacity come from

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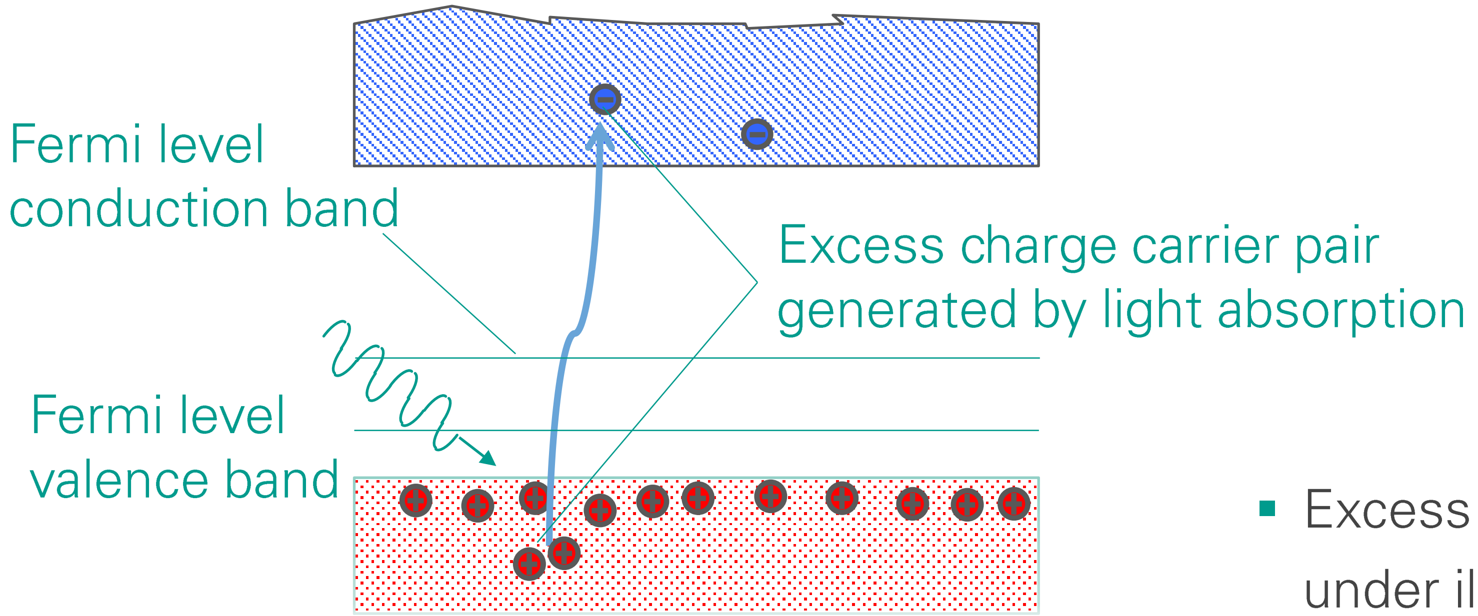
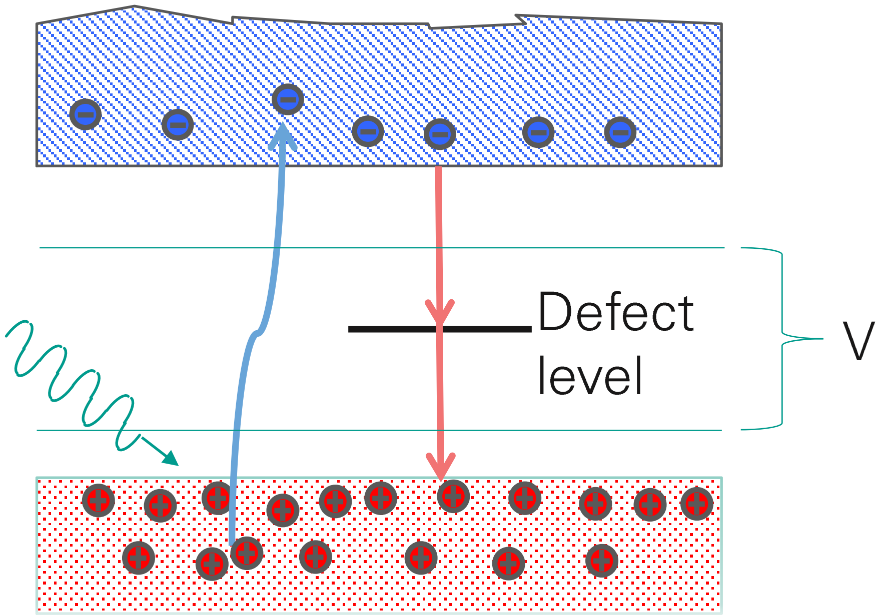


- Excess charge carriers generated under illumination

Background – where does solar cell capacity come from



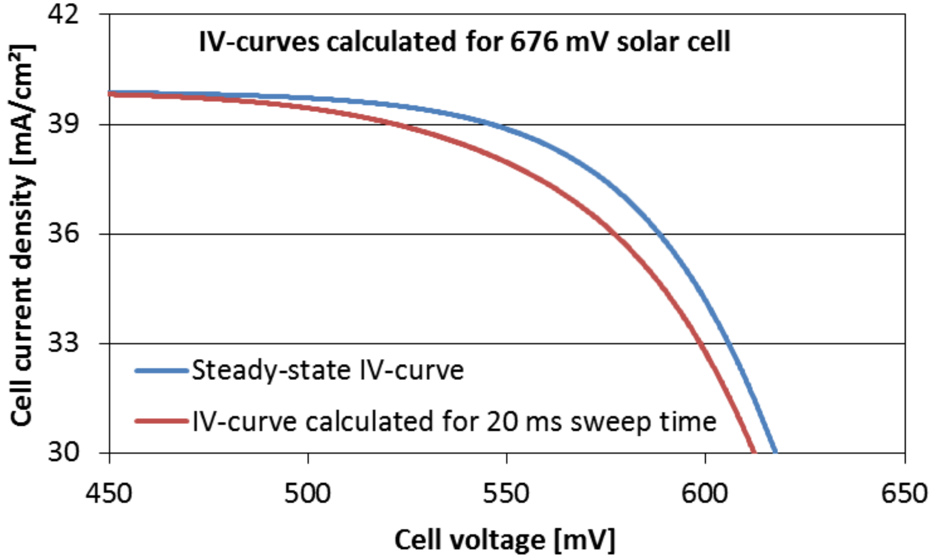
- Equilibrium under illumination:
  Generation rate (G) = Recombination rate (U)

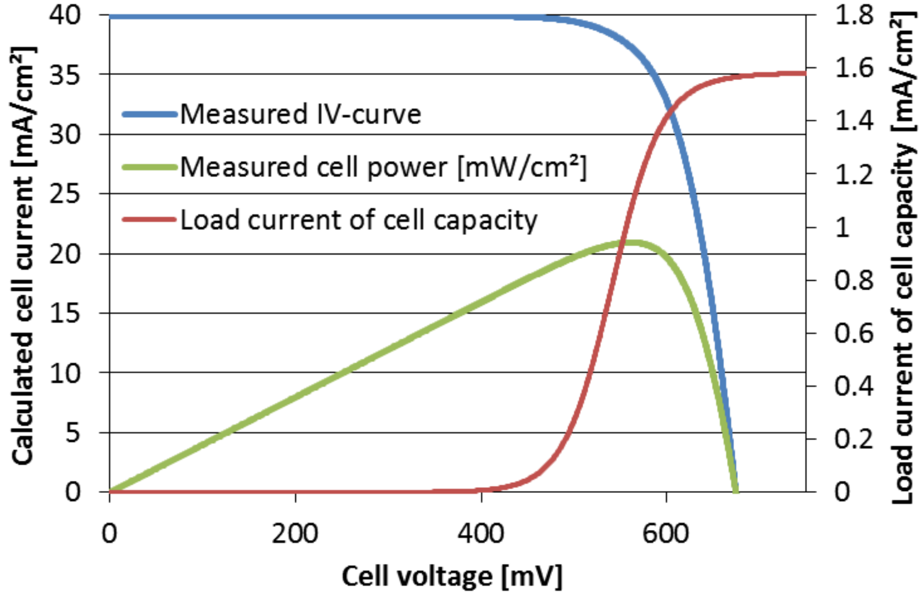
- $\tau = \Delta n / U$
  $\Delta n \sim \Delta Q \sim \mathbf{C_{diff}}$
  $\Delta n \sim \mathbf{exp(V/V_t)}$

Δn excess carrier density
τ charge carrier lifetime
ΔQ generated excess charge
C_{diff} diffusion capacitance
V separation of Fermi levels

The impact of solar cell capacity on measurement of electrical parameters

- Charging the cell capacity reduces the current delivered by the cell
- Capacity is intrinsic to material – can‘t be simply avoided
- Wiring resistance and voltage sweep speed determine saturation of capacitance load current





Required sweep times to avoid transient effects in standard single sweep measurements

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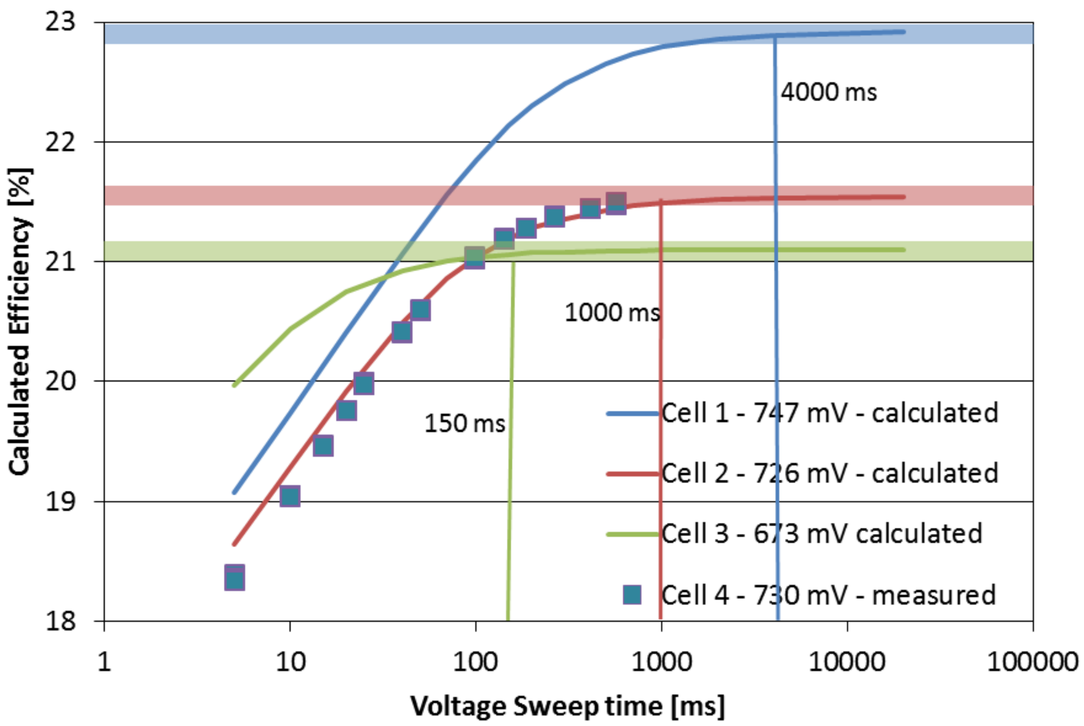
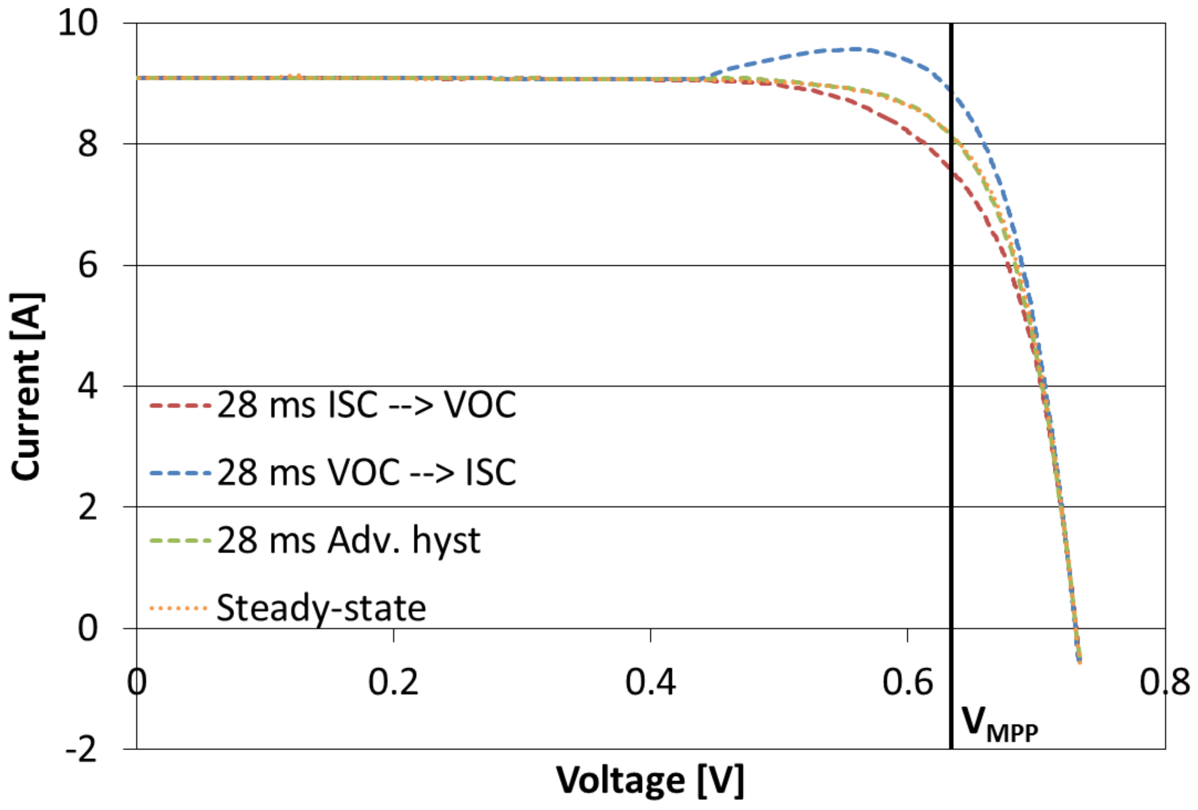
- Accuracy requirement: ΔEta < 0.05%
- **673 mV** cell requires approx. **150 ms**
- **726 mV** cell requires approx. **1000 ms**
- **747 mV** cell requires approx. **4000 ms**
- **Not compatible with throughput requirements!!!**
- High accuracy measurements on **high efficiency cells** in production **require** some kind of **smart approach…**



h.a.l.m. single flash hysteresis – a smart approach

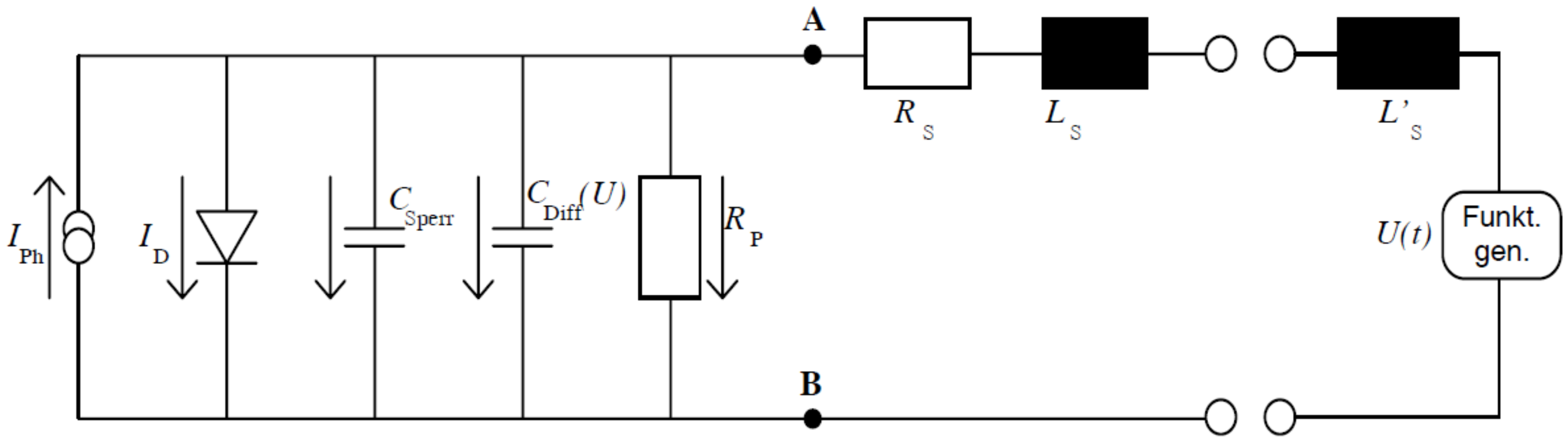
.h.a.l.m.

- Two voltage sweeps within **single flash** ($I_{SC} \rightarrow V_{OC}$ and $V_{OC} \rightarrow I_{SC}$)
- Measurement of effective hysteresis of *IV*-curves
- Evaluation based on diode model and the two measured curves
- **No parameters to adjust**
- **Full steady-state *IV*-curve** is derived self consistently



Measurement of a 730 mV cell

h.a.l.m. advanced hysteresis - model



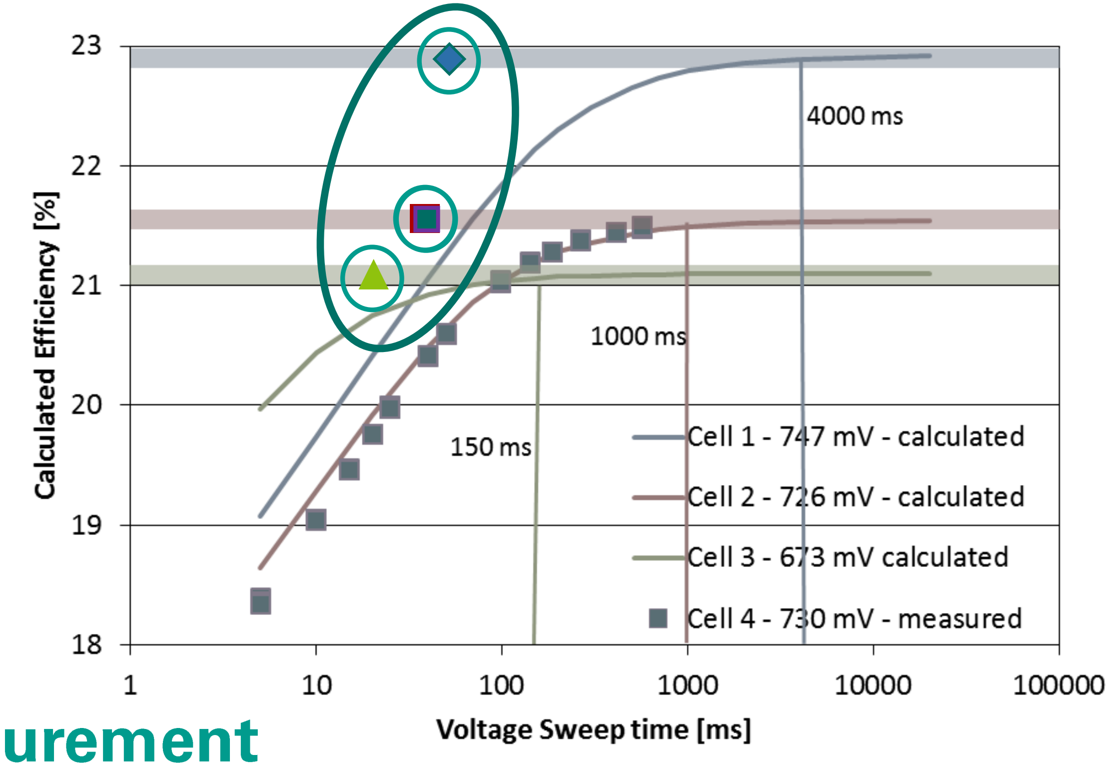
- Extended diode model circuit diagram as proposed by Winter et al.*
- External Voltage U(t) is applied
- Cell Voltage V(t) is measured between A and B
- C_{diff}(U) and R_S lead to an asymmetric splitting between I_{SC} → V_{OC} and V_{OC} → I_{SC} sweep

*S. Winter et al.; Proc of the 2nd World Conf. On Solar Energy Conversion, Wien, 1998

Required sweep times to avoid transient effects in single flash hysteresis measurements

.h.a.l.m.

- Accuracy requirement: ΔEta < 0.05%
- **673 mV** cell requires approx. ~~**150 ms**~~ **2 x 12 ms**
- **726 mV** cell requires approx. ~~**1000 ms**~~ **2 x 22 ms**
- **747 mV** cell requires approx. ~~**4000 ms**~~ **2 x 27 ms**



60 ms are sufficient for precise IV-measurement of solar cells with up to 750 mV in V_{oc}

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Electroluminescence (EL) imaging

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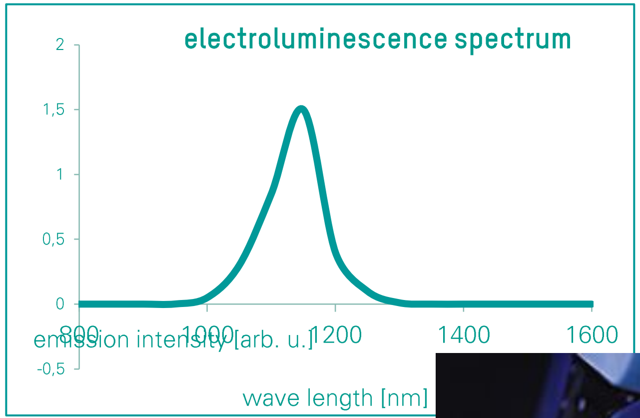
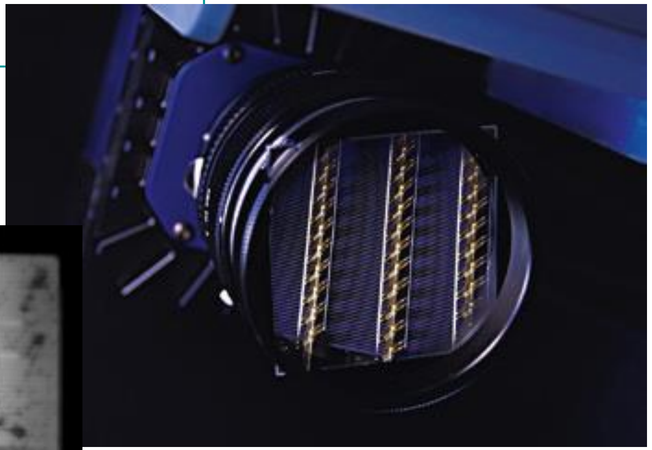
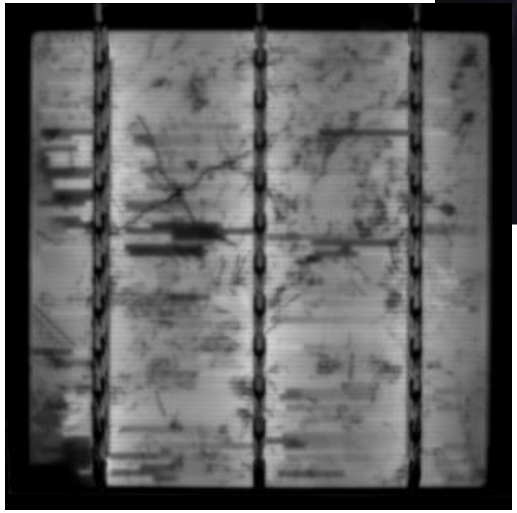
What is electroluminescence imaging?

- Short wavelength infrared (SWIR) light emission in forward bias
- Light capturing with SWIR sensitive cameras
- Defect recognition by locally reduced light emission







Automated defect detection

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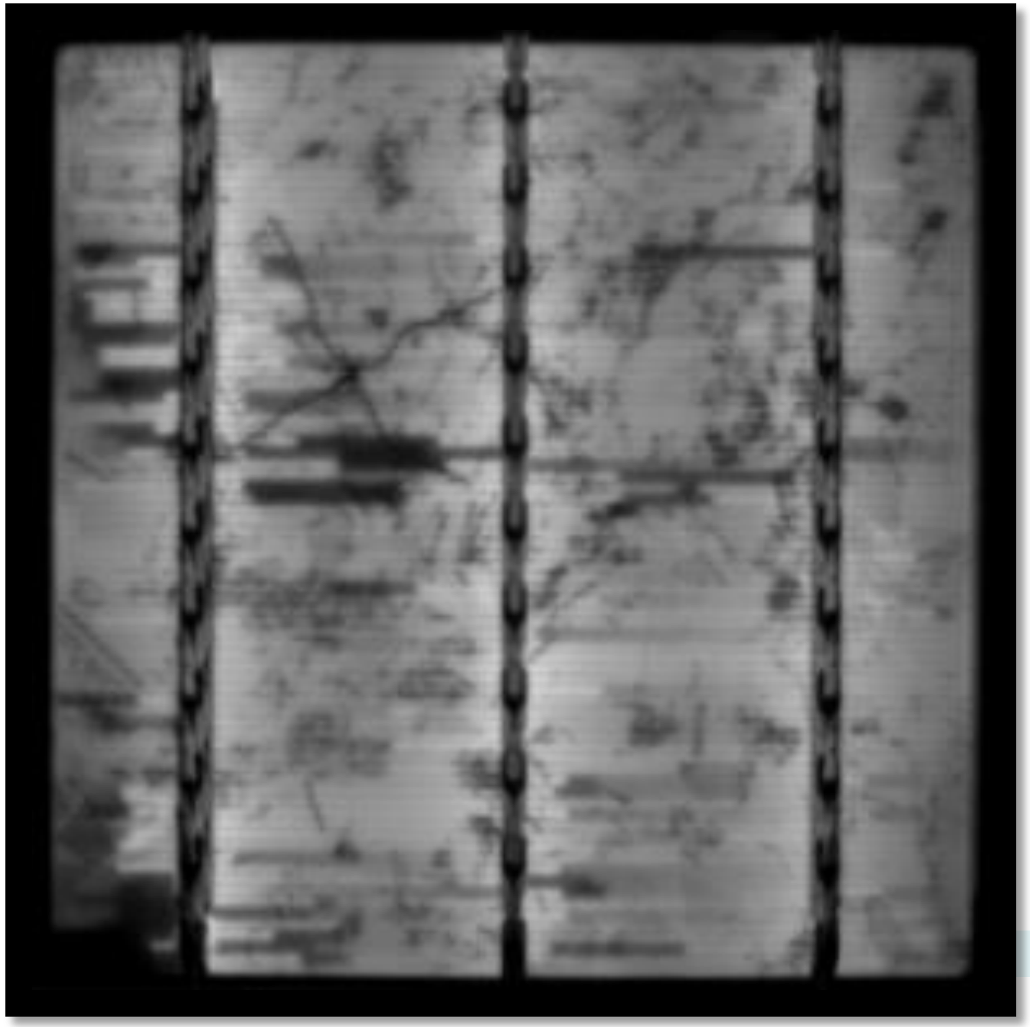
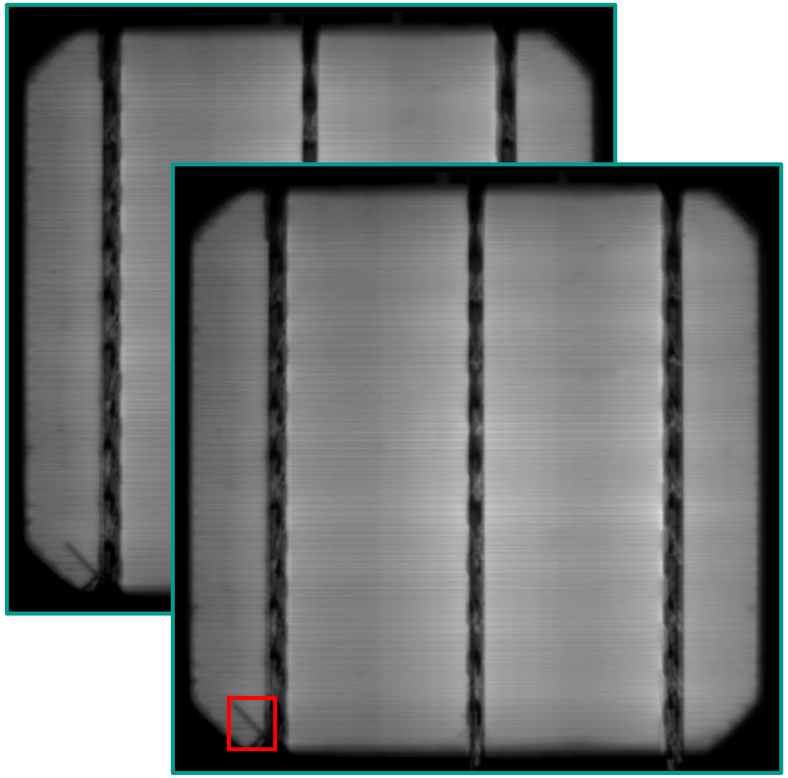
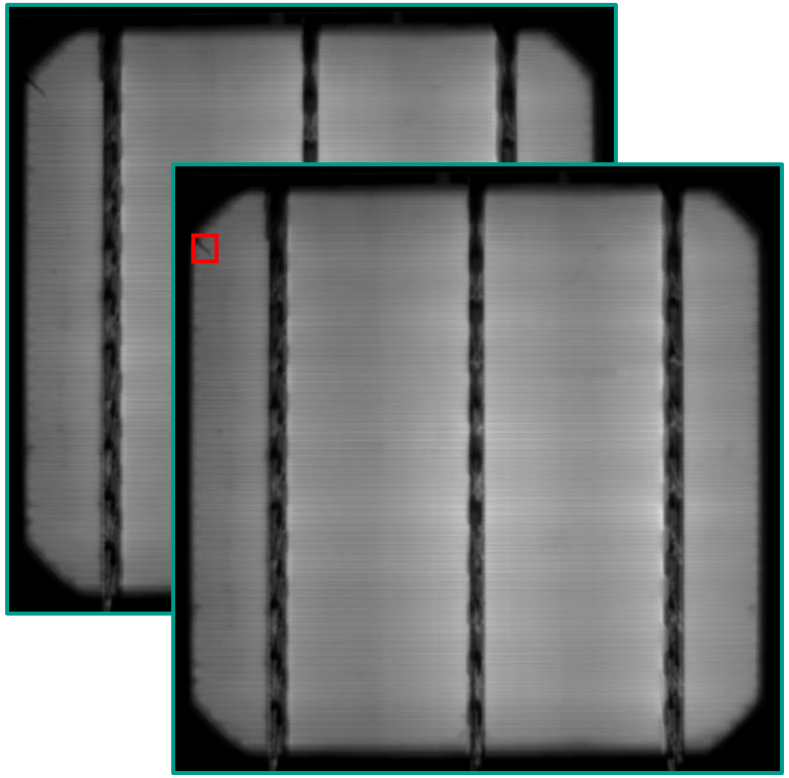
- detection quality depends on cell and wafer type
- Locally reduced light emission
  - recombination (no current)
  - blocking of light emission
  - cell defects (cracks, finger defects, etc.)
  - crystal structure
- Tool for **process** and **quality control**

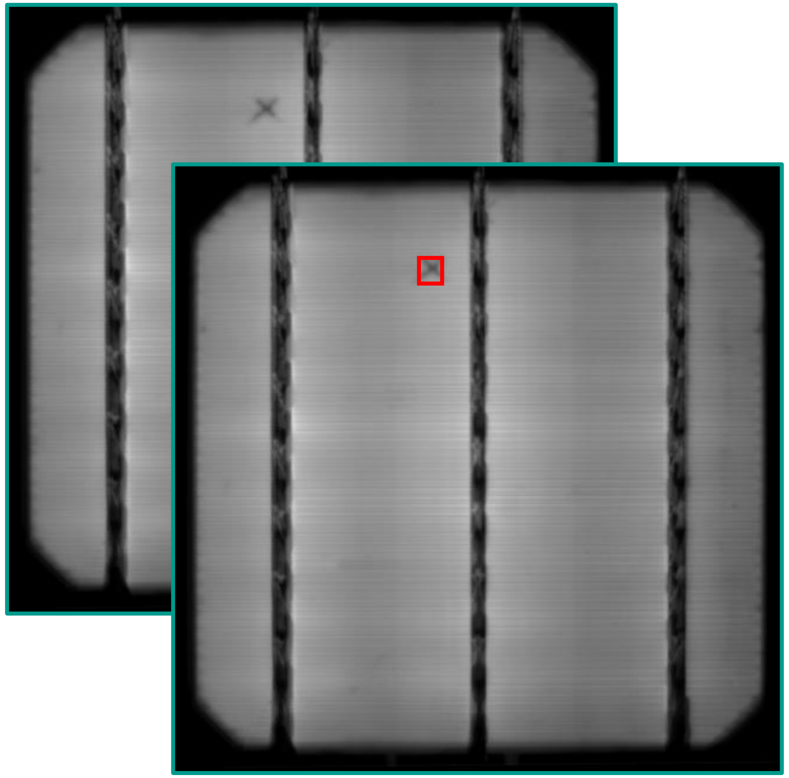


Crack detection on monocrystalline solar cells

- **Examples:** Detected cracks







Dark area detection on monocrystalline solar cells

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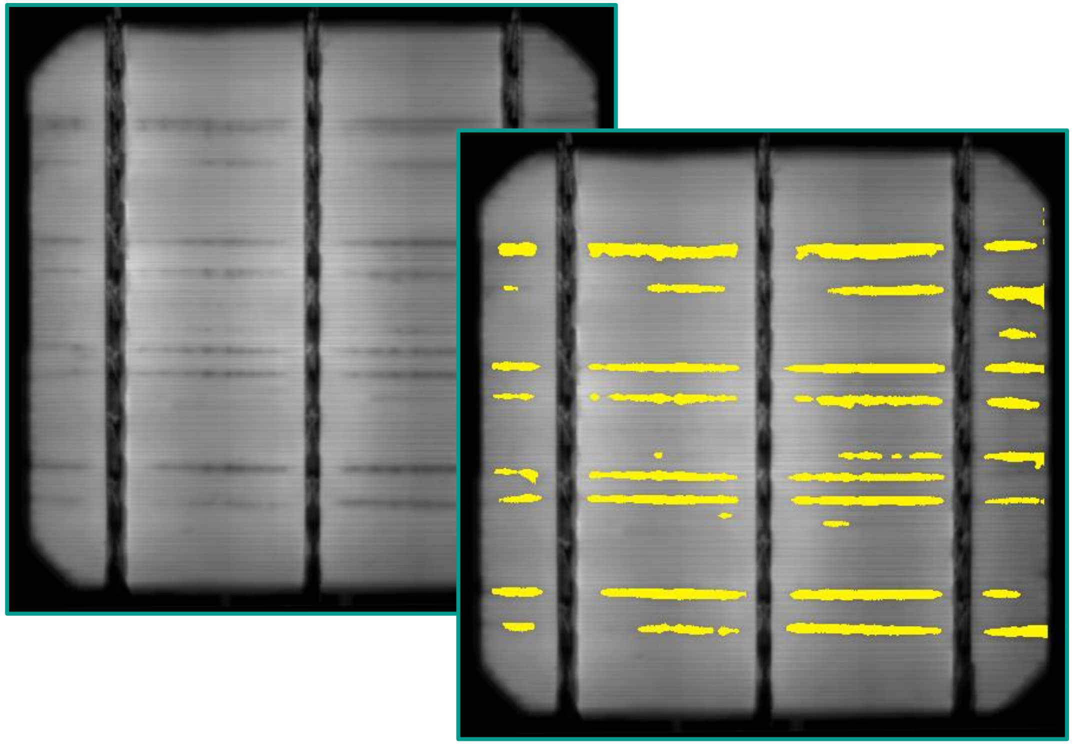
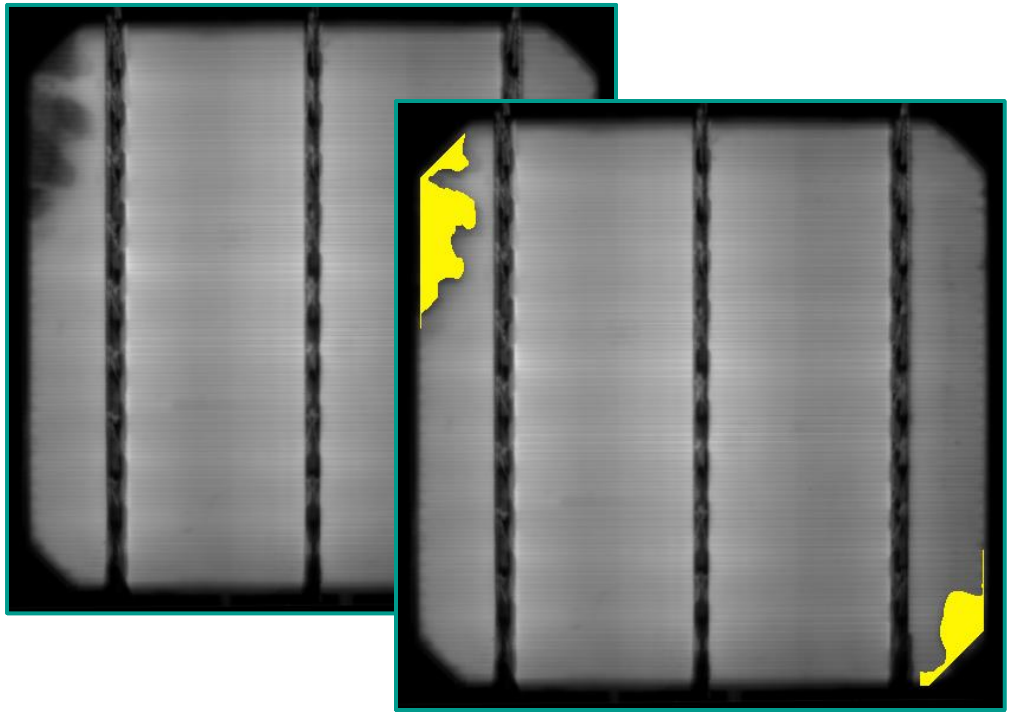
- **Examples:** Detected dark area from 5 to 8 %





Finger defect detection on monocrystalline solar cells

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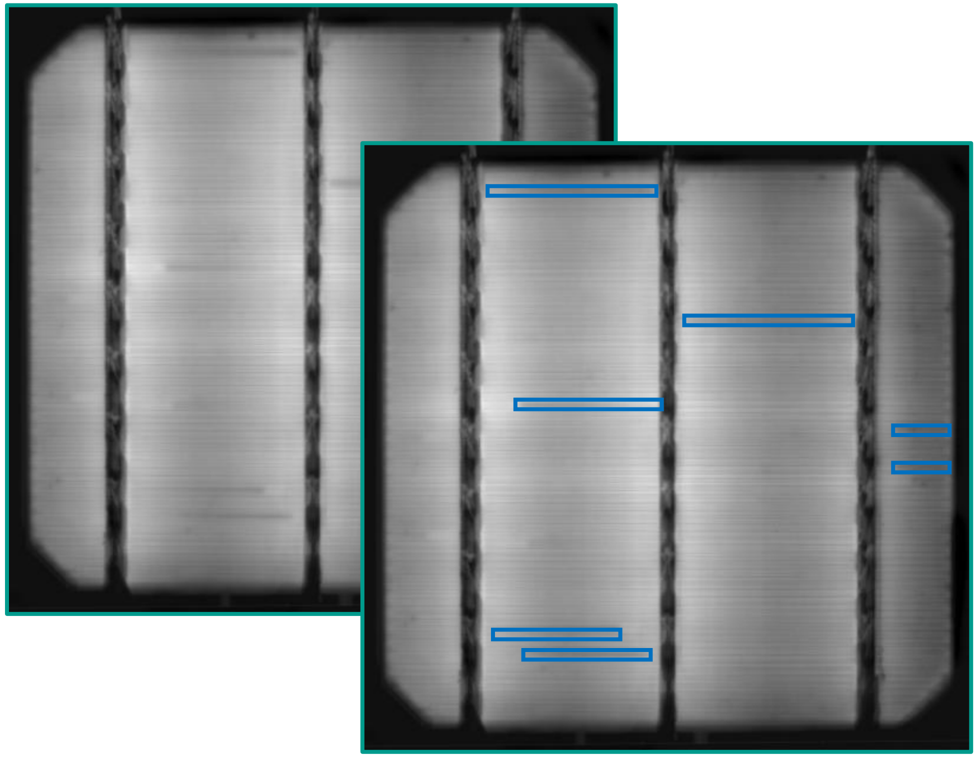
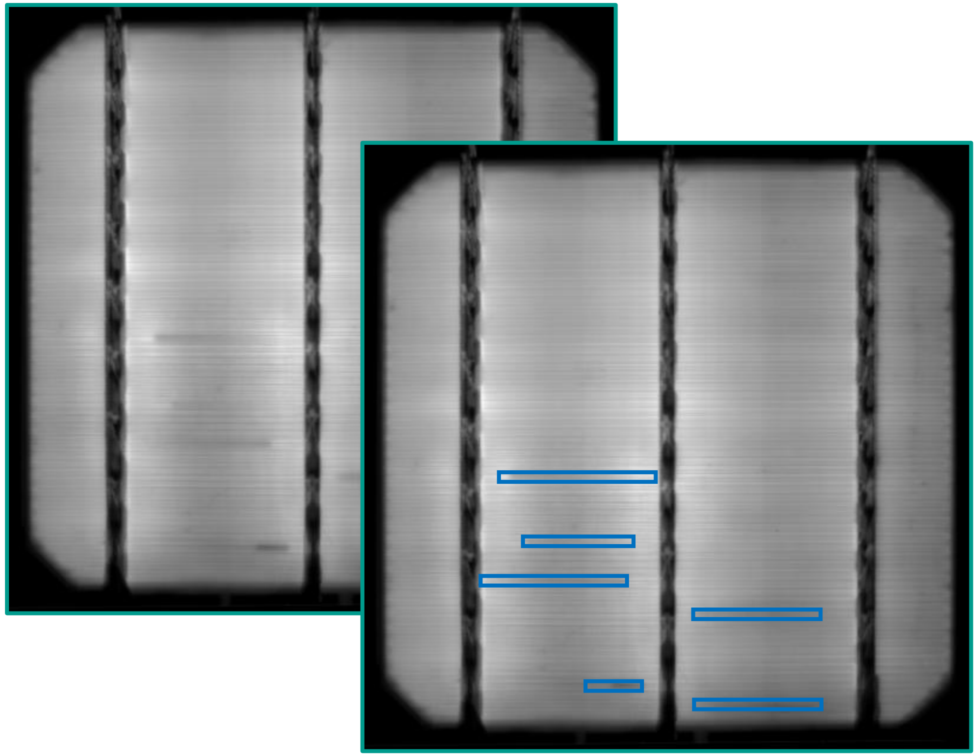
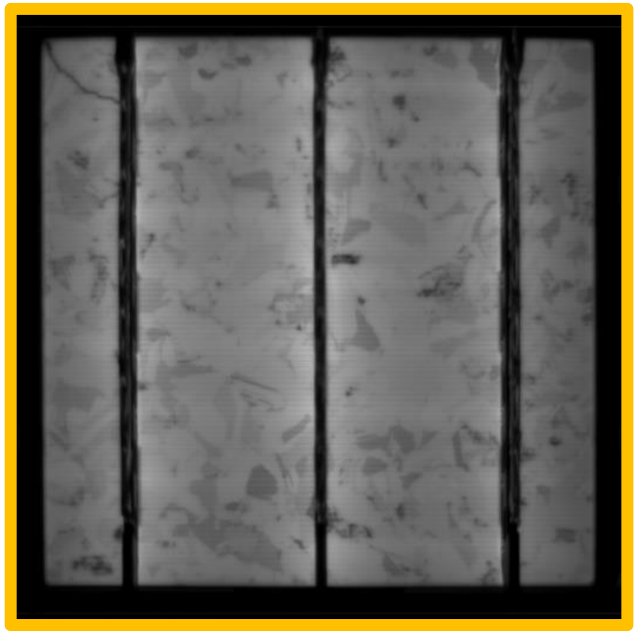
- **Examples:** Detected finger defects



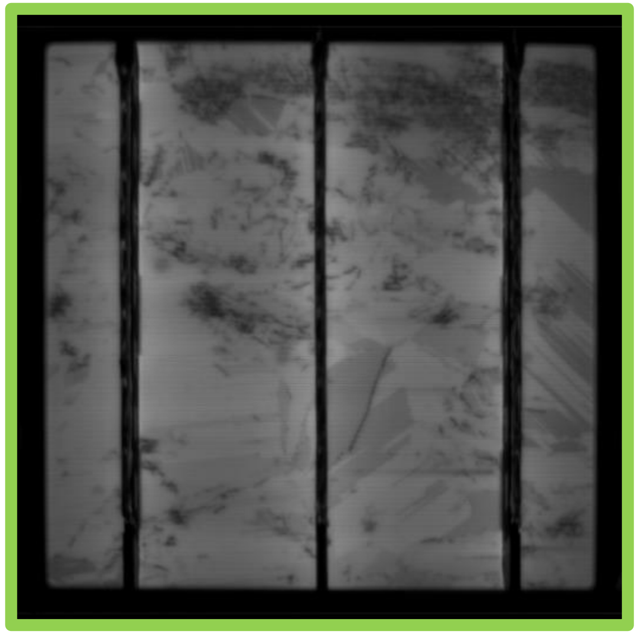


Challenge on multicrystalline cells

Cracks



Crystal structure



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Hotspot detection by infrared imaging

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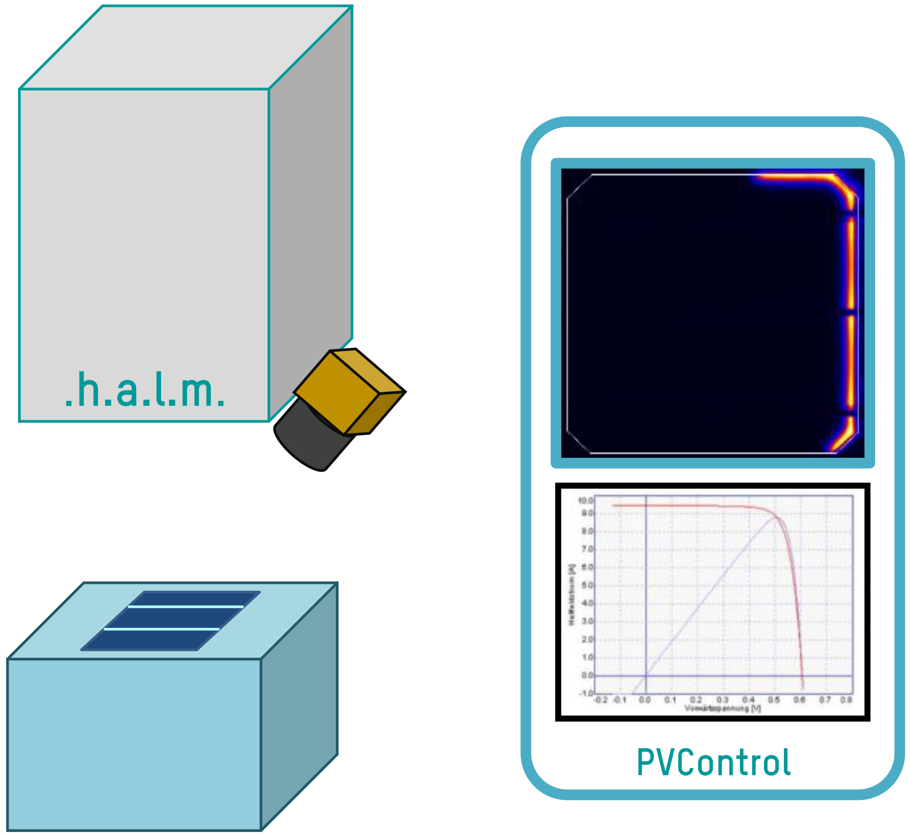
- High-speed infrared imaging
- Process and quality control
- Shunt detection and hot spot localization
- Available for high throughput cell testers



Process control by IR-imaging

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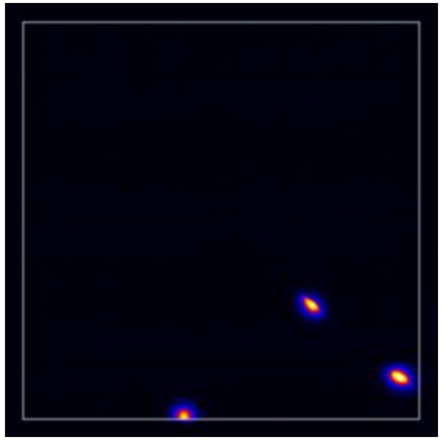
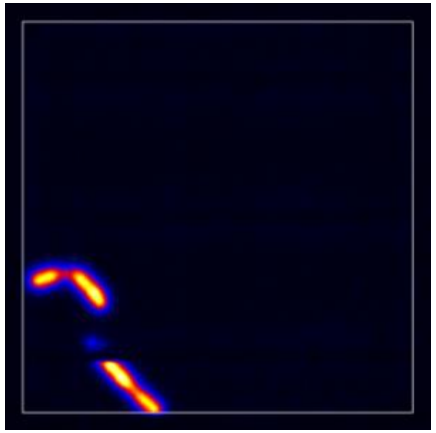
- localization of hot spot sources
- valuable tool for process optimization

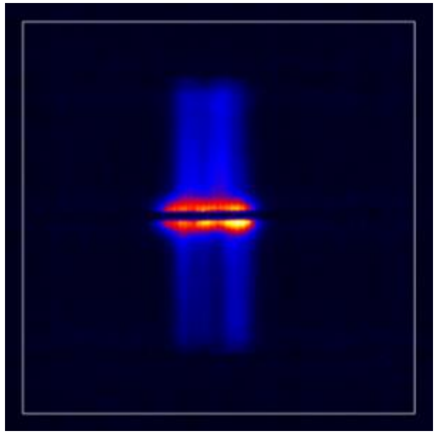
Al-contamination



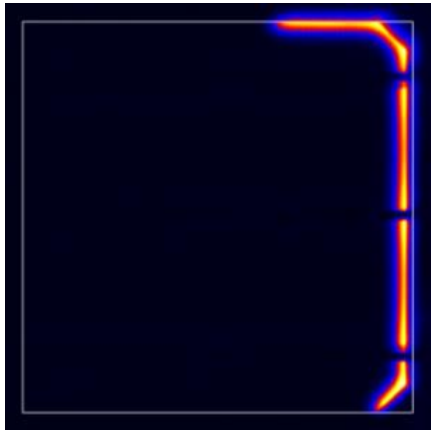
metallized crack



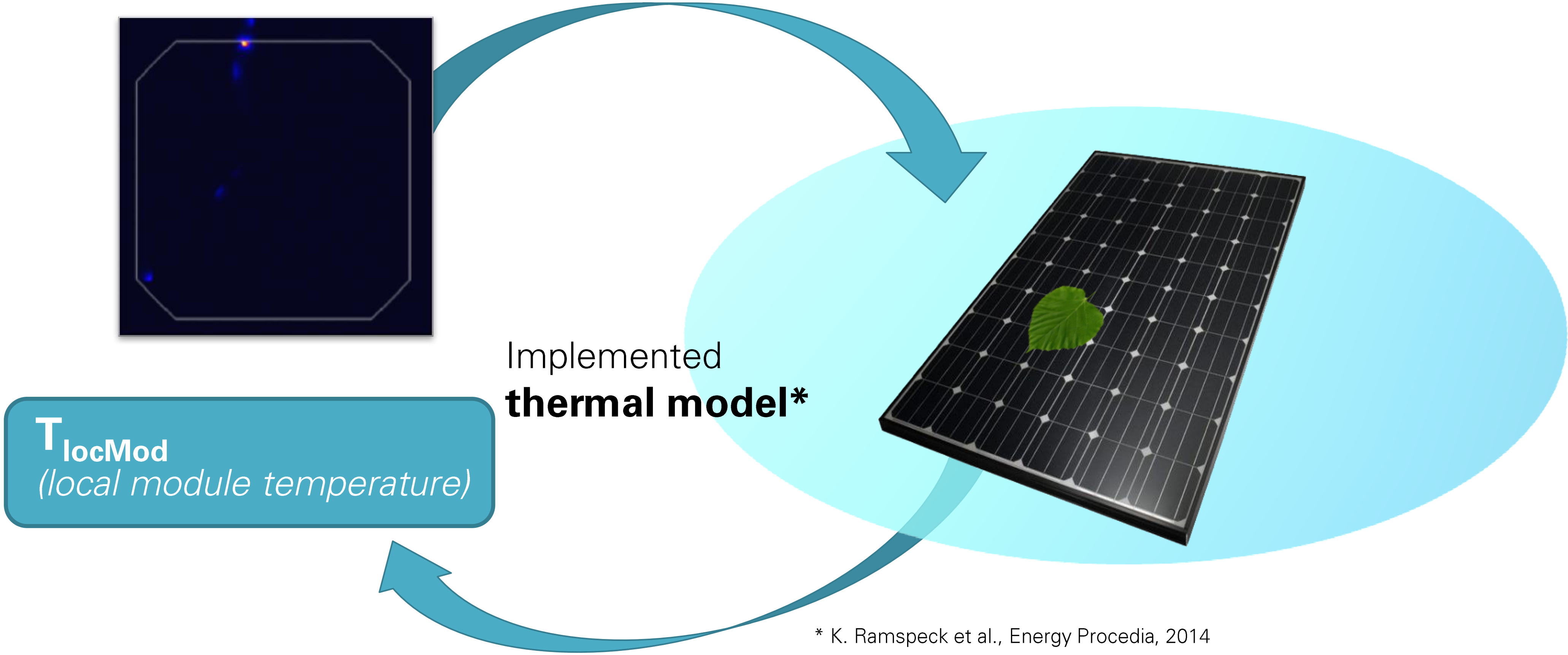
defect below busbar



edge isolation



Advanced hotspot evaluation on module level



* K. Ramspeck et al., Energy Procedia, 2014

Quality control by advanced thermography evalutation

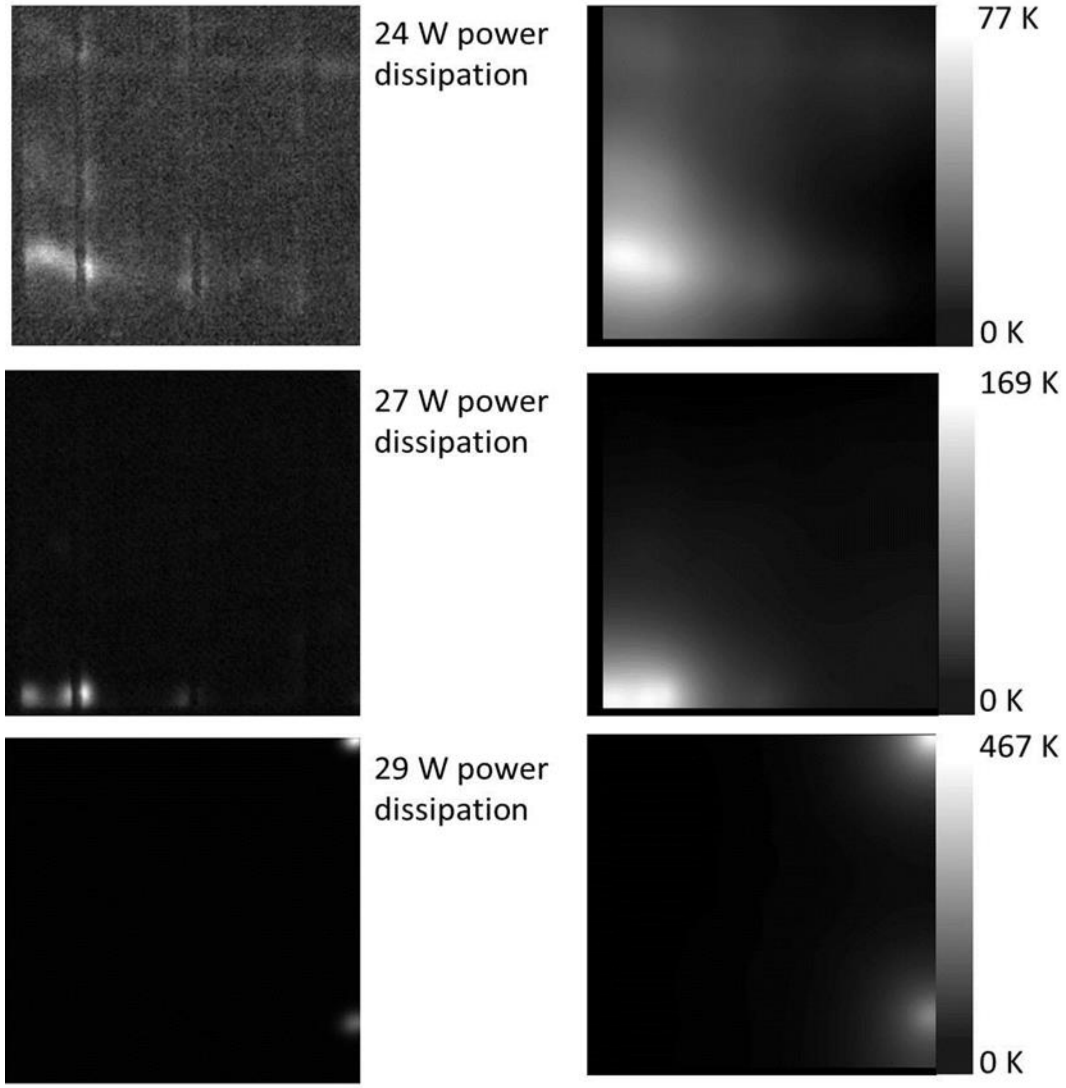
.h.a.l.m.

- Prediction of module temperatures in critical operating conditions (thermal model)
- Determination of really critical cells
- Reducing yield loss in cell production
- Software option for cetisPV-IR-package

Advanced thermography evaluation

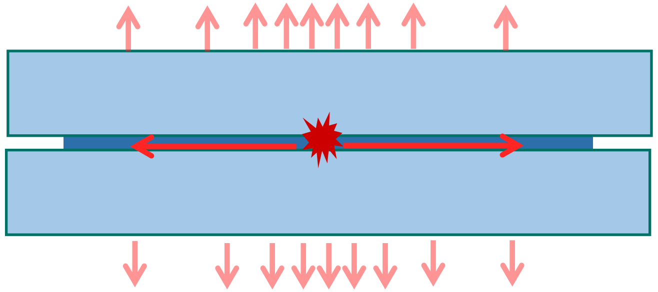
.h.a.l.m.

- Examples of different current distributions
- Similar power dissipation but strongly differing module temperature prediction



Model of advanced thermography

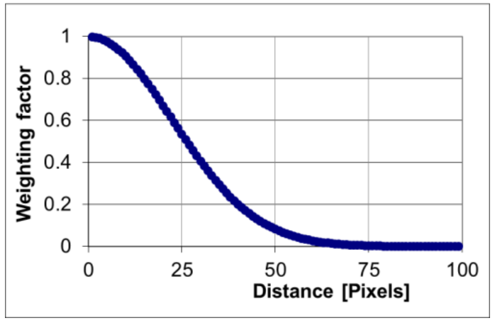
.h.a.l.m.

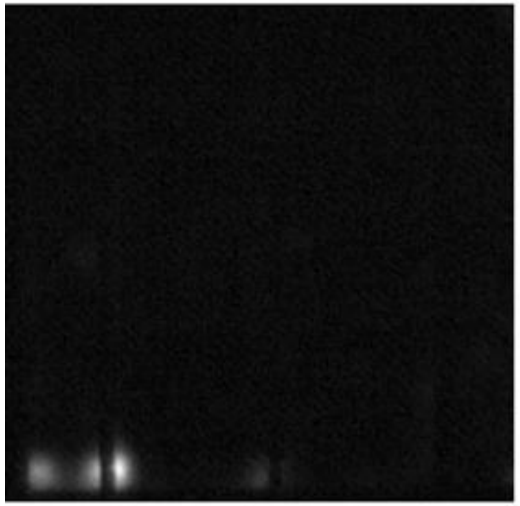


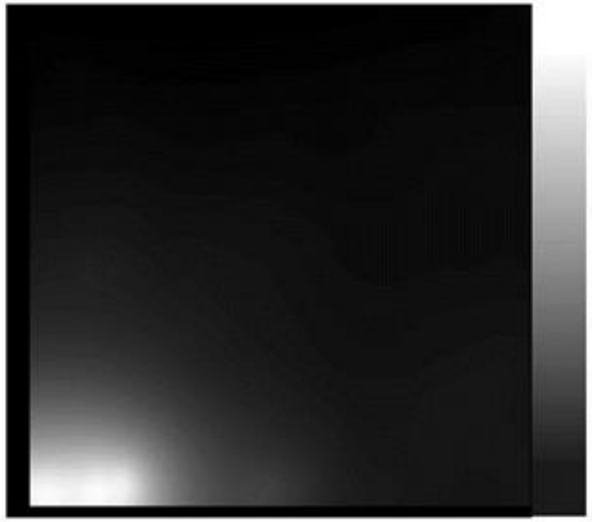
Lateral heat flow

Vertical heat losses

Radial symmetric blurr matrix







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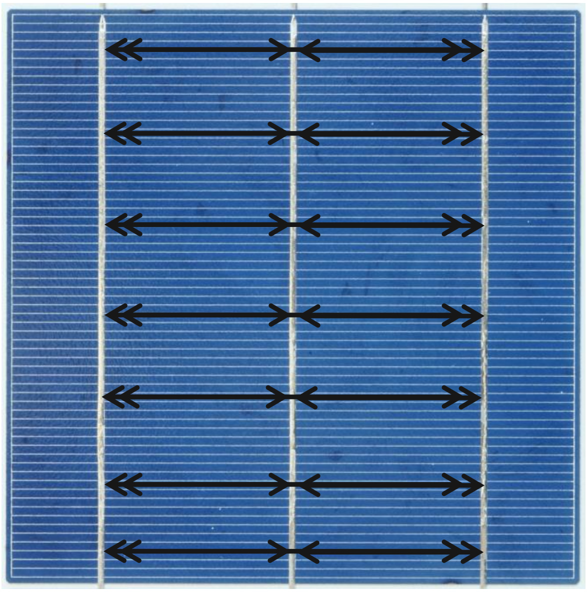
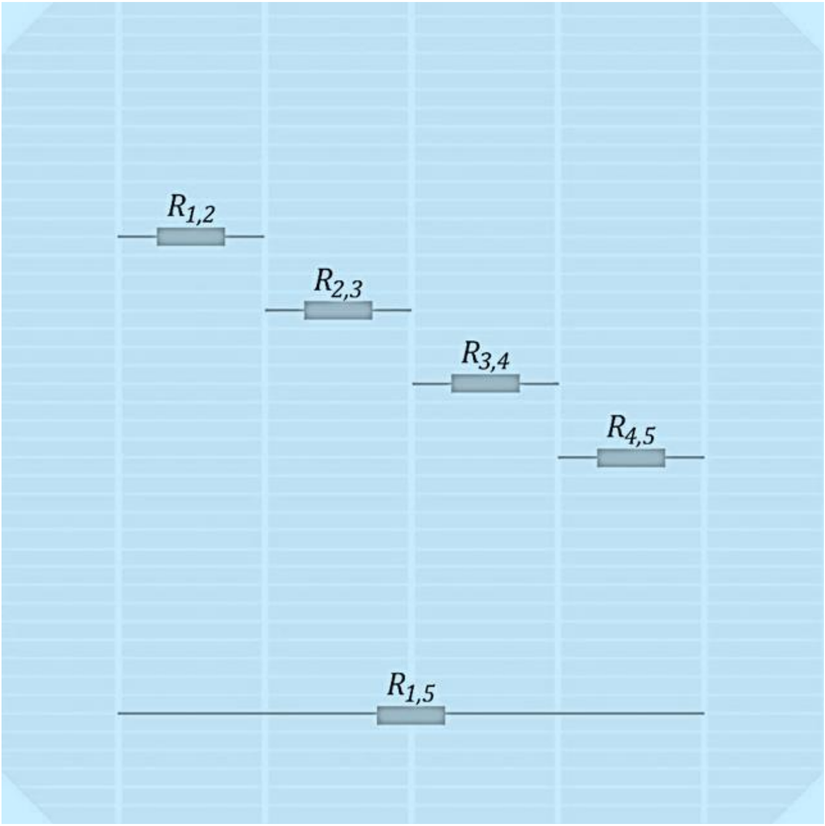
Control of metallization process

.h.a.l.m.

- Measurement of resistance between any combination of two busbars
- Monitoring of paste/printing/metallization quality
- Simple tool for process control
- Up to five busbars





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Detection of recombination losses

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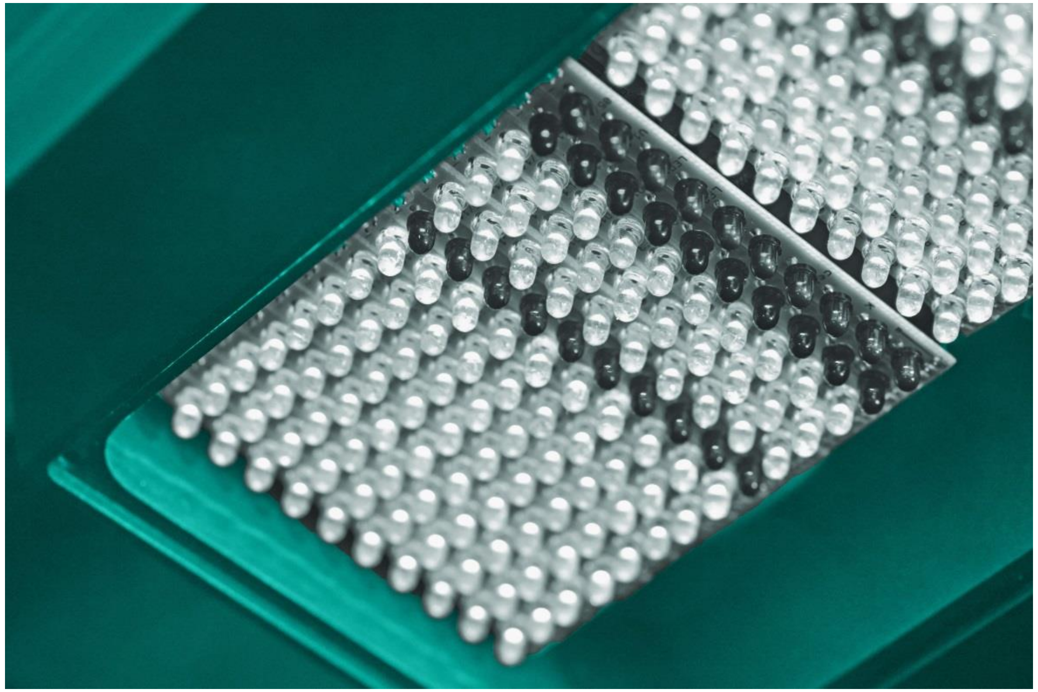
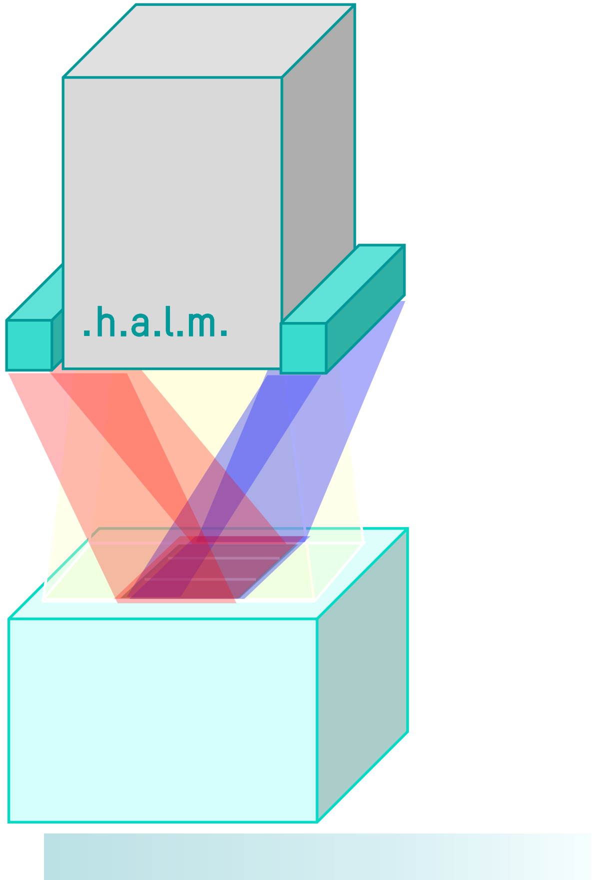
- 2-wavelength spectral response measurement for solar cells in production
- Identifying **front** and **rear** surface losses



Inline spectral response measurement

.h.a.l.m.

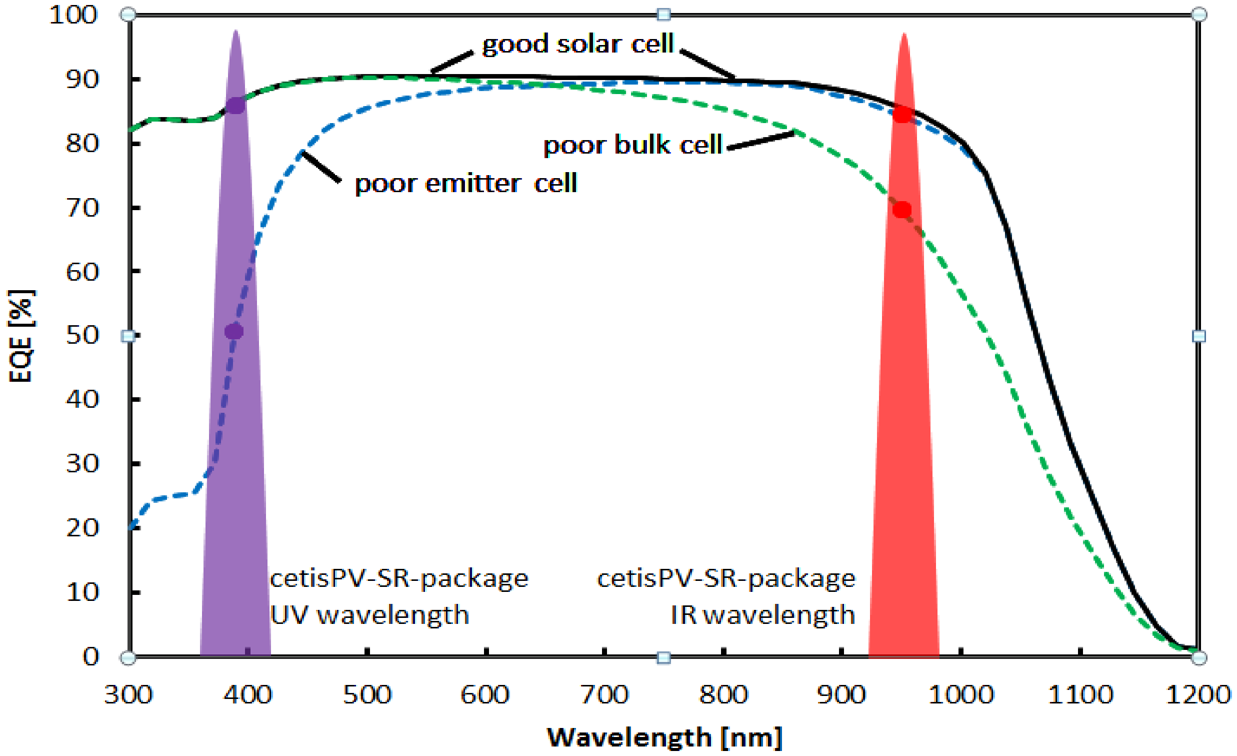
- 2 wavelengths: **390 nm (UV)** and **950 nm (IR)**
- discrimination between front and rear surface losses
- identification of deficiencies of various process steps
  e.g. **anti-reflection coating, emitter diffusion, rear side passivation or metallization**
- available for high throughput



Inline spectral response measurement

.h.a.l.m.

- Extremely high repeatability
- High sensitivity for front and rear-side losses
- Detects small process variations before they impact cell efficiency
- Narrow spectral distribution of light source



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Properties and bifaciality – solar cells

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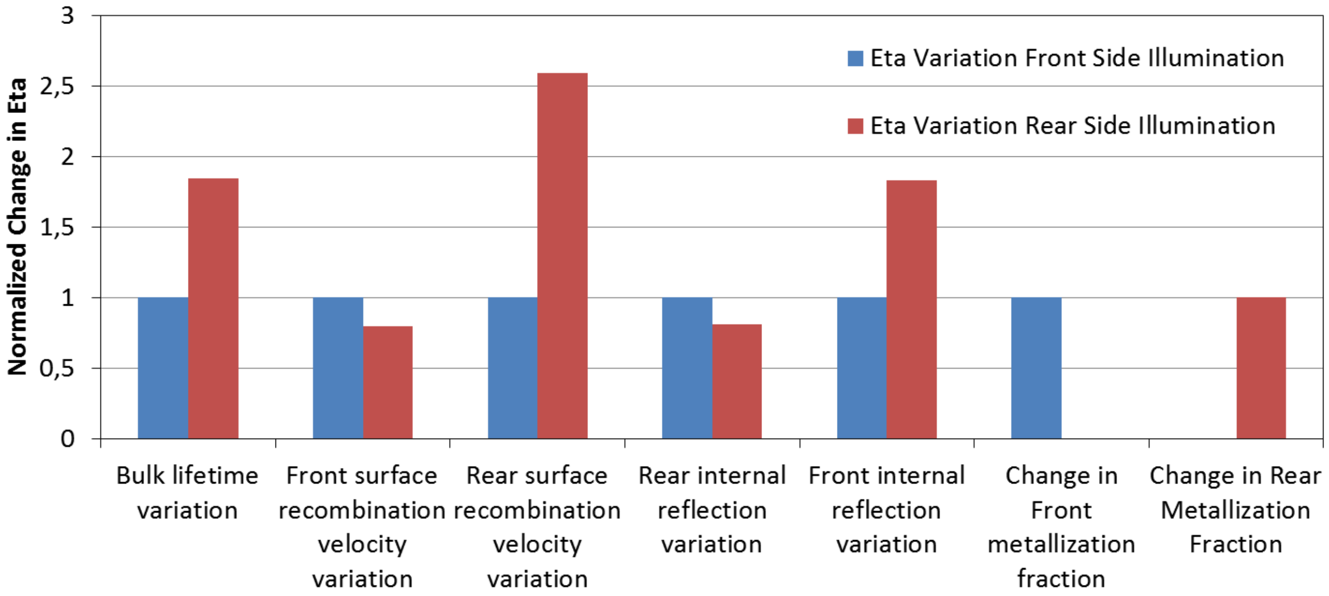
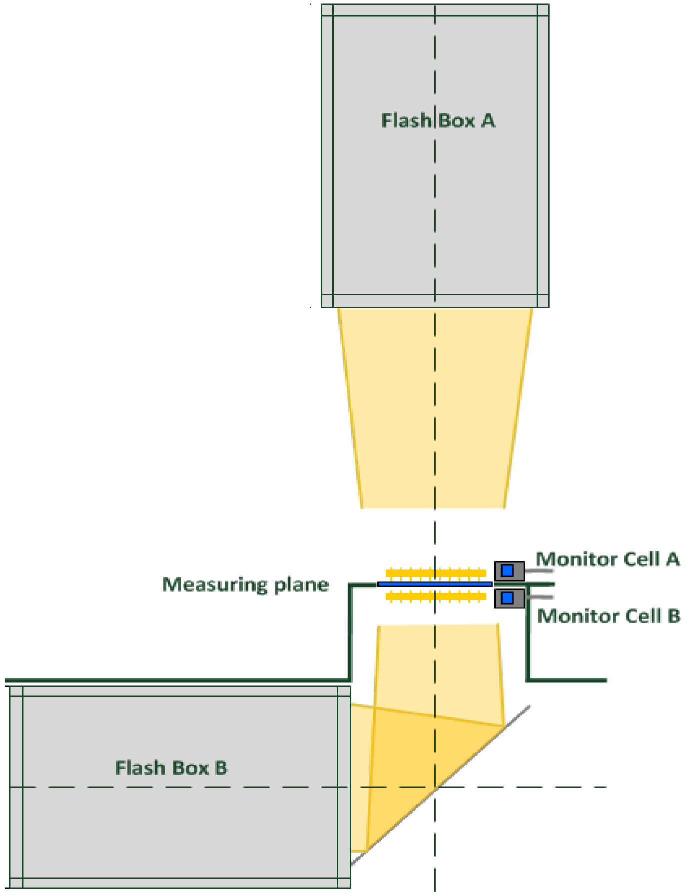
- Impact of solar cell parameters on front and rear efficiency is different
- Numerical values depend on cell architecture and performance
- Strongly different impact on front and rear efficiency: Surface recombination velocity and optical parameters



PC1D simulation of impact of parameter variations on front and rear efficiency

IV – parameters of base-cell simulated:
V_{OC}: 668.7 mV; J_{SC}: 39.56 mA/cm²; Eta: 22.04 %

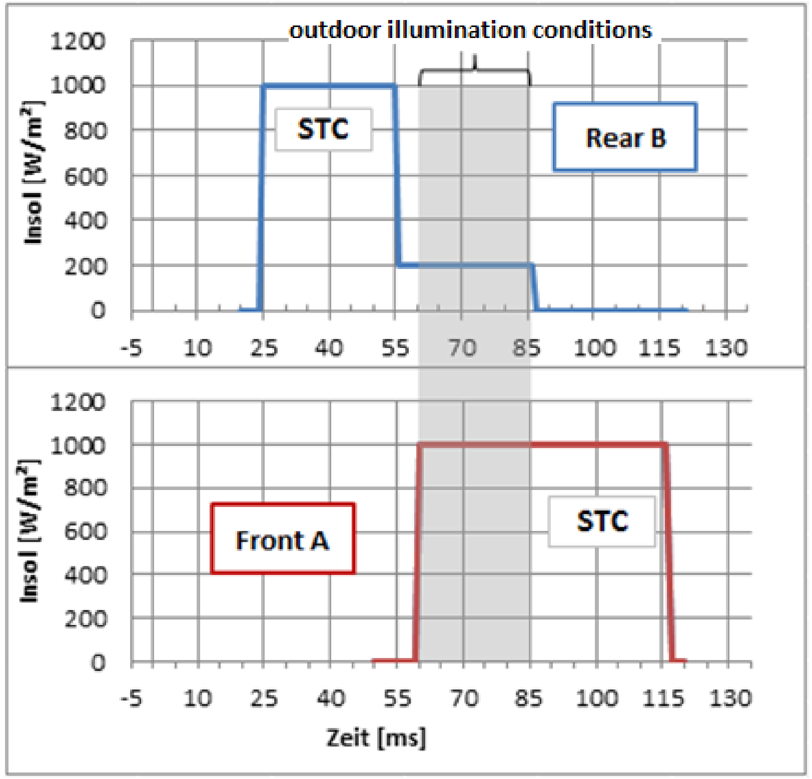
Bifacial h.a.l.m. flasher solutions – solar cells

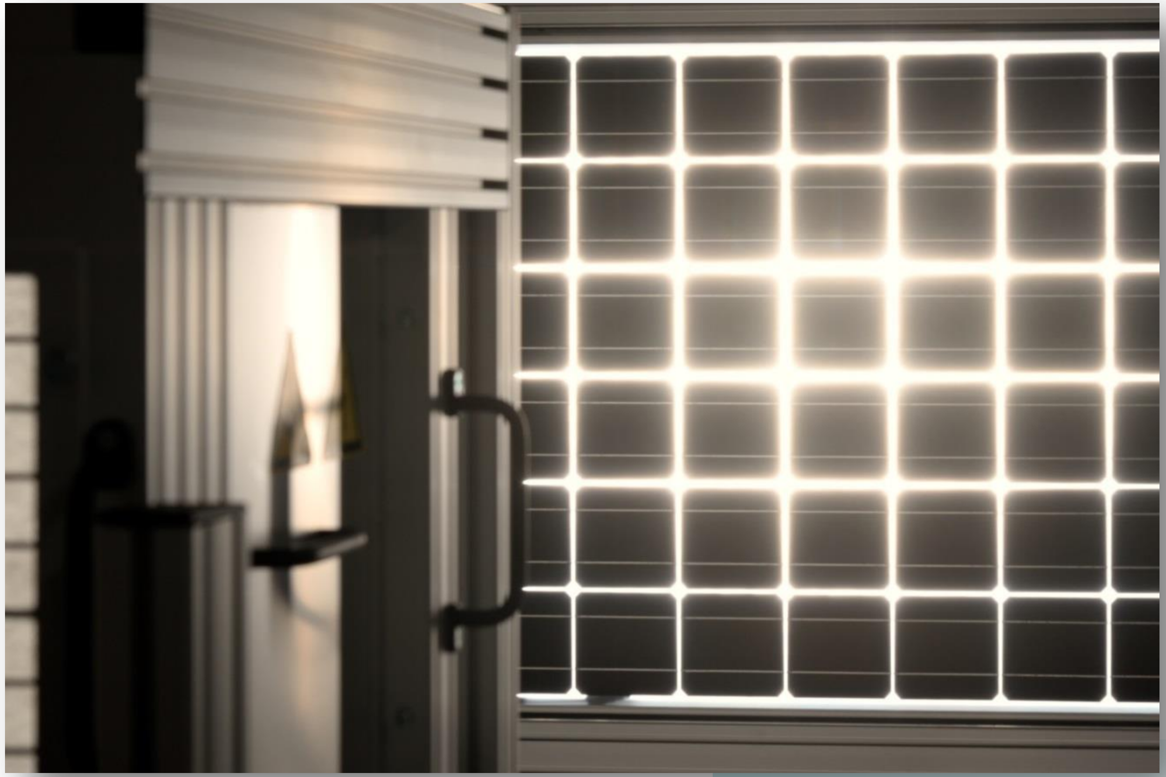


- **One** IUCT-3600 **electronic cabinet**
- 2 flash boxes, one of them directed to the rear side of the cell via mirror
- One **measurement electronic**
- Light sources are synchronized and independently regulated
- Allows for **maximum variability** in flash sequence

Bifacial h.a.l.m. flasher solutions – flash sequence

- One flash sequence allows illumination from front, rear and bifacial within 90 ms





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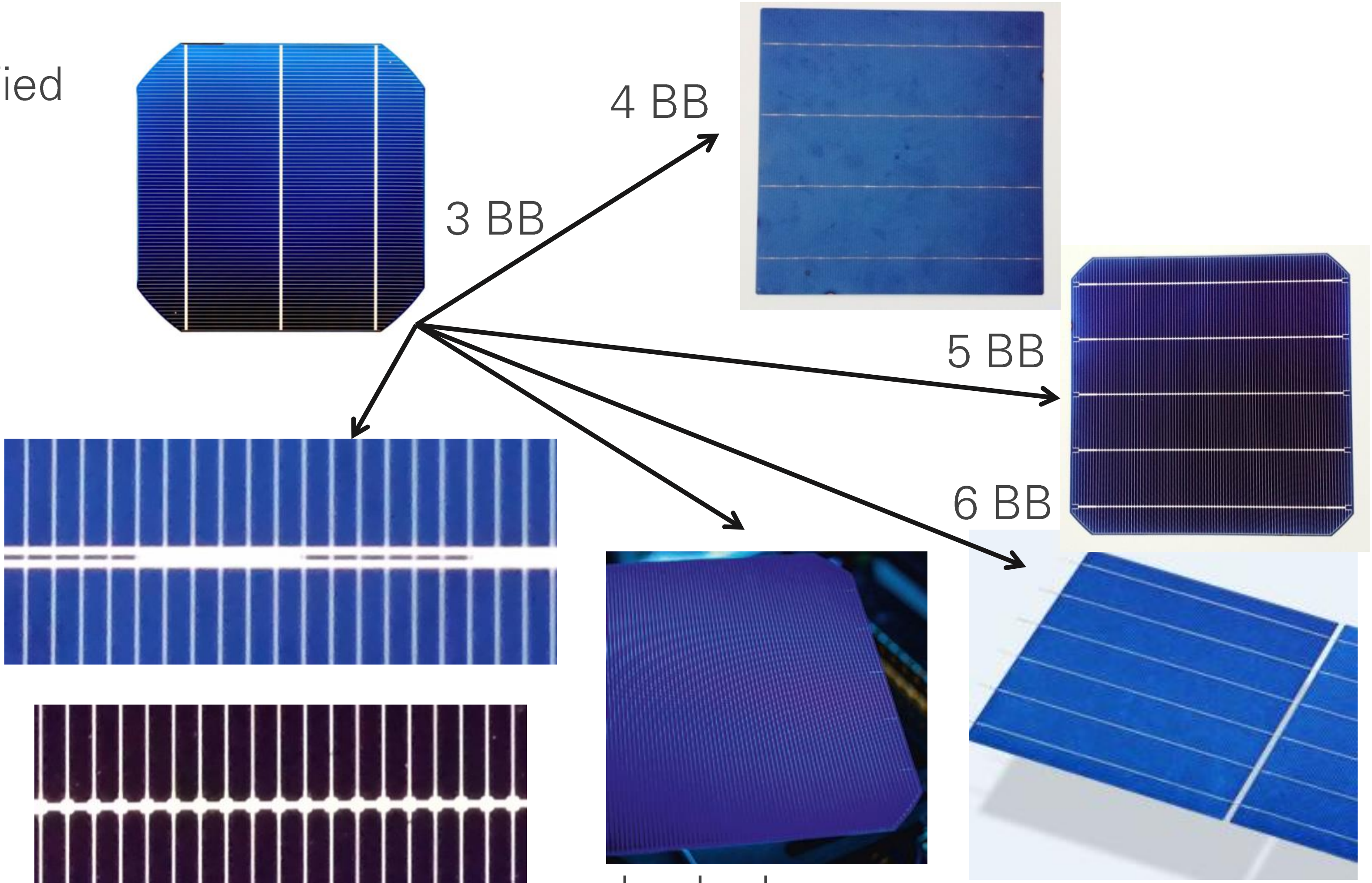
Contacting challenges for new cell designs

.h.a.l.m.

- Metallization layouts diversified
- More flexible contacting solutions required
- Contacting of cell fingers for busbarless cells
- Bifacial contacting
- Shingling
  → front and rear contacts not at same position
- More busbars
  → more shadowing



busbarless

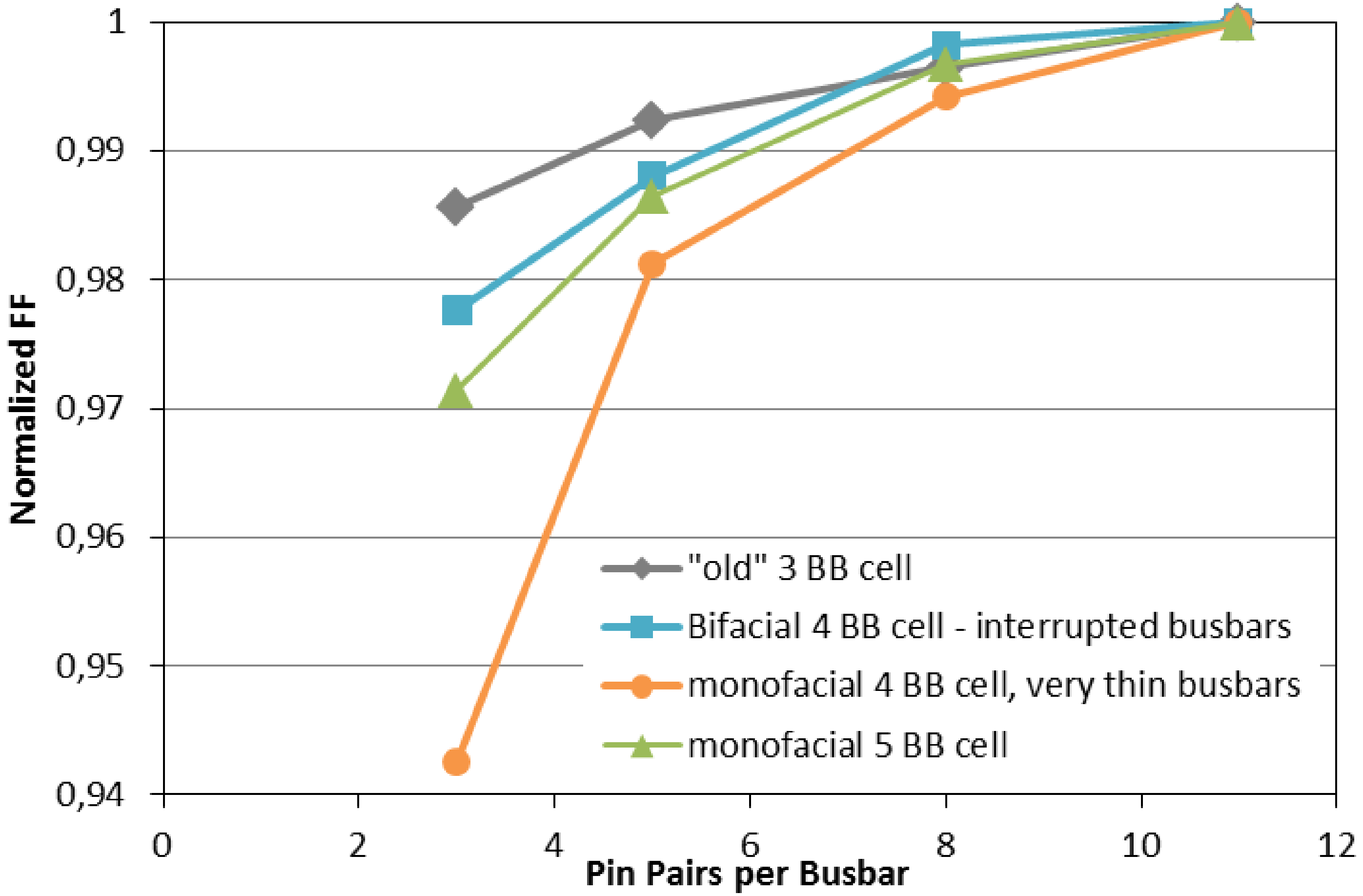
variable cross section

Image taken from: http://www.teamtechnik.com/en/solar/new-technologies/

Contacting challenges – busbar conductivity

.h.a.l.m.

Measured dependence of FF on number of probe pairs



- Strong dependence of FF on busbar conductivity
- Precise FF measurement requires large number of probe pairs

Contacting challenges – busbar layout

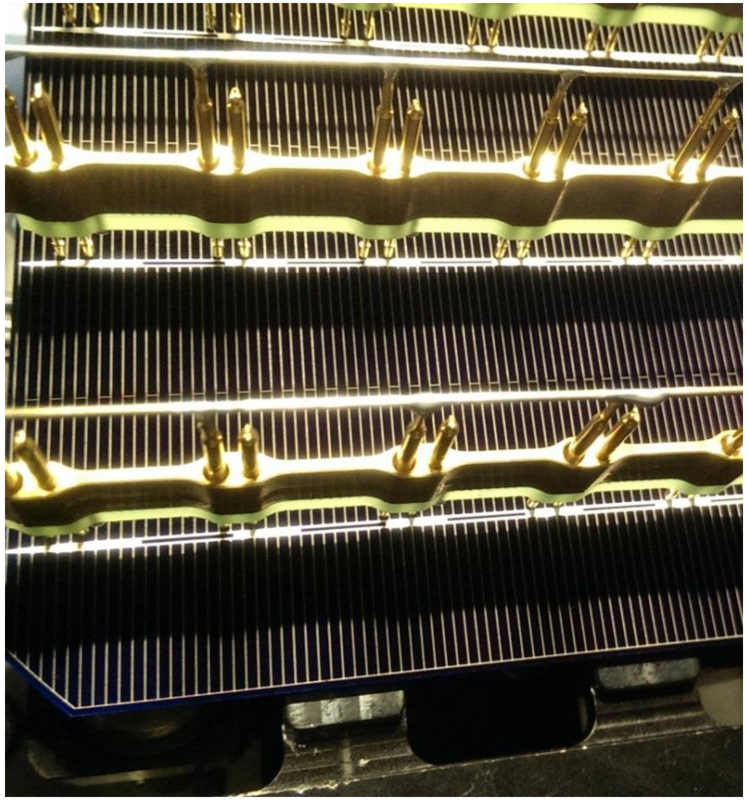
.h.a.l.m.

Interrupted Busbars – how to place the probes?

- probes must be placed on „solder“ islands
  → possibly limits number of probes

Busbarless cells

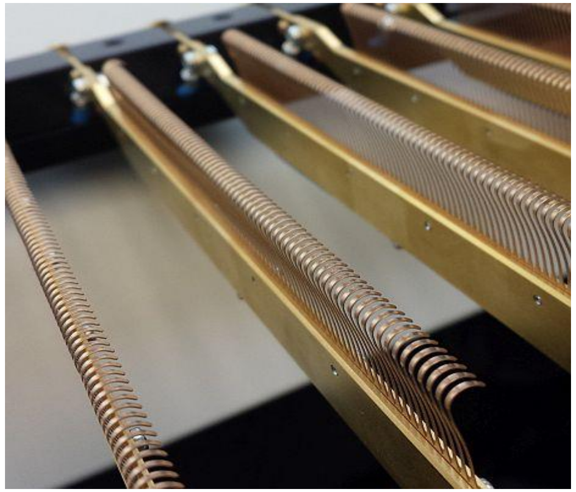
- Fingers need to be contacted directly



Reliable solution for different grid layouts required

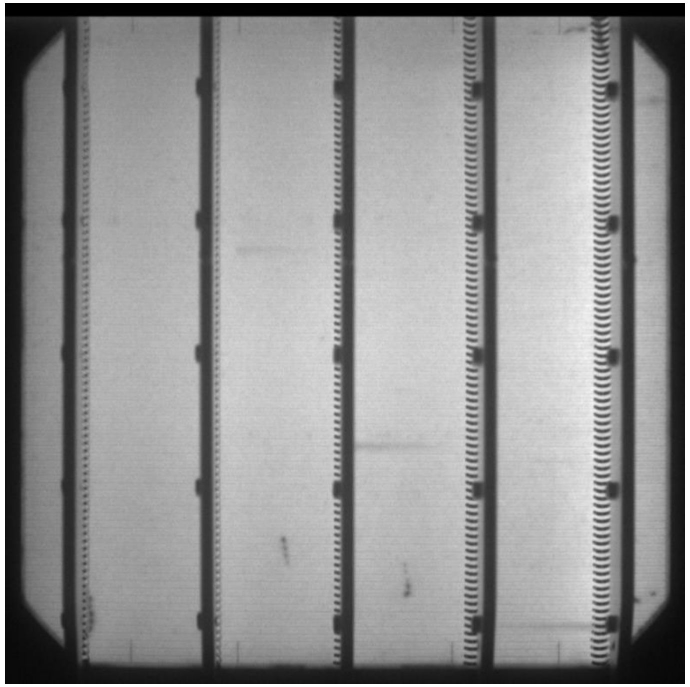
h.a.l.m. solution for busbar independent contacting

- Large number of probes per busbar
- Probes independent from busbar design
- Suitable tapered or interrupted busbars
- Enables contacting busbarless cells in mass production
- Calibration of cells easy and compatible to existing solutions

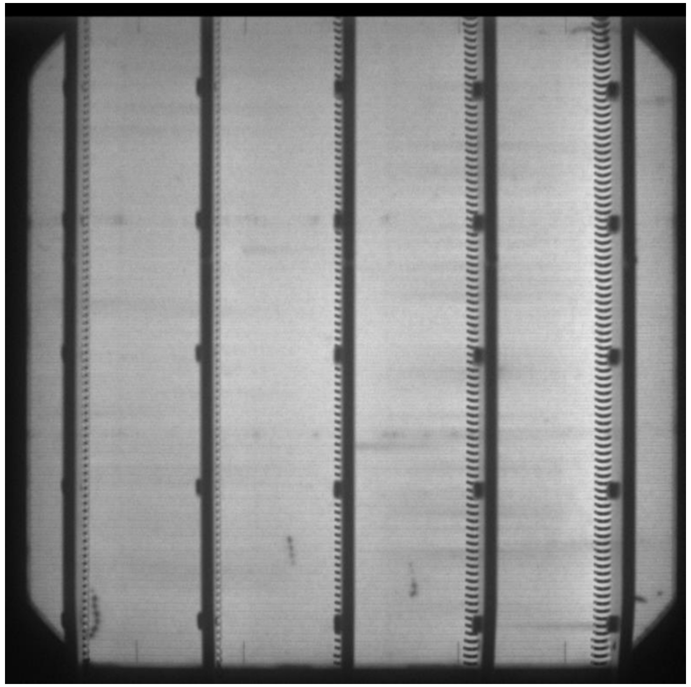


EL – imaging to check contacting quality on busbarless solar cells

.h.a.l.m.



I = 1.2x Isc



I = 2x Isc

- Measurement on the same cell
- Contact is very homogeneous, only few of contacts which are not perfect

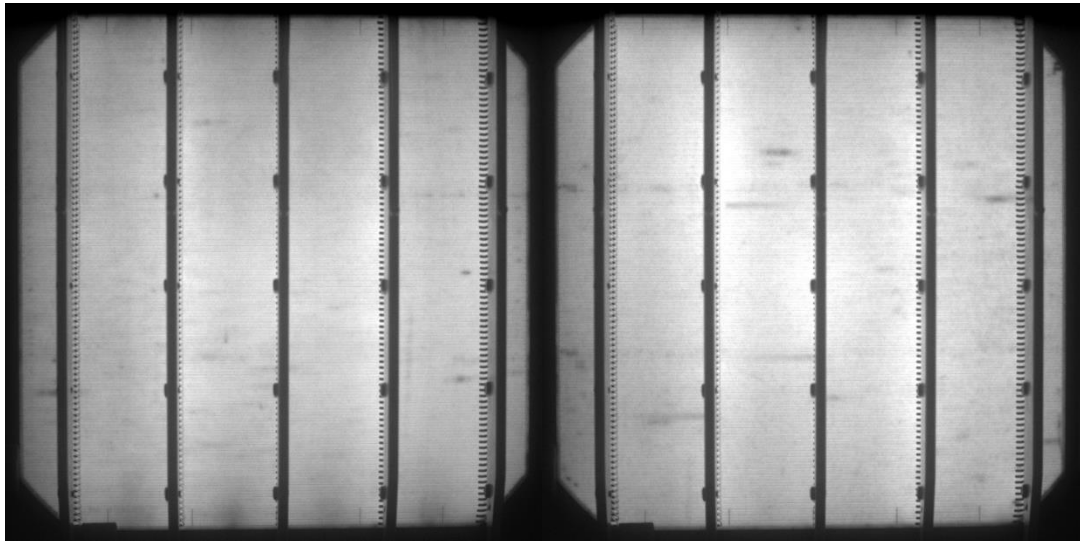
Reliability – EL imaging after 4 million contacting cycles

.h.a.l.m.

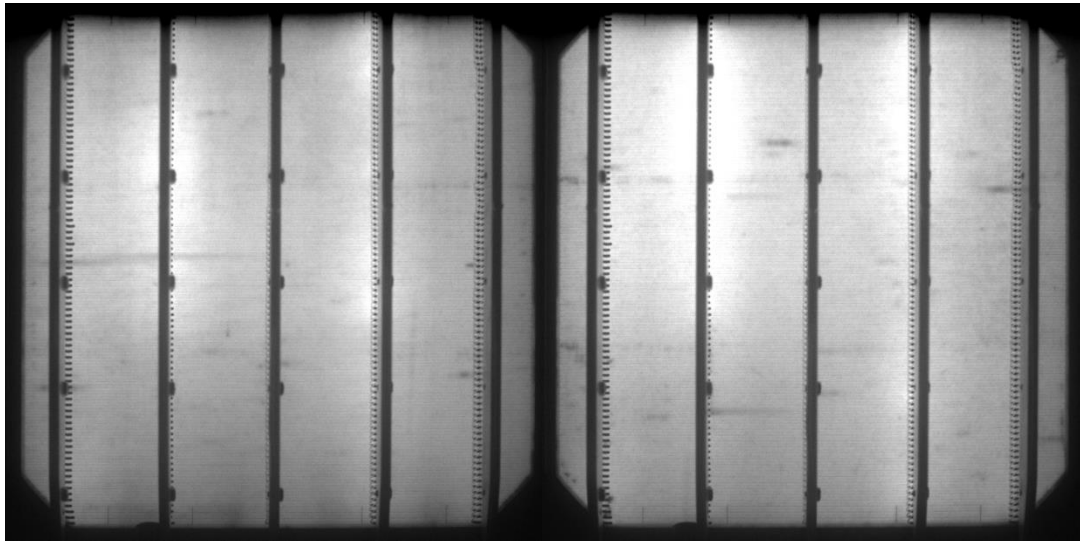
- Long – term test of contacting unit, with 4 million mechanical cycles
- Measurements on reference cells to check contacting quality
- Contacting performed on non-busbar areas of dummy cells
- Series resistance before test: 2.57 mOhm, after test: 2.69 mOhm

→ **very low wearing of the probes**

Before test



After test



Conclusion

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Contact time e.g. 350 ms

Comm-unication	Light – IV (60 ms)	Dark – IV (60 ms)	Reverse – IV +TG	Electroluminescence (40 ms)	Inline-SR	Grid-Resistance	Comm-unication

Example for hetero-junction technology, 60 ms IV-sweeps required, but EL is fast

Contact time e.g. 350 ms

Comm-unication	Light – IV (30 ms)	Dark – IV (30 ms)	Reverse – IV +TG	Electroluminescence (100 ms)	Inline-SR	Grid-Resistance	Comm-unication

Example for PERC technology, IV-sweeps shorter, but EL needs more time

Sequences including all shown methods are possible in ≤ 350 ms

Conclusion

.h.a.l.m.

- Fast evolution of crystalline silicon PV technology results in a **variety of cell designs** with **more complex process sequences**
- Steadily increasing cell efficiencies cause a **higher sensitivity** to **material properties** and **process deviations**
- Light IV-curves of **high capacitance cells** can be measured precisely with **single flash ≤ 60 ms** using advanced hysteresis method

Conclusion

.h.a.l.m.

- **Advanced inline characterization** methods are required to:
  - **Improve quality control** (eg. IV, hotspot, cracks)
  - Ensure **high yield** through better process control (eg. recombination losses, metallization)
  - Enable **fast ramp-up** of new production lines and new technologies

High throughput inline characterizations methods are available

