End of line characterization for back-contact solar cells

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10th workshop on back-contact solar cell and module technology, Konstanz, 22.11.2022

Content

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- Throughput and timing constraints in *IV*-testing
- Hysteresis – steady-state *IV* of high-efficiency cells
- Using hysteresis – determination of base doping concentration of finished solar cells from *IV*-measurements
- Complementary characterization – electroluminescence and thermography imaging

What we need to do before the measurement… contacting

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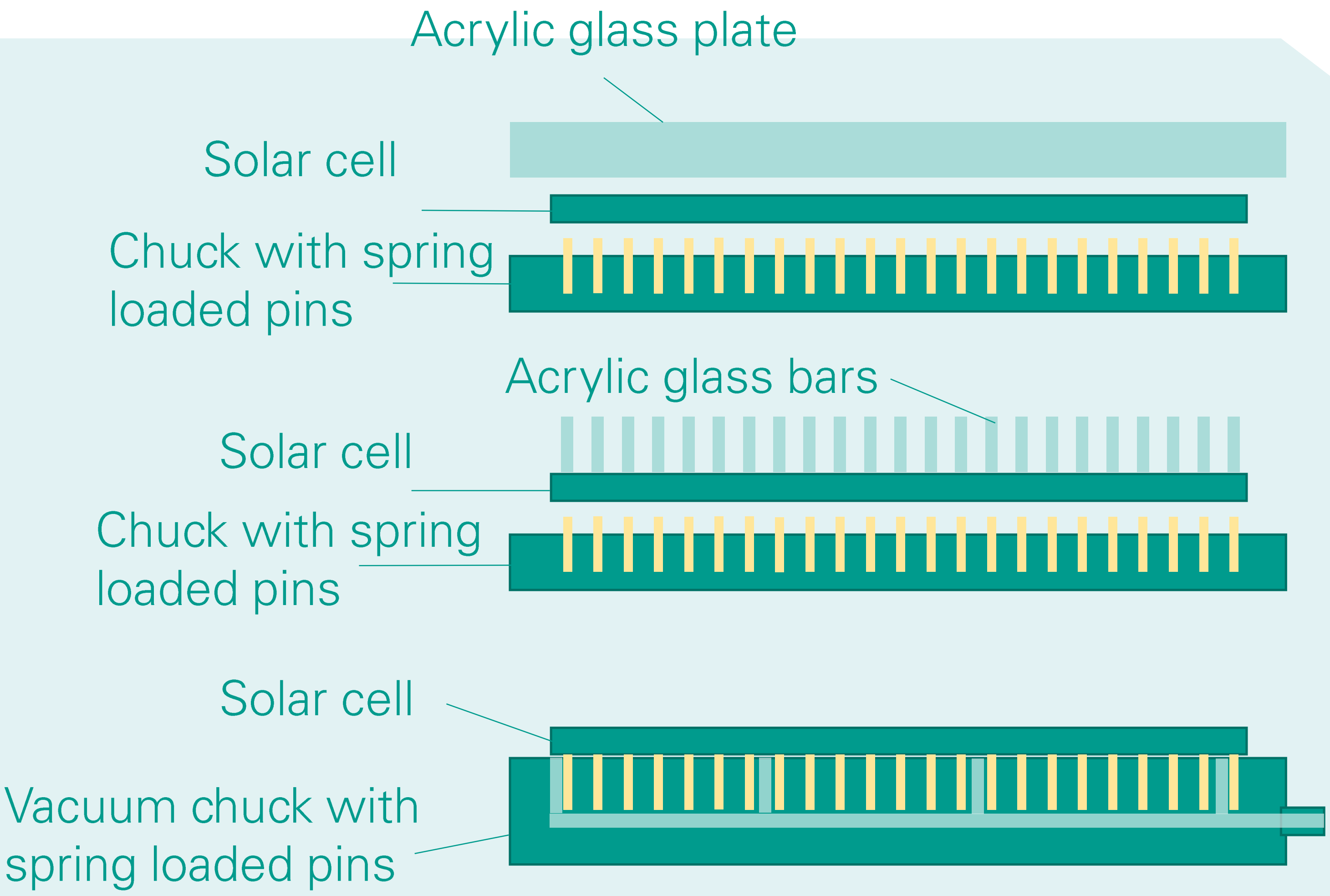
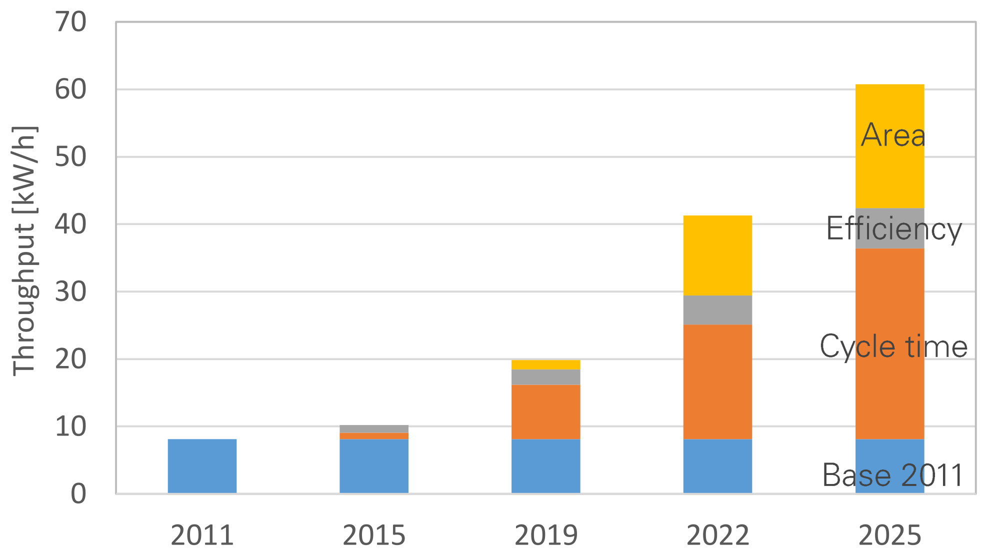
- Several methods for contacting BC cells are still under discussion
- Transparent plate as downholder
- Transparent downholders
- Vacuum suction



Evolution of throughput

- Nominal cell tester throughput increased from 8 kWp/h (2011) to 40 kWp/h (2022) due to
  - Larger cell area
  - Higher cell efficiency
  - Shorter cycle time
- Note: 60 kWp/h equal 475 MWp/year at 90% utilization rate

Evolution of cell tester throughput (illustration)

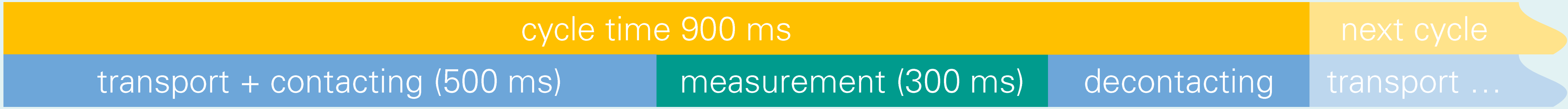


Cell technology	Al-BSF	PERC	PERC	TOPCon	TOPCon/IBC
Edge length [mm]	156	156	166	210	225
Efficiency	18.5 %	21.0 %	22.5 %	24.0 %	25 %
W/cell	4.5	5.1	6.2	10.6	12.7
Throughput [w/h]	1800	2000	3200	3900	4800
Cycle time [s]	2.0	1.8	1.13	0.92	0.75

Sources:
- Jörg W. Müller, Hanwha Q CELLS GmbH, Silicon PV / bifi PV Workshop 2022
- ITRPV 13th Edition, 2022

Cycle time

- Throughput of 4000 cells/h (cycle time 900 ms)



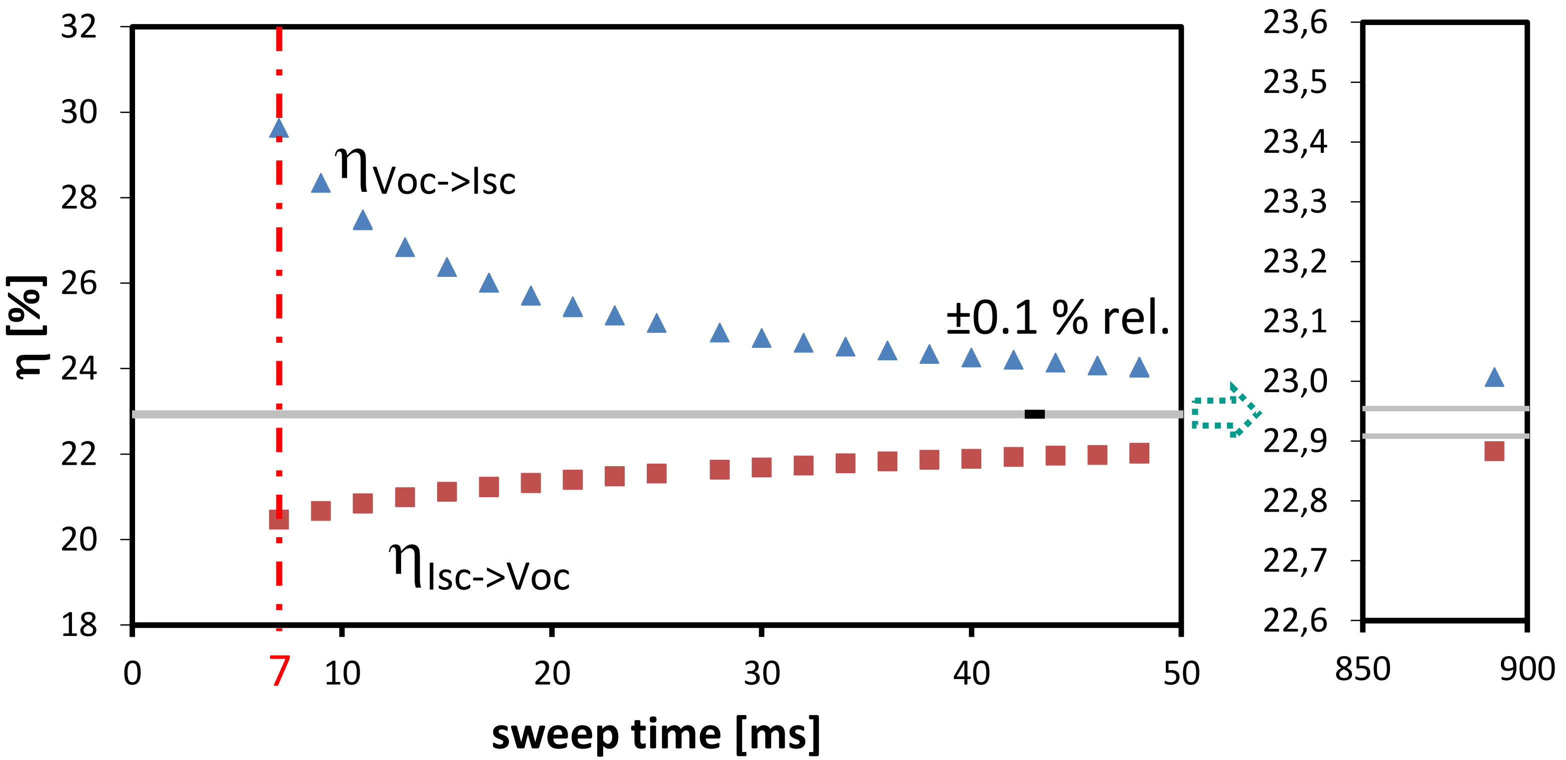
- Measurement consists of

▪ Light *IV*	efficiency, I_{SC}, V_{OC}, FF, …	**40 ms** (multiply by 2 or 3 for bifacial)
▪ Dark *IV* forward	series resistance	40 ms
▪ Dark *IV* reverse	reverse current, shunt resistance	10 ms
▪ Electroluminescence	defect detection	10 ms (IBC) - 50 ms (PERC)
▪ Thermography	hot spot detection	60 ms (in parallel to dark *IV* reverse)
▪ Preparation and transition times		about 60 ms

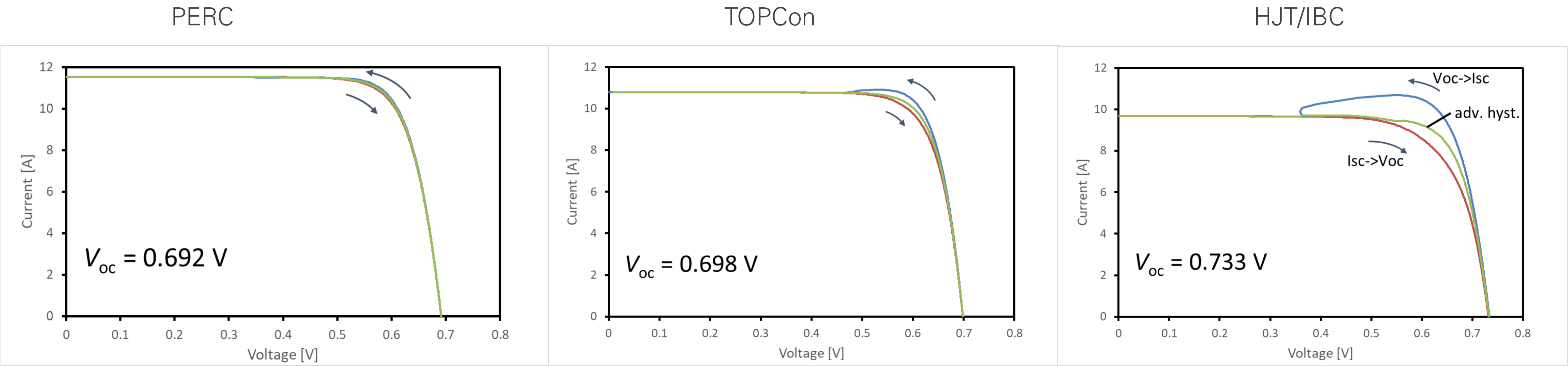
Efficiency with single sweep

- *IV* measurement of high-efficiency cells is strongly affected by cell capacitance
- They exhibit strong split in η and FF for short sweep times
  ΔEta = 9% abs. @ 7 ms
  ΔFF = 11% abs. @ 7 ms
- Very long measurement times (> 1 s) are required to approximate steady state

Efficiency (η) as a function of sweep time
High efficiency cell with V_{oc} = 733 mV



Light *IV*-measurement of capacitive cells
halm advanced hysteresis



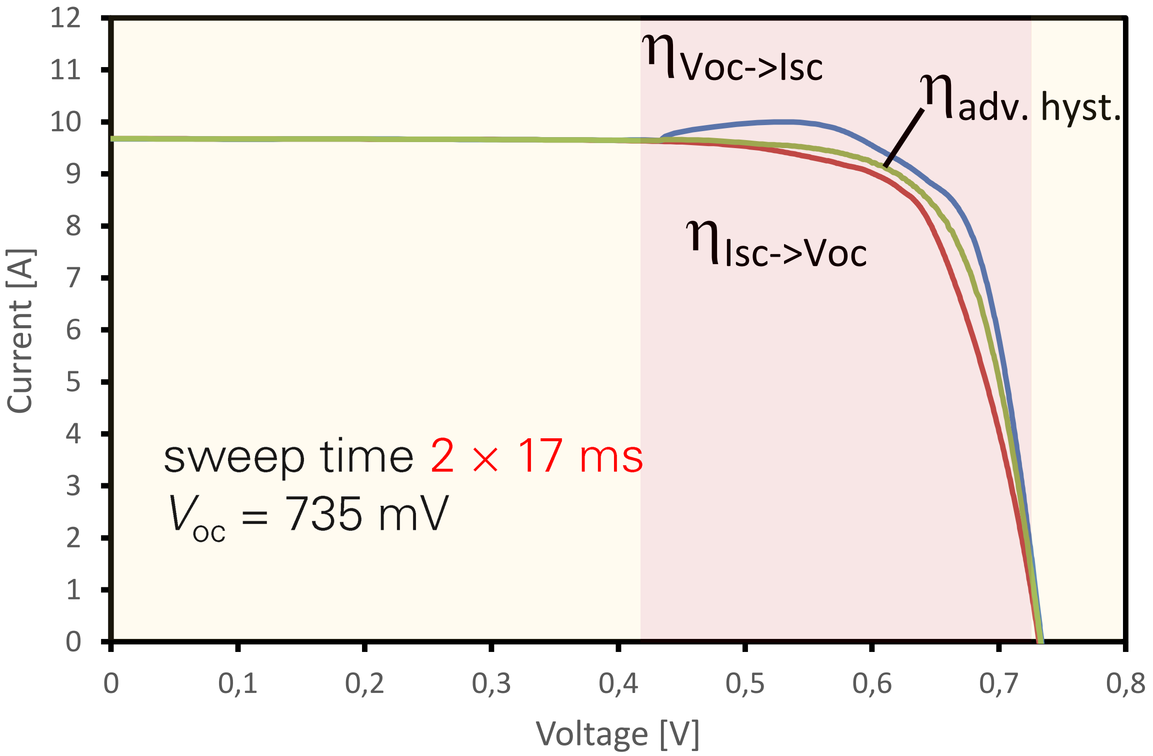
		PERC	TOPCon	HJT/IBC
halm advanced hysteresis 2 x 17 ms	Eta for- / back-ward Eta Adv. Hyst.	22.7% / 23.1% 22.9%	22.5% / 24.0% 23.1%	21.2% / 26.0% 23%
Single sweep time required for steady-state result		20 – 200 ms	200 – 800 ms	1000 – 5000 ms

[1]K. Ramspeck et al. Accurate Efficiency Measurements on Very High Efficiency Silicon Solar Cells Using Pulsed Light Sources. in Proc. 29th EUPVSEC, p. 1253, 2014

halm advanced hysteresis with nonlinear load voltage sweep

- Hysteresis reduction by nonlinear load voltage sweep
  - Fast sweep rate where *IV*-curve is linear
  - Slow sweep rate where *IV*-curve is bended
- Slow sweep rate in critical range allows to minimize total measurement time

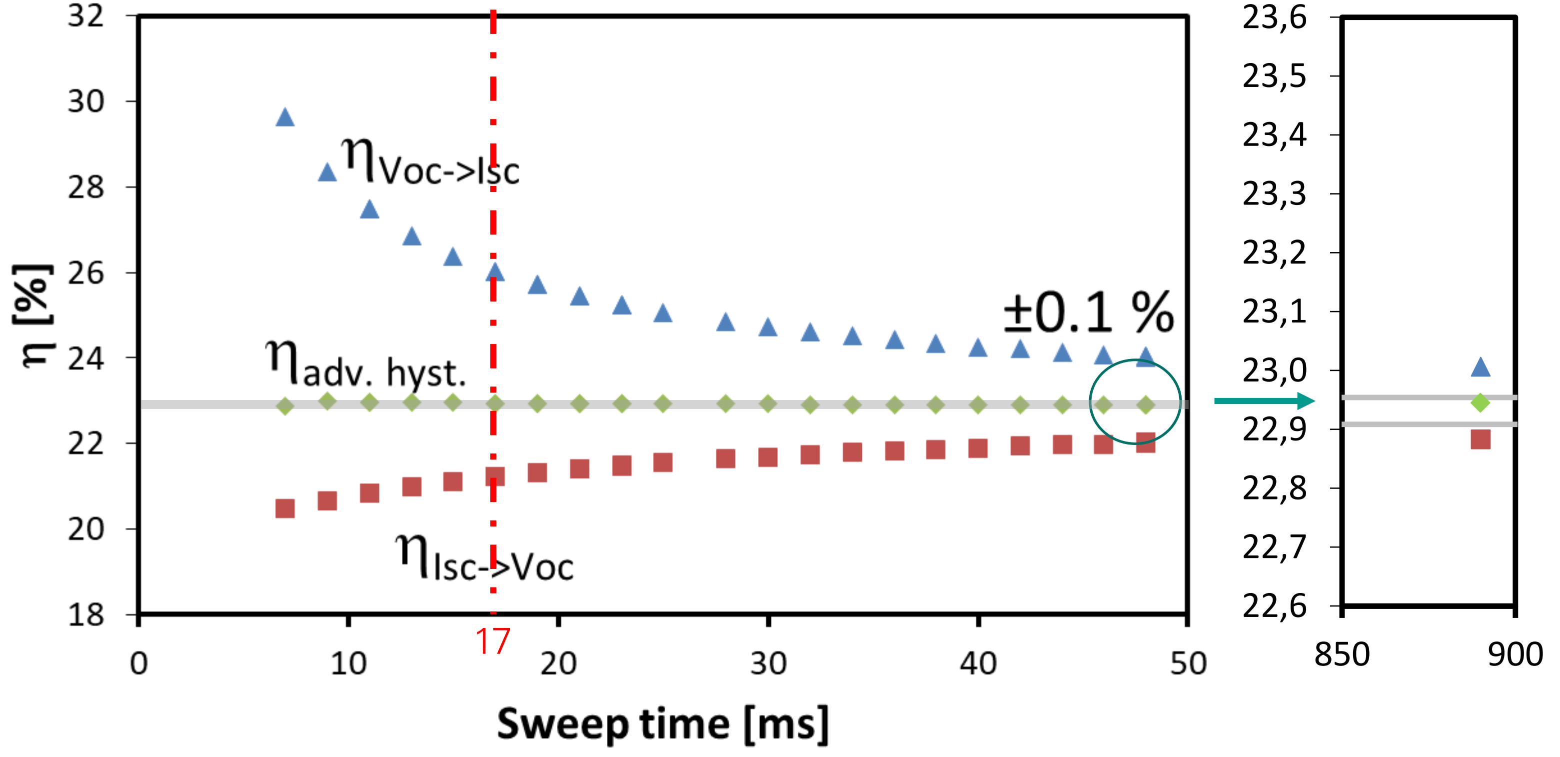
IV-curves of a high efficiency cell



Stable measurement results using advanced hysteresis for all sweep times

- Long measurement time (> 1000 ms) is required to approximate steady state
- Measurement time of 2 x 17 ms = 34 ms is sufficient for advanced hysteresis
- Efficiency even stays in tolerance band for shorter sweep times

Efficiency (η) as a function of sweep time
high efficiency cell with V_{oc} = 733 mV



IV-data analysis

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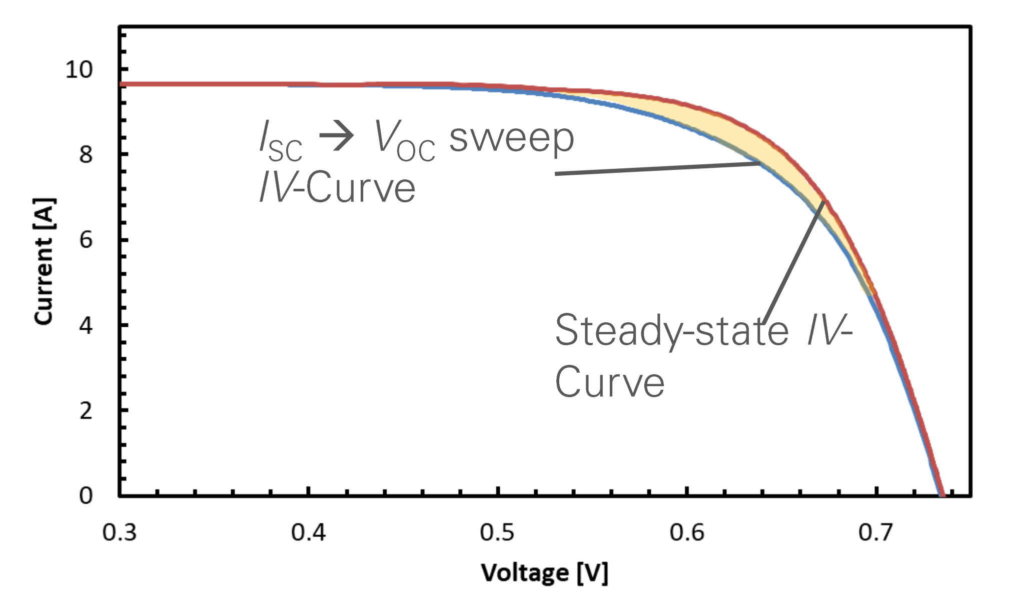
- Series and shunt resistance
- Diode saturation currents
- Pseudo FF
- **Base doping concentration**[1]
- Effective carrier concentrations and lifetimes
- Reverse characteristics
- Variation analysis in production

[1]K. Ramspeck et al. AIP Conference Proceedings 2487, 030008 (2022); https://doi.org/10.1063/5.0090130
Published Online: 24 August 2022

Base doping derived from *IV*-curve hysteresis

- halm is an electrotechnical company – we like to do what we are good at, we count charge carriers
- To be more precise: we count the minority charge carriers, which are stored in the cell
- To do this we require:
  - a single sweep *IV* - curve and a steady-state *IV* - curve
  - the single sweep *IV* – curve's lapse of time
- The steady-state *IV*-curve is obtained from advanced hysteresis

Measured IV curves of a high capacitance cell. At 30 ms sweep-time transient effects occur.



The colored area is evaluated for base doping determination

From counted charge carriers to base doping concentration

- After counting them, we transform the number of charge carriers into the minority carrier density

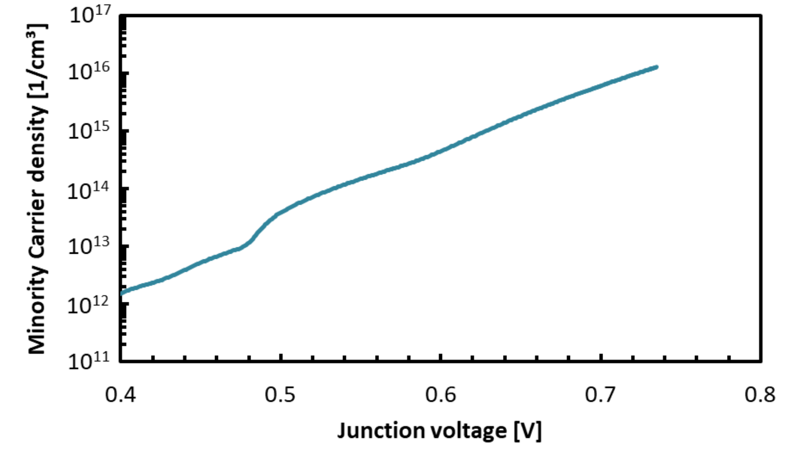
$$\Delta n = \frac{Q}{A \times w}$$

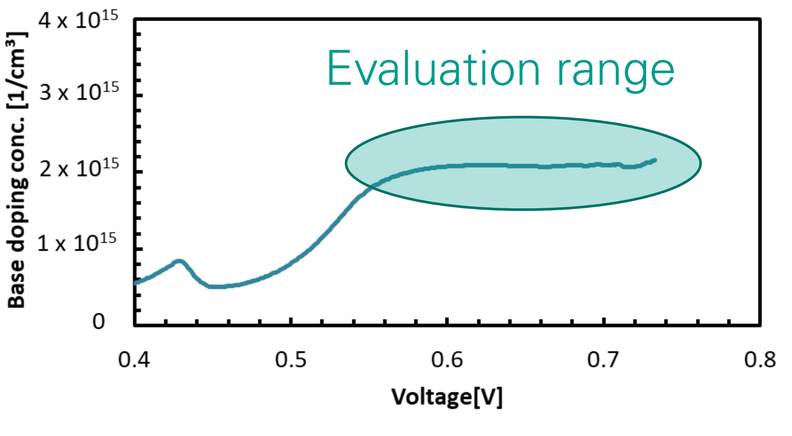
- The minority carrier density reaches about 2×10^{16} cm^{-3} at V_{OC} of this cell

- Transformation to base doping concentration is performed using the equation[1]:

$$N_{dop} = \frac{n_i^2}{\Delta n} exp\left(\frac{qV_j}{kT}\right) - \Delta n$$

- Base doping evaluation is done slightly below V_{OC}

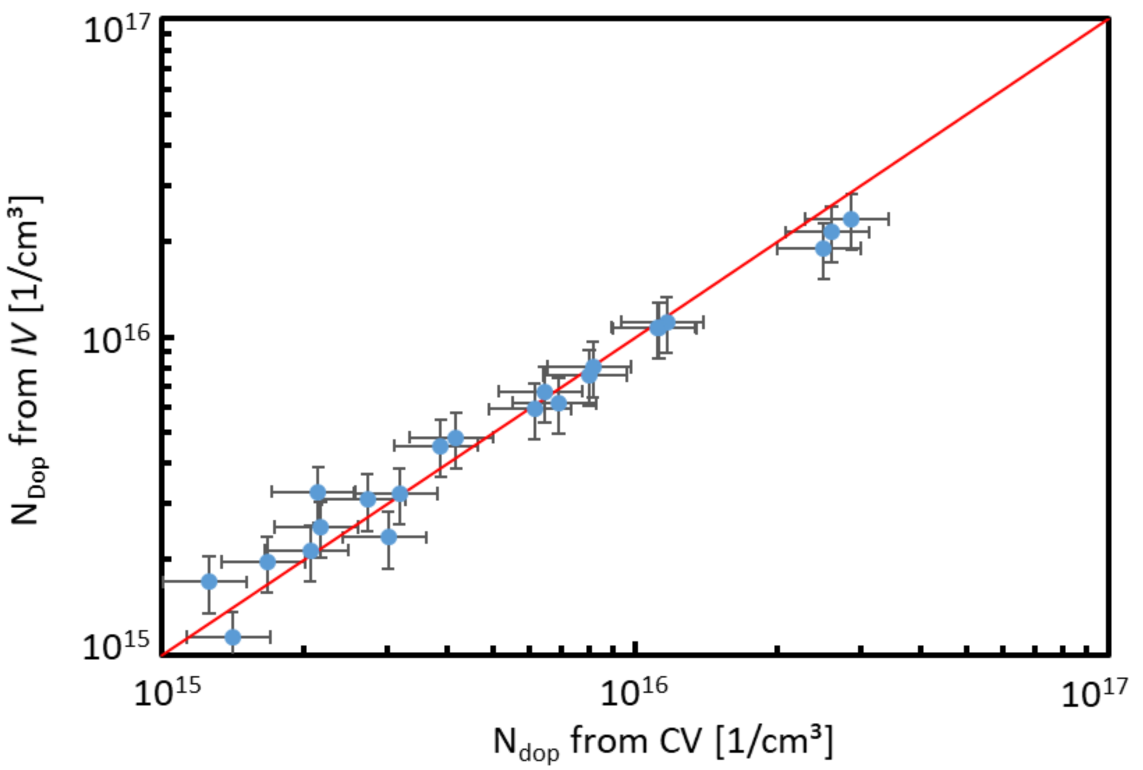




[1] M.A. Green, "Solar Cells – Operating principles, Technology and System Applications", (Prentice-Hall Inc., 1982)

Independent confirmation of base doping results by capacitance voltage (*CV*) method

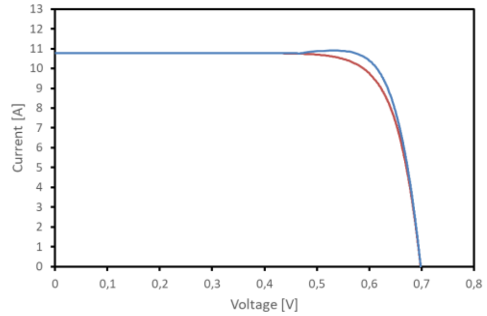
- Correlation between *CV*-measurements performed at ISFH and base doping density determination from *IV*-curves
- The red line represents the perfect one-to-one correlation
- A very high degree of agreement is achieved over more than one order of magnitude (10^{15} cm^{-3} to 3×10^{16} cm^{-3})
- Agreement is comparable to the two setups for *CV*-measurements



IV – curves give a lot of information but something is still missing

- Defect classification, process control and optimization through electroluminescence imaging

- Distribution, criticality of reverse current flow and process control for contact separation through thermography imaging



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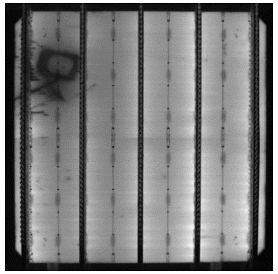
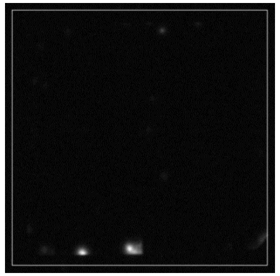


and



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EL imaging of different solar cell types

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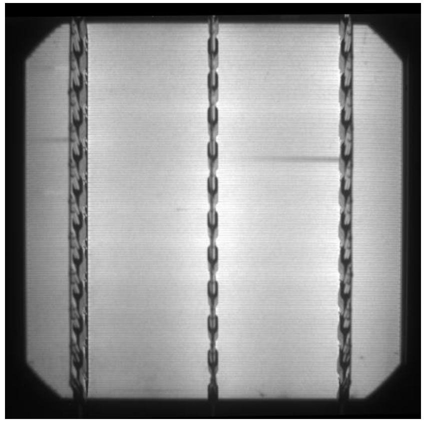
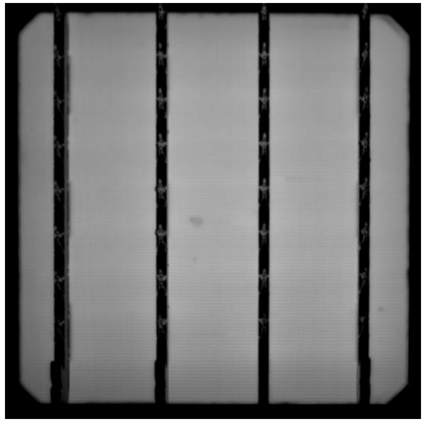
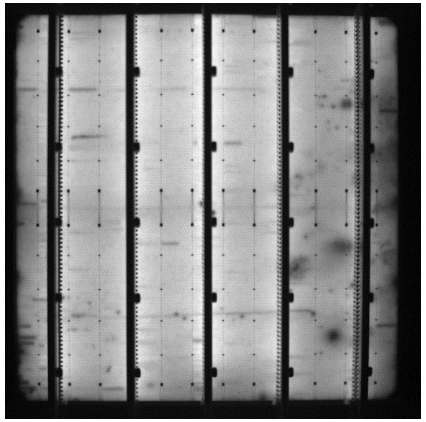


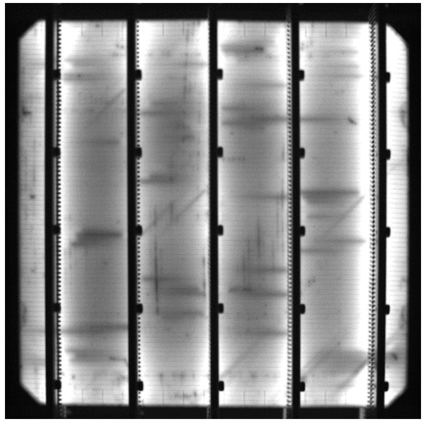
1). Al-BSF (156 mm)



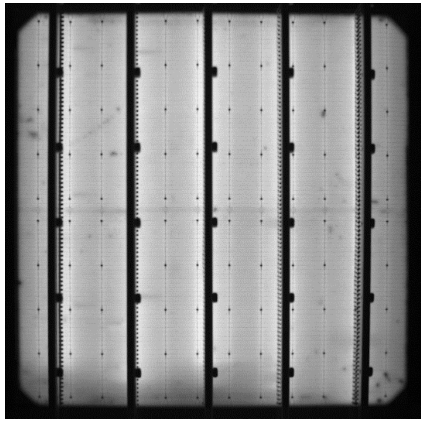
2). PERC (156 mm)



3). TOPCon (162 mm)



4). HJT (156 mm)



5).HJT (166 mm)

6). IBC

	Cell Type	Size	BB	Voc	Eta
1	Al-BSF	156 mm	3	~0.630 V	~18%
2	PERC	156 mm	4	0.662 V	21.2%
3	TOPCon	162 mm	12	0.692 V	22.3%
4	HJT	156 mm	0	0.719 V	22.5%
5	HJT	166 mm	12	0.748 V	23.7%
6	IBC			~0.74 V	> 24%

There is not always a direct correlation between defects visible in EL images and IV parameters of the cells

Defects visible in EL

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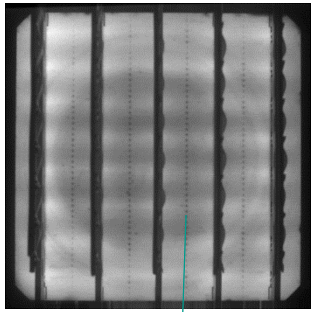
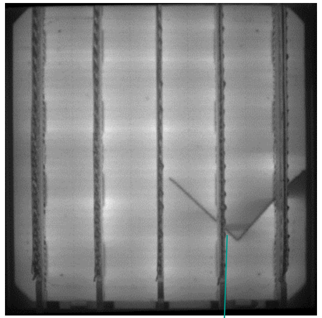
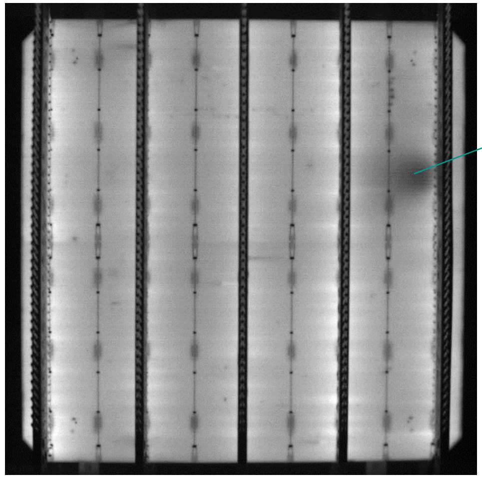


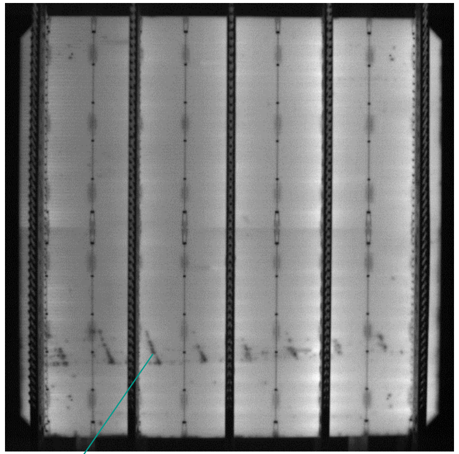
Oxygen



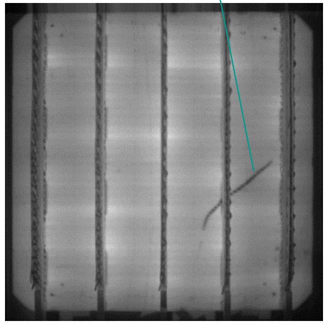
Cracks



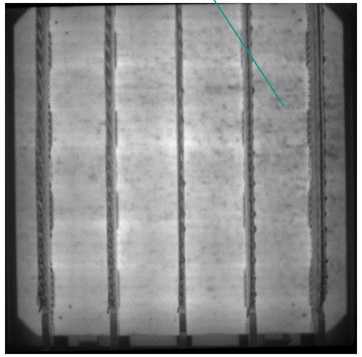
Contaminations



Scratches



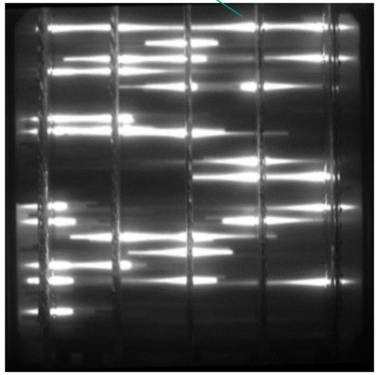
Metal semi-conductor contact

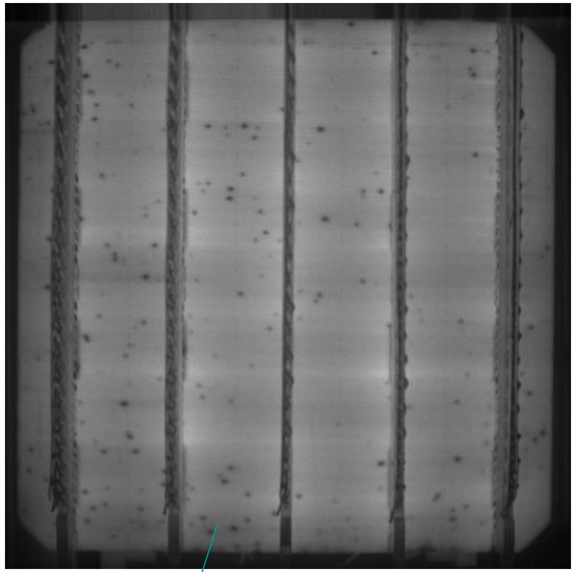


AND
Finger defects
Gripper Marks
Belt marks
Boat marks
Edge isolation
And dozens of other defects…

BUT NO SHUNTS!!!

Mispositioning

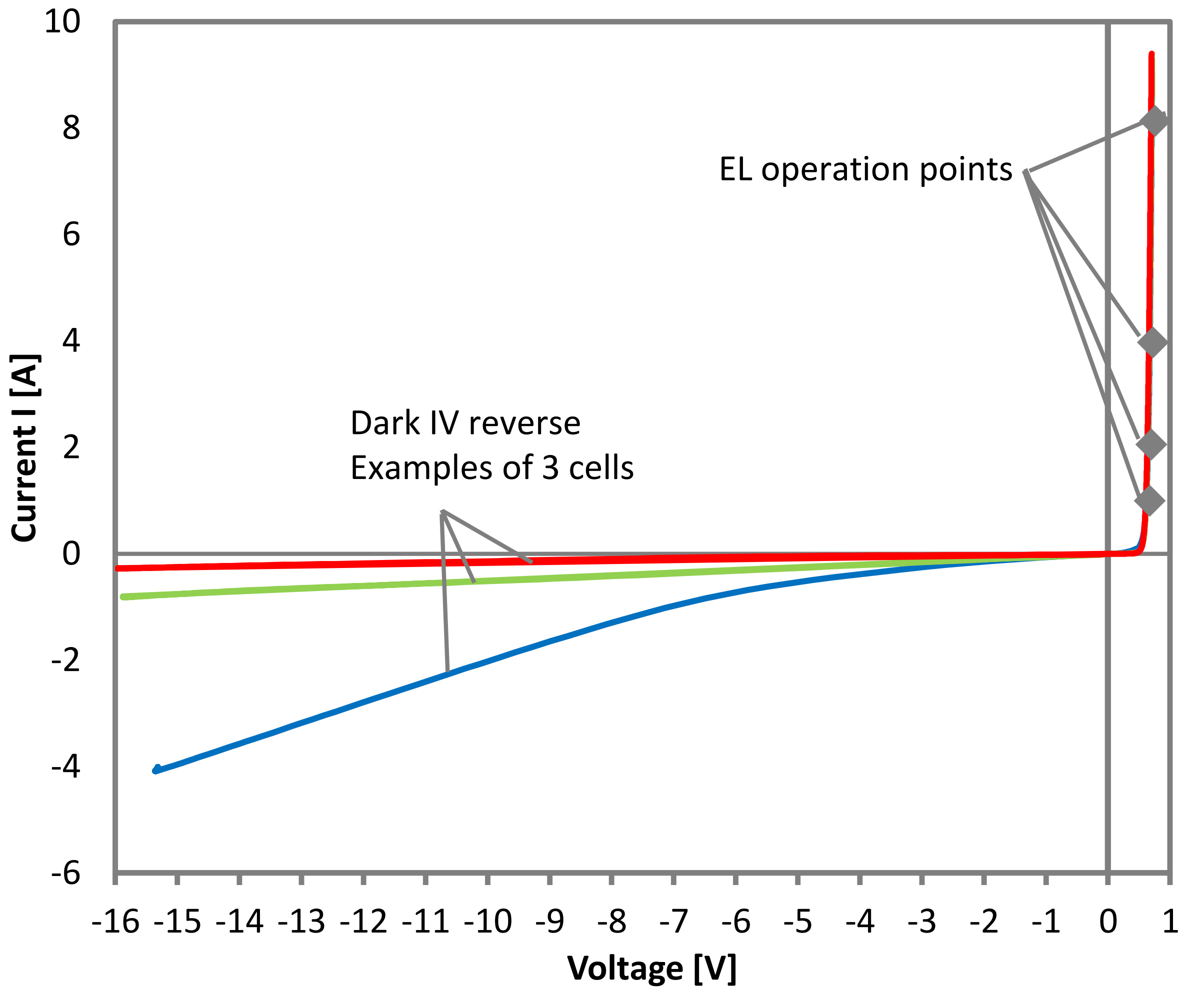




Sprinkles

Why shunts are not visible in EL-imaging

- Shunts are relevant at reverse bias conditions where they may cause damage to solar modules
- They dissipate 400 times as much power at -12 V than at +0.6 V
- What methods are available?
  - Dark IV reverse to identify shunts
  - Thermography (IR) to localize shunts
  - halm. advanced thermography to quantify the impact of shunts in modules already at cell sorting



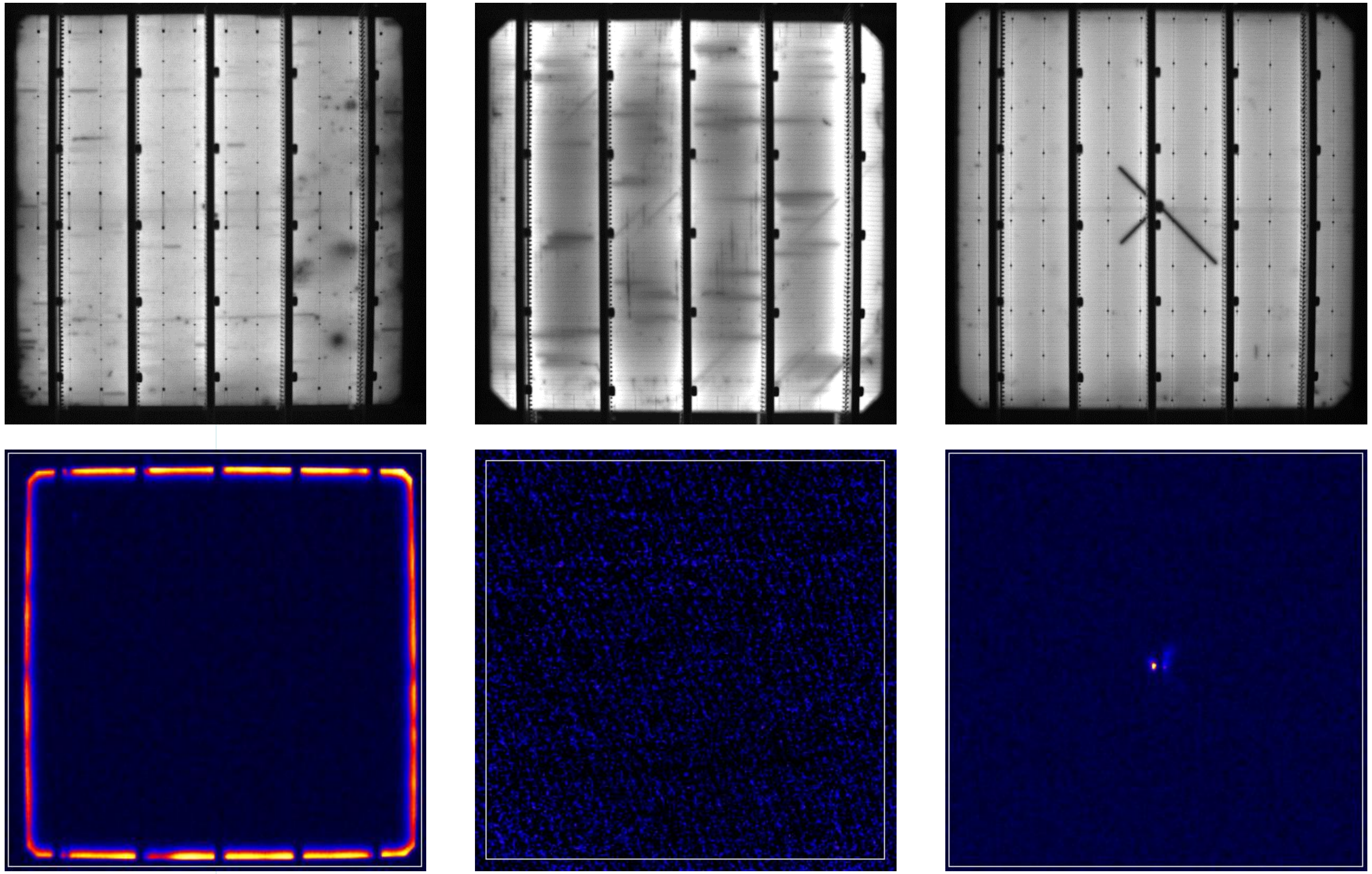
Comparison of EL and IR images

- EL and IR images visualize different defects
- IR images visualize hot spots
- Advanced IR evaluation converts this information to module temperature

Cell 1 | Cell 2 | Cell 3

EL images

IR images (thermography)



edge shunt | finger interruptions but no shunt | laser induced crack with small shunt

Conclusions

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- While contacting is still somewhat open, *IV*-measurements of back-contact cells can routinely be done
- Hysteresis compensation is required
- Hysteresis can as well be used to deduce further information than just *IV*
- Complementary EL and TG characterization help to identify defects, perform advanced process control and optimize product quality

