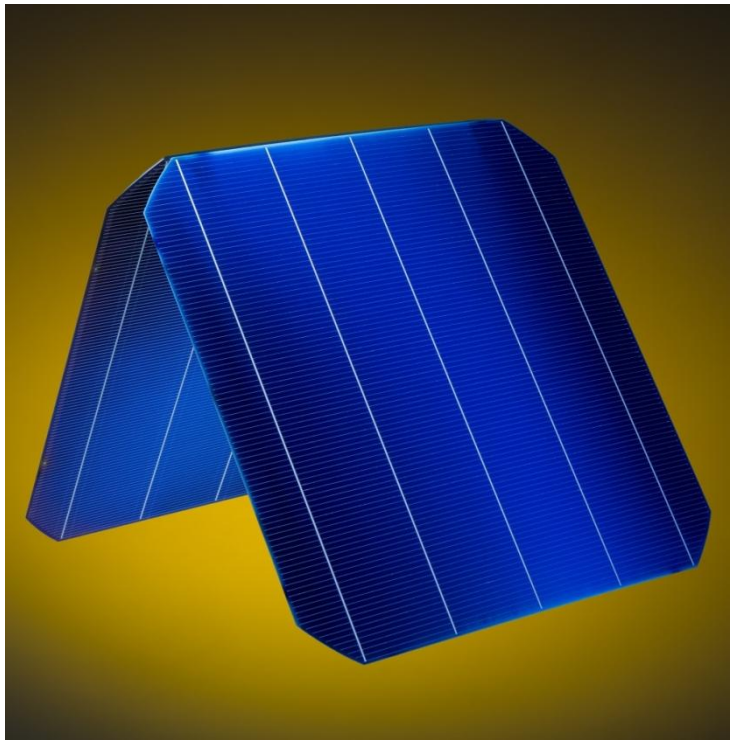


21.6% bifacial PERC+ solar cell at ISFH

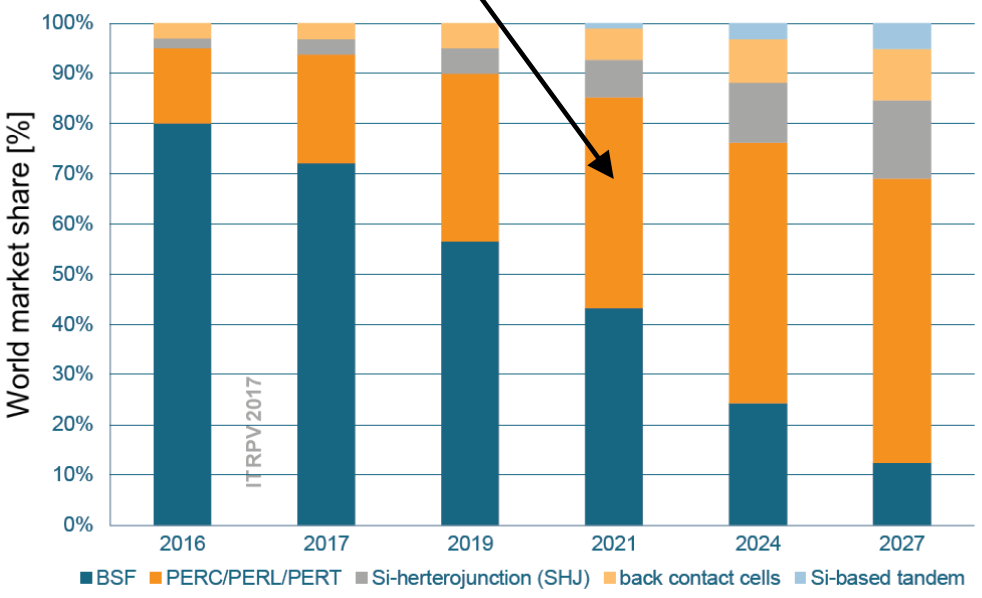
Bifacial PERC+ solar cells: status of industrial implementation and future perspectives

T. Dullweber, H. Schulte-Huxel,
H. Hannebauer, S. Blankemeyer,
U. Baumann, S. Schimanke, R. Witteck,
M. Köntges, R. Brendel

Institute for Solar Energy Research Hamelin (ISFH)

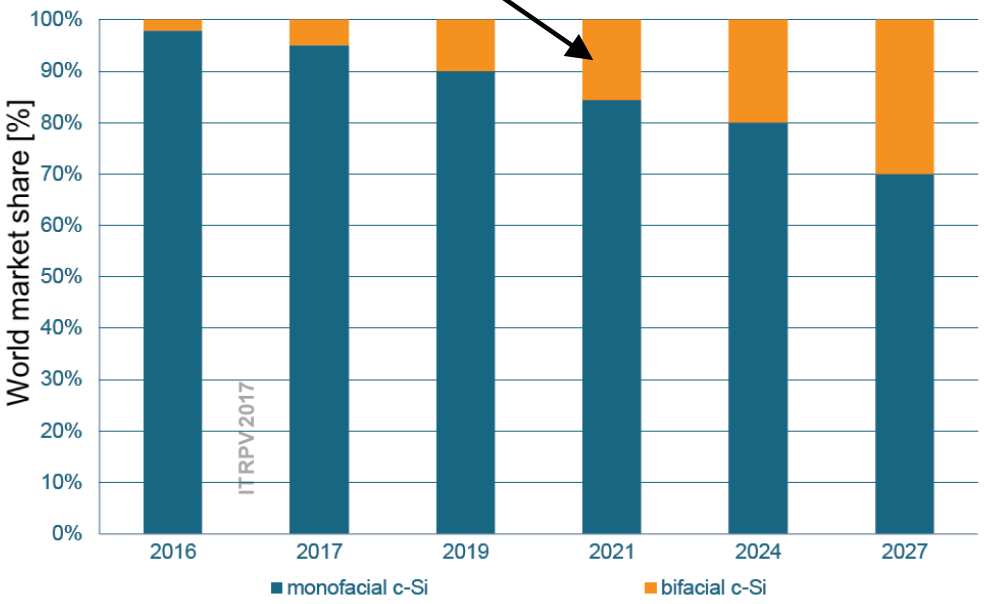
PERC vs. bifacial: market share

PERC



~ 60% market share in 2027

Bifacial cells



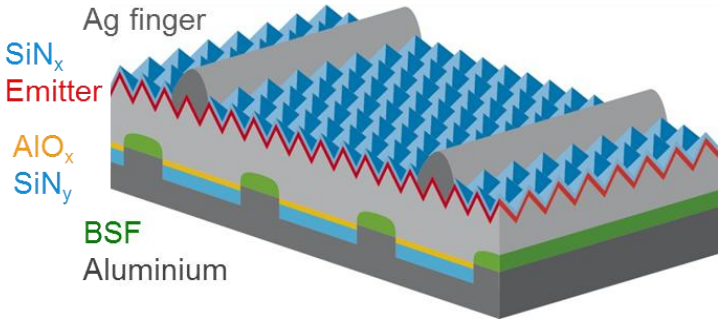
~ 30% market share in 2027

Bifacial PERC cells = PERC+

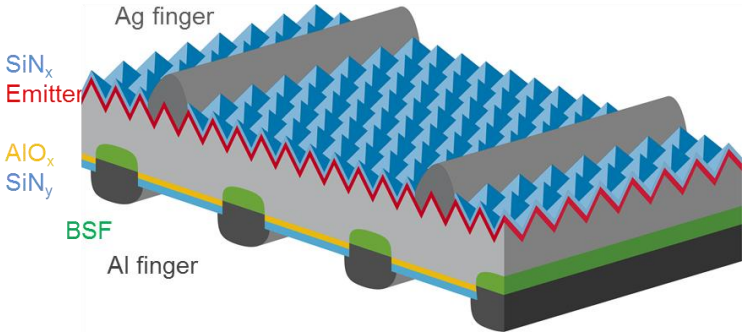
Data from ITRPV roadmap, March 2017

ISFH PERC+ solar cell process

PERC



PERC+

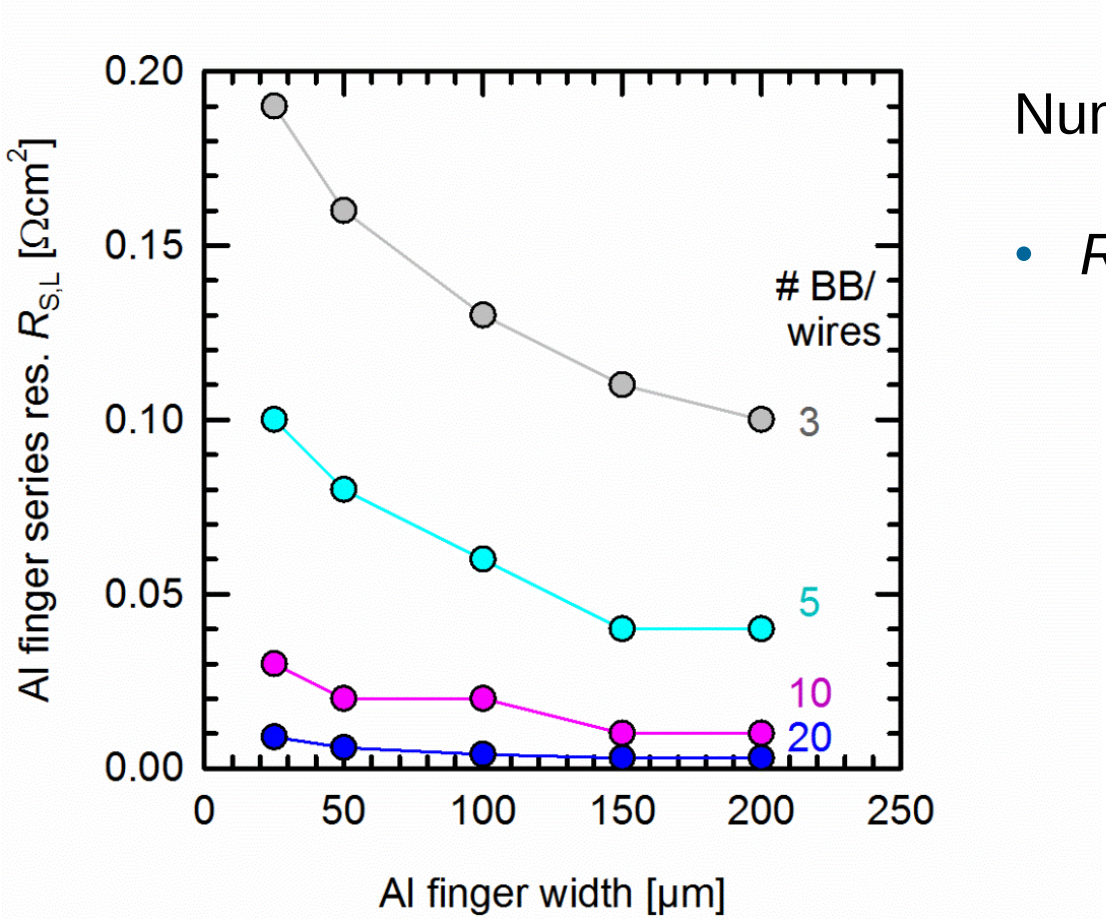


	Wafer cleaning	
	Rear protection layer	
	Texturing	
	Phosphorus diffusion	
	PSG + dielectric etch	
200 nm	Rear: AlO_x/SiN_y	80 nm
	Front: PECVD-SiN_x	
pitch	Rear: LCO	1.5 x pitch
Full area	Al screen-printing	5 BB Grid
	Ag screen-printing	
	Co-firing	

T. Dullweber et al., 31st EUPVSEC (2015), p. 341
T. Dullweber et al., Prog. Photovolt.: Res. Appl., **24** (2016), p. 1487

Challenges with PERC+

Resistivity of Al paste (20 µΩcm[1]) 6 times higher than Ag paste



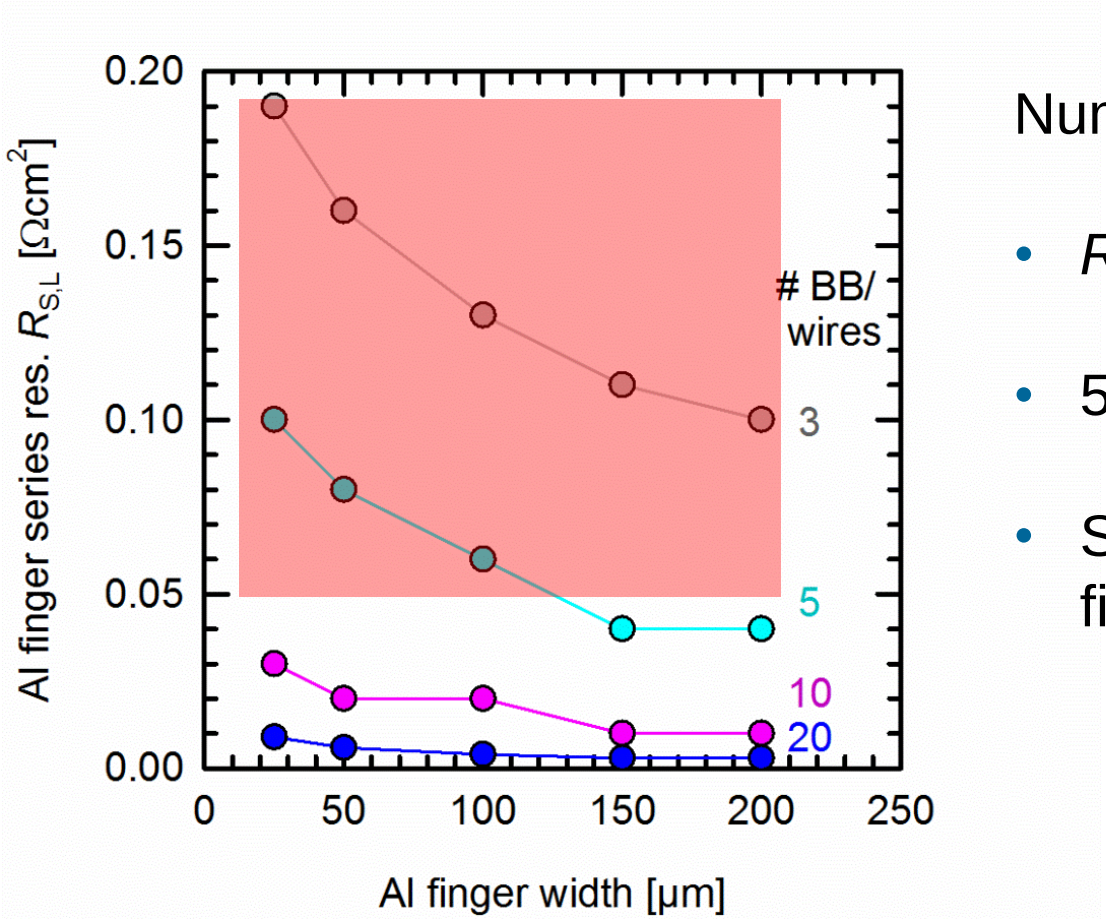
Numerical modelling: high η_{front}

- $R_{s,L}$ < 0,05 Ωcm² required

[1]T. Dullweber et al., Prog. Photovolt.: Res. Appl. **24** (2016), p. 1487

Challenges with PERC+

Resistivity of Al paste (20 µΩcm[1]) 6 times higher than Ag paste



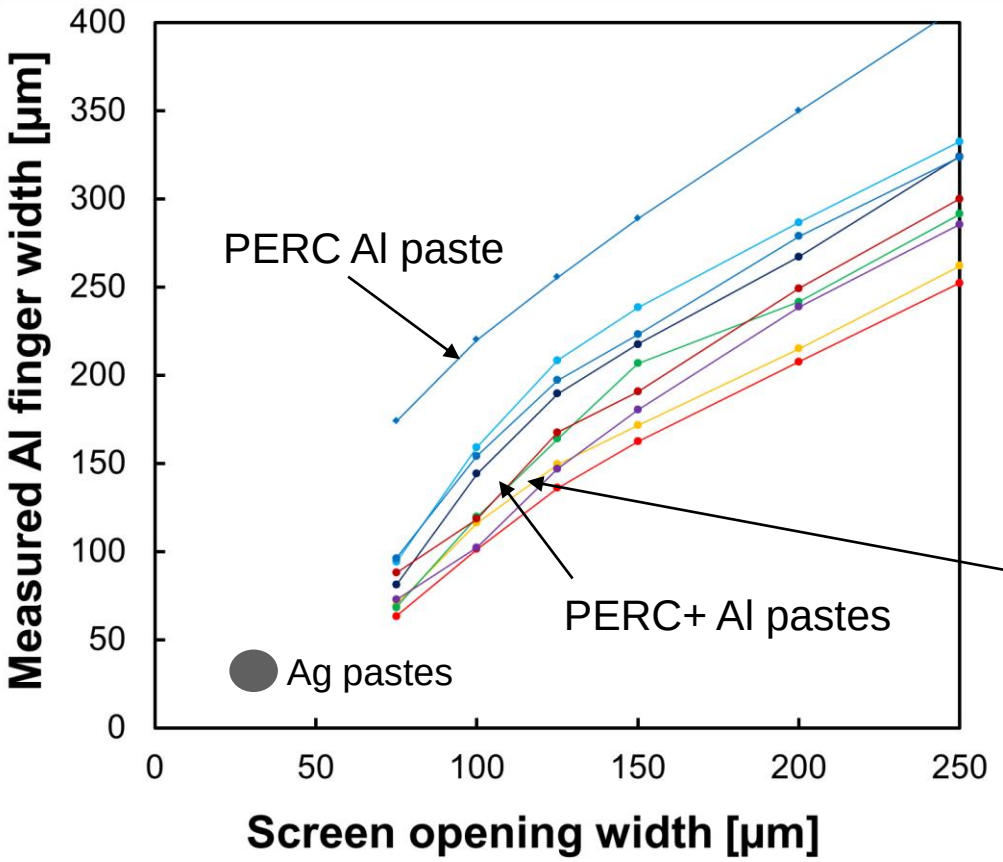
Numerical modelling: high η_{front}

- $R_{s,L}$ < 0,05 Ωcm² required
- 5 BB design enabled PERC+
- Smart Wire enables narrow Al finger designs

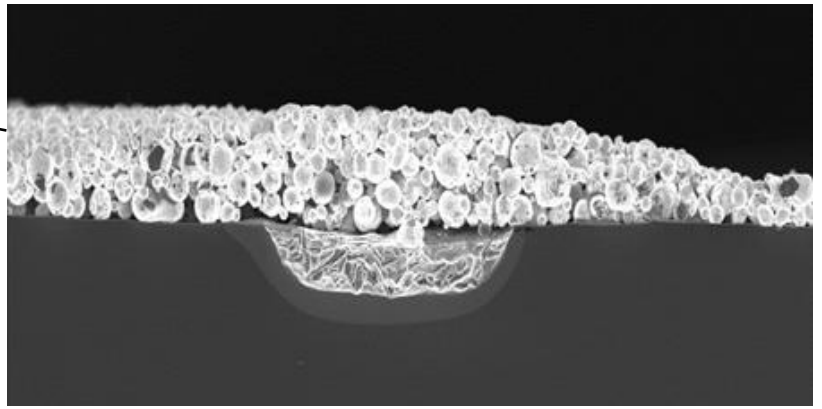
[1]T. Dullweber et al., Prog. Photovolt.: Res. Appl. **24** (2016), p. 1487

Challenges with PERC+

Printing narrow Al fingers

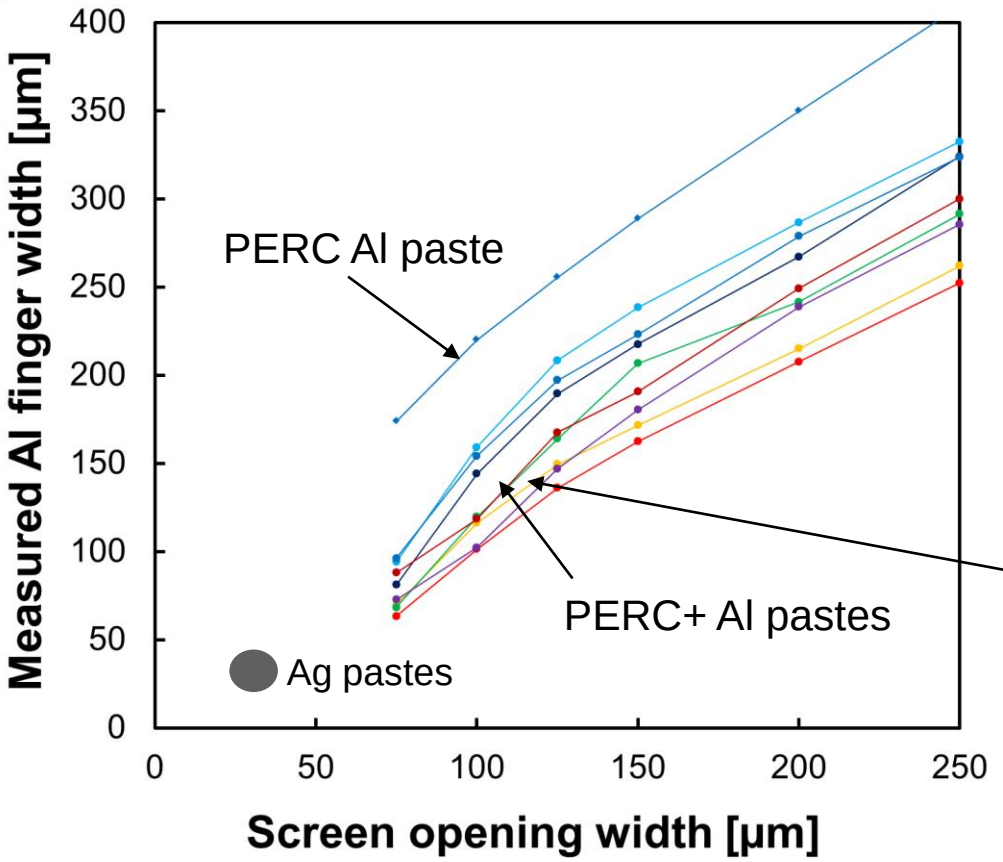


- PERC Al pastes exhibit extreme spreading > 200 µm
- PERC+ Al pastes enable finger widths < 150 µm

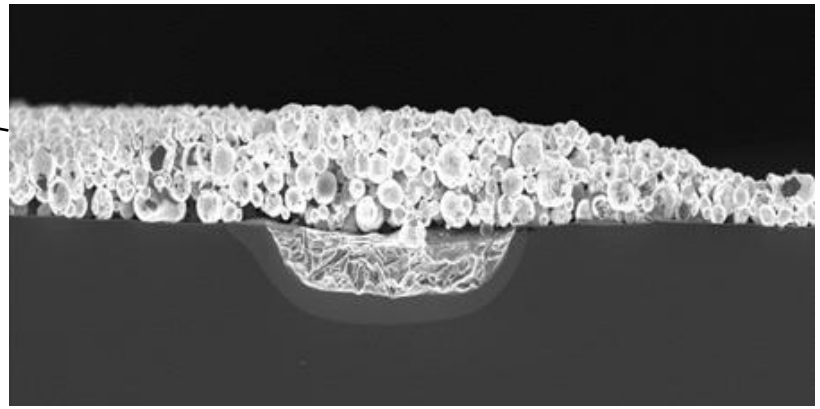


Challenges with PERC+

Aligning Al fingers to LCO

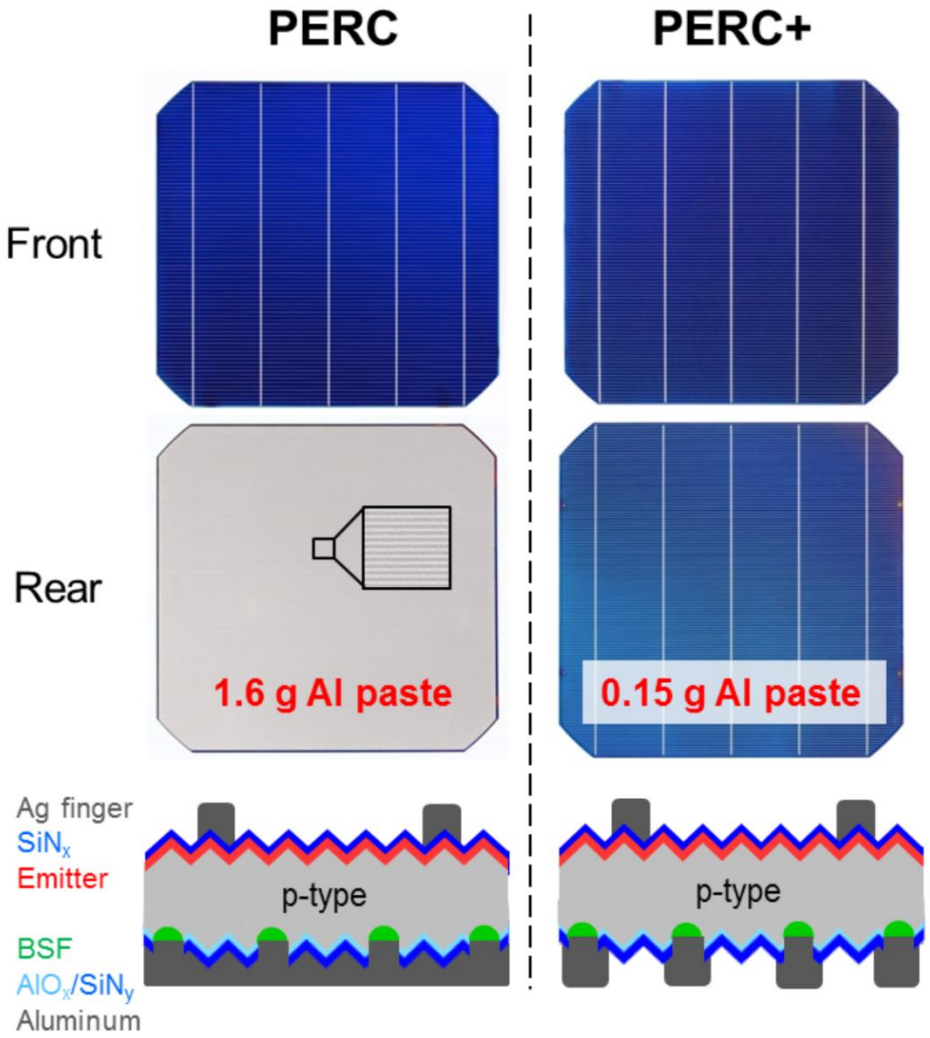


- Al screen print to LCO align. tolerance < ± 30 µm
- Requires cameras and high precision screens and lasers



Toyal Toyo Aluminium K.K.

ISFH PERC+ solar cells



5 busbar PERC+ cells

- η_{front} up to 21.6%*
- η_{rear} up to 16.7%
- Bifaciality up to 80%
- Al paste reduced by 90%

*independently confirmed by ISFH CalTeC

T. Dullweber et al., 31st EUPVSEC (2015), p. 341
T. Dullweber et al., Prog. Photovolt.: Res. Appl. **24** (2016), p. 1487

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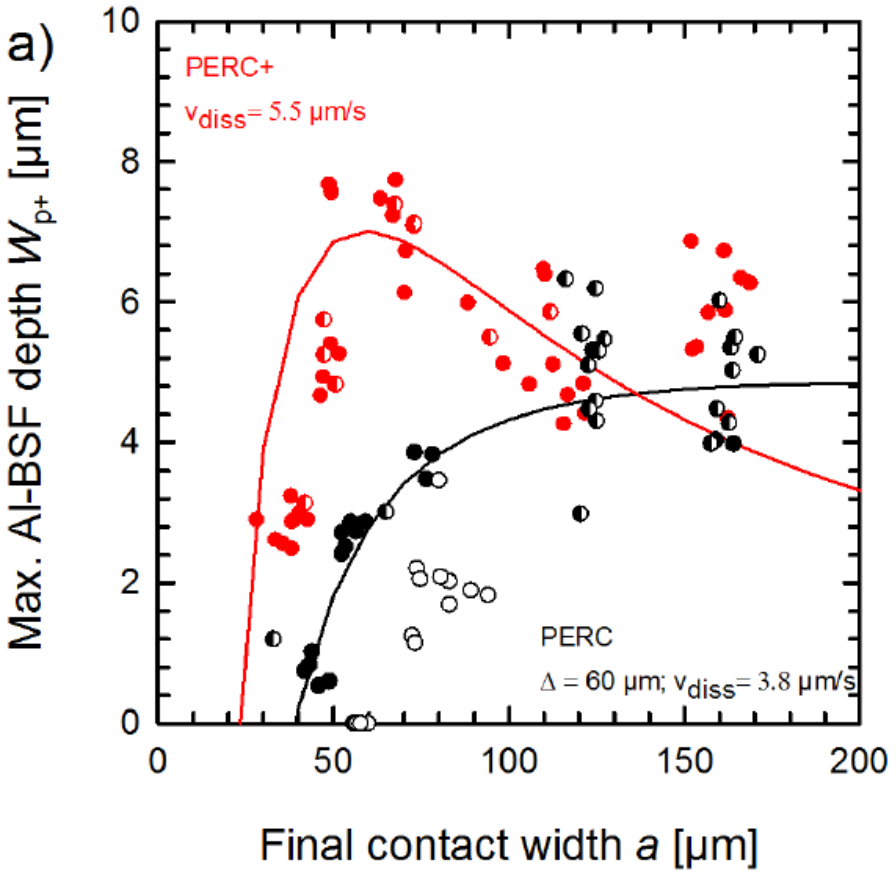
PERC+ with deeper Al-BSF



- PERC+ with 7 µm deep Al-BSF
- New physical model to calculate Al-BSF depth:

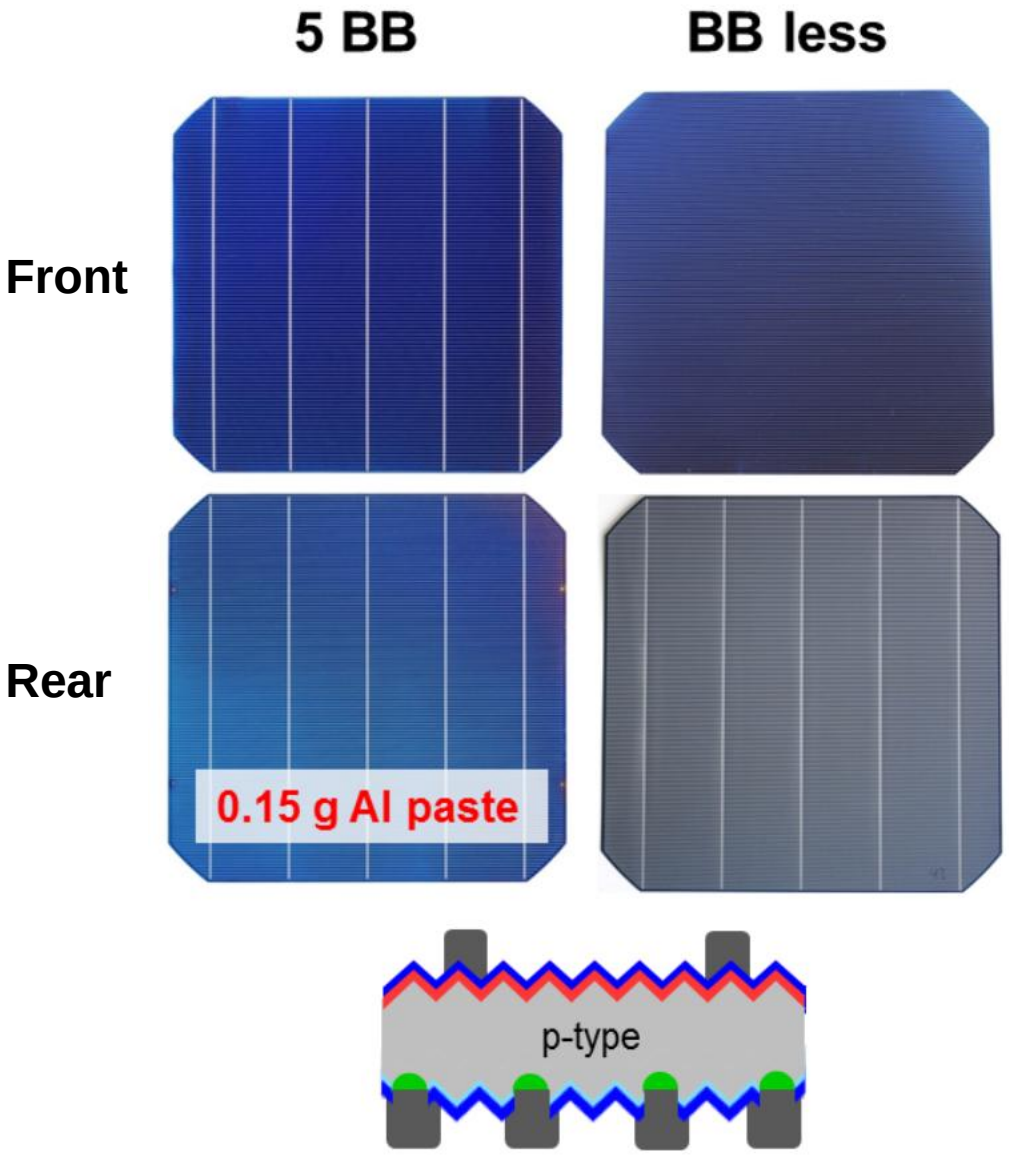
$$W_{p^+} = \frac{m_{Al}}{A\rho_{Si}}\left(\frac{F\left(1-e^{-\frac{A}{m_{Al}}\frac{\rho_{Si}v_{diss}}{F}t_{firing}}\right)}{1-F\left(1-e^{-\frac{A}{m_{Al}}\frac{\rho_{Si}v_{diss}}{F}t_{firing}}\right)}-\frac{E}{1-E}\right)$$

$$\frac{m_{Al}}{A} = \frac{A_{Al-finger}\ \rho^*_{Al}}{a}$$

- Explains higher V_{oc} of PERC+ compared to PERC
- PERC+ has no voids

C. Kranz et al., *IEEE Journal of Photovoltaics,* **6** *(*2016), p. 830

22.1 % PERC+ cell at ISFH



Busbar less PERC+ cell

- η_{front} = 22.1%*
- Missing BB shadowing increases η_{front} by 0.4%$_{abs.}$
- η_{rear} not measured
- Rear Al grid optimized for high η_{front}
- 5 BB on rear not required

*measured at ISFH with IV tester from PASAN

Industrial introduction of PERC+

Year	η [%] front / rear	Organization
2015	21.5 / 16.7	ISFH
2015	20.3 / n.p.	Trina Solar
2016	20.7 / 13.9	Big Sun Energy Technology
2017	21.5 / 16.1	JinkoSolar
2017	21.4 / n.p.	Neo Solar Power
2017	21.6 / 17.3	LONGi Solar
2017	21.6* / n.p.	ISFH (5 BB)
2017	22.1 / n.p.	ISFH (BB less)

*idependently confirmed; n.p. = not published

- PERC+ in (pilot) production at SolarWorld, LONGi, Trina Solar, Neo Solar Power, …
- 5 largest solar cell comanies are producing PERC and evaluating PERC+

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Commercial PERC+ modules

Company	Product	Max. power rating [Wp]	Comments
SolarWorld	Bisun	290	5 BB, 60 cells, Cz
Neo Solar Pow.	Glory Bifi	300	4 BB, 60 cells, Cz
Trina Solar	Duomax	300	5 BB, 60 cells, Cz
LONGi Solar	LR6-60P	305	4 BB, 60 cells, Cz

Bisun module from SolarWorld

- ~ 300 Wp power rating stated for front side illumination, only
- Additional rear side illumination (e.g. 10%) will increase P_{max} (e.g. to ~ 320 Wp)

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PERC+ outdoor test sites

SolarWorld installations, Germany:

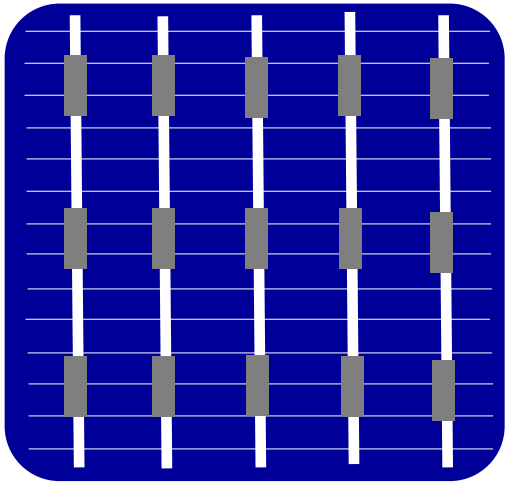
- 3.2 kWp Bisun modules
- 74% albedo (white), 0.28 m mou. height
- 13.0% increased energy yield of PERC+ vs. PERC (13.3% predicted)

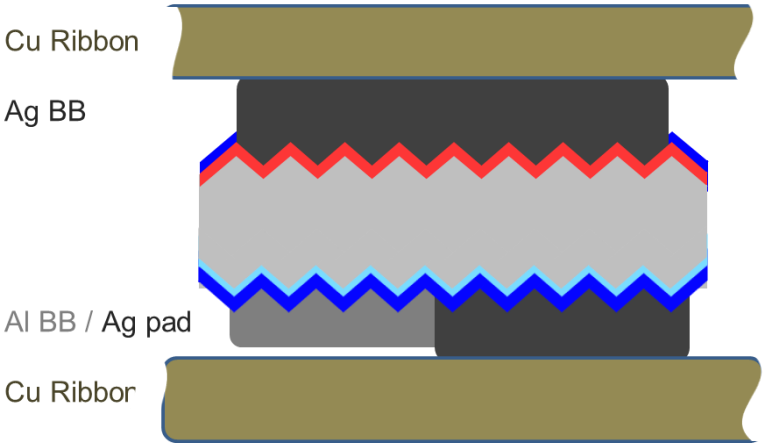
- 13 kWp Bisun modules on 1 axis tracker
- 17% albedo (sand), 0.9 m mou. Height
- 21.6% increased energy yield of PERC+ vs. PERC

H. Neuhaus (SolarWorld), presented at PV CellTech Conference, Malaysia (2017)

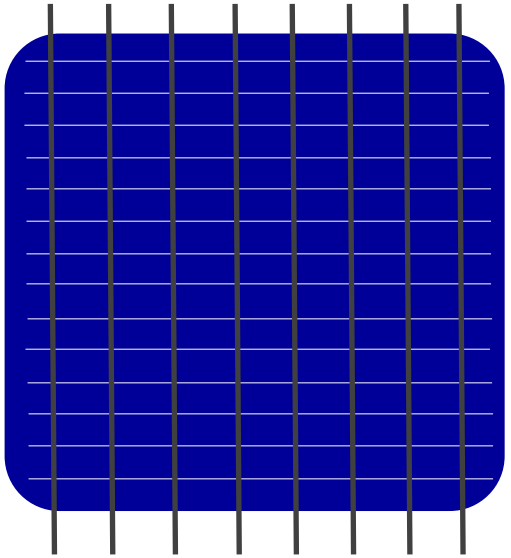
Novel PERC+ SWCT modules

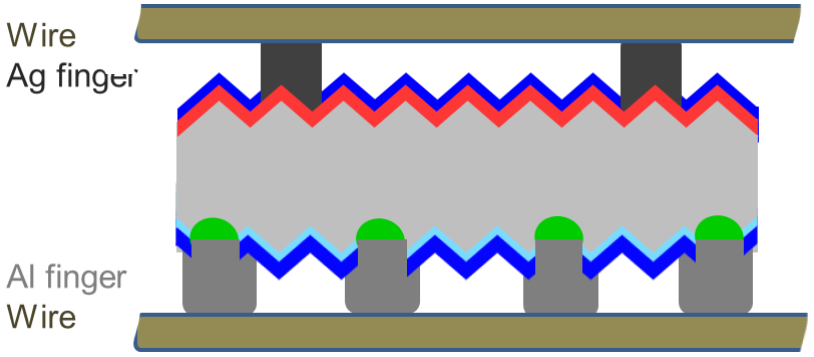
Conventional Ag pads





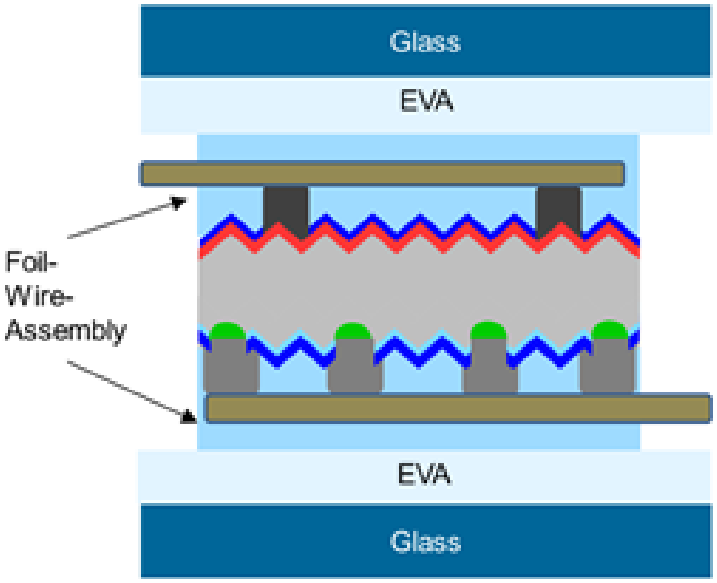
Smart Wire Connection Technology (SWCT)

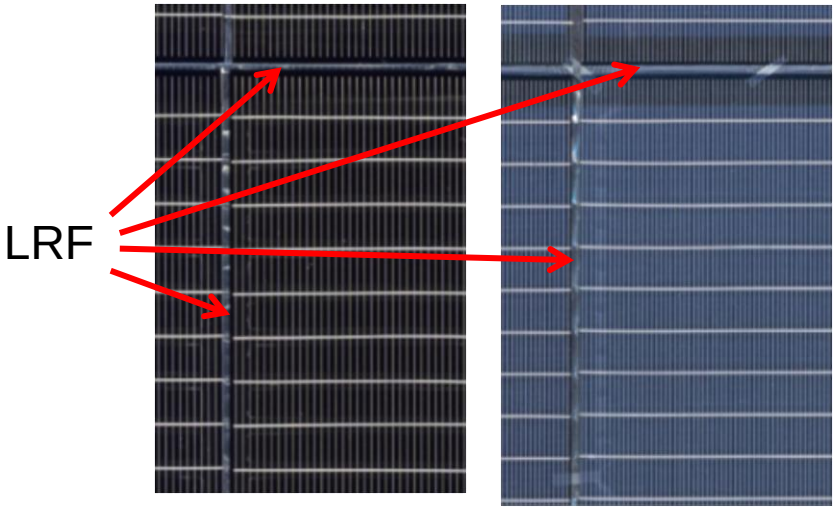




T. Dullweber et al., 33rd EUPVSEC (2017), in press

PERC+ module processing





- 18 PERC+ cells without busbars => 55 mg Ag paste per full-size PERC+ cell
- Half cell design
- Smart Wire Connection Technology
  - 18 wires coated with InSn
  - 200 µm wire diameter
  - Foil with glue on one side
- 1.5 mm Light Reflective Film (LRF) from 3M in-between PERC+ cells
- Glass-glass module with AR coating

T. Dullweber et al., 33rd EUPVSEC (2017), in press

PERC+ module results

	V_{oc} [V]	I_{sc} [A]	FF [%]	η [%]
18 PERC+ cells, front	11.9^{Σ}	$4.91^{ø}$	$77.3^{ø}$	$20.5^{ø}$
Module front	11.8	4.80	78.7	**19.8***
Module back	11.8	3.94	78.8	**16.4***

*Independently confirmed by

TÜVRheinland®
Precisely Right.

T. Dullweber et al., 33rd EUPVSEC (2017), in press

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PERC+ module results

	V_{oc} [V]	I_{sc} [A]	*FF* [%]	η [%]
18 PERC+ cells, front	11.9^{Σ}	$4.91^{ø}$	$77.3^{ø}$	$20.5^{ø}$
Module front	11.8	4.80	78.7	**19.8***
Module back	11.8	3.94	78.8	**16.4***

$\eta_{eq,0.1} \equiv \eta_{front} + 0.1^* \eta_{rear} =$ **21.4%**

Bifaciality = **83%**

*Independently confirmed by

TÜVRheinland®
Precisely Right.

T. Dullweber et al., 33rd EUPVSEC (2017), in press

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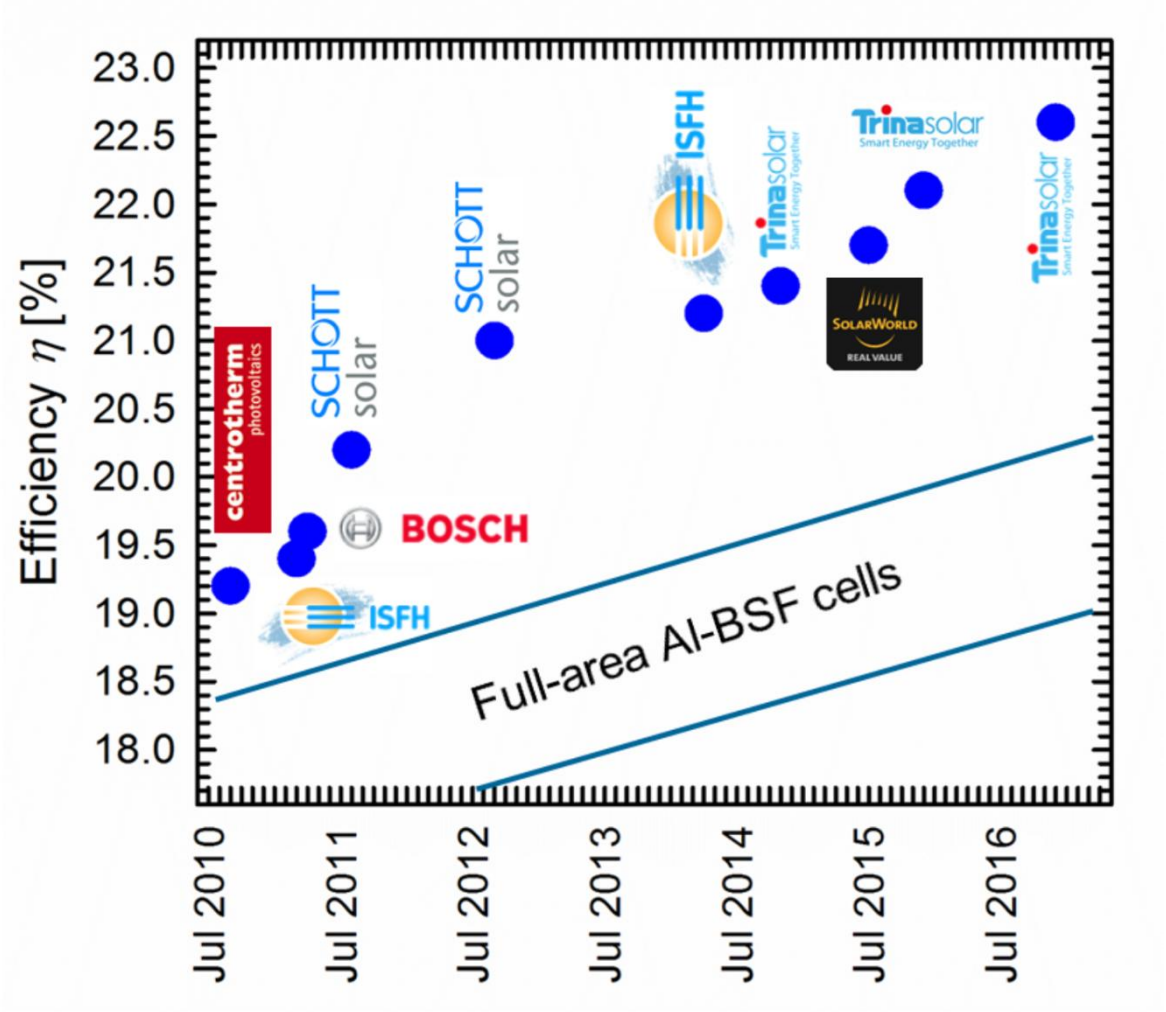
PERC efficiency potential



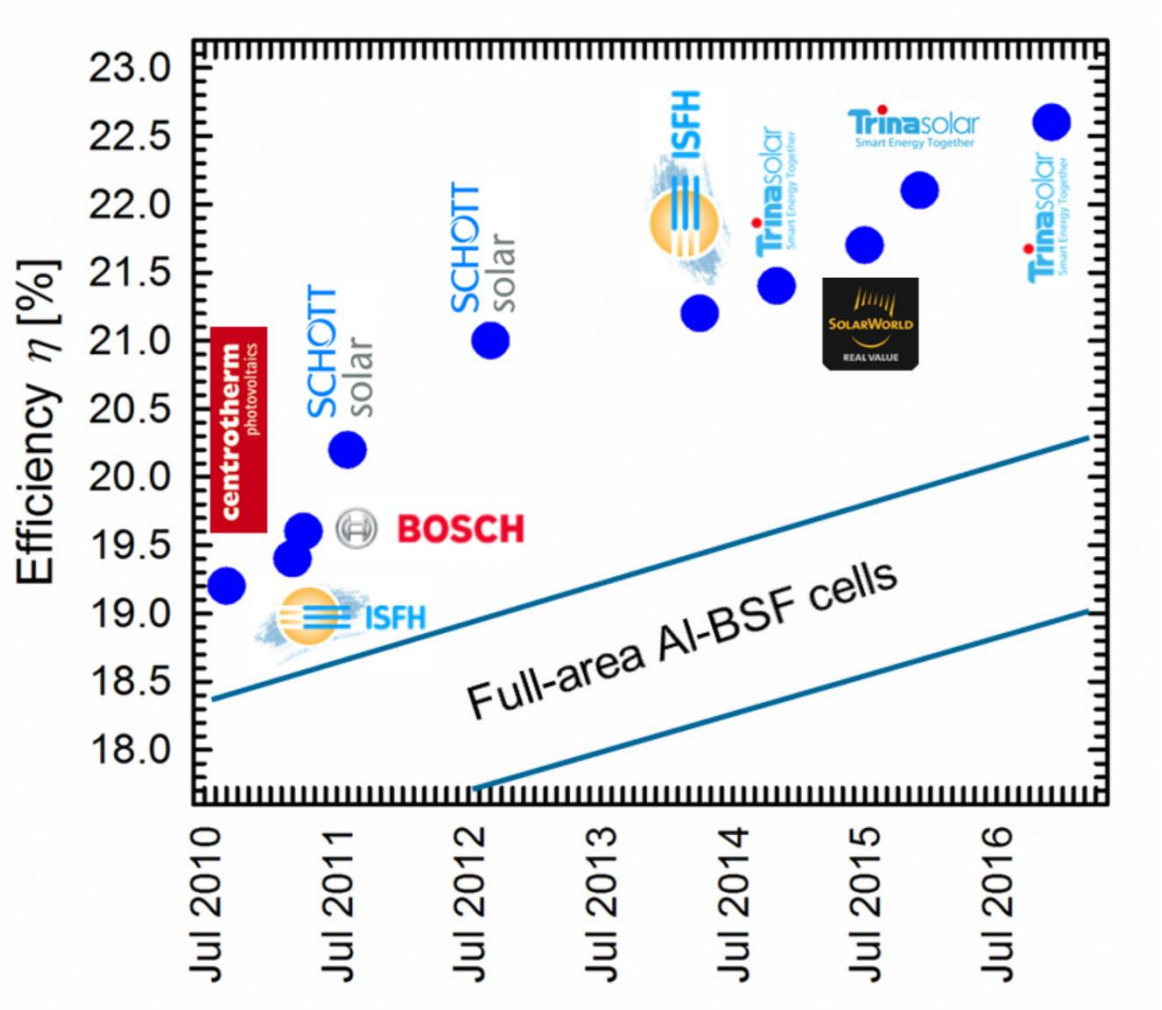
Selection criteria

- large area > 148 cm^2
- p-type, monocrystalline
- screen-printed contacts

K.A. Münzer et al., *25th EUPVSEC* (2010), 2314
S. Gatz et al., *Phys. Status Solidi RRL* 5 (2011), 147
Bosch Solar Energy AG, press release April 2011
Schott Solar AG, press release August 2011
P. Engelhart et al., *26th EUPVSEC* (2011), 821
A. Lachowicz et al., *27th EUPVSEC (*2012) , 1846
B. Tjahjono et al., *28th EUPVSEC* (2013), 775
H. Hannebauer et al., *Phys. Status Solidi RRL* 1-5 (2014)
P. Verlinden et al., 6th WCPEC (2014), in press
SolarWorld AG, press release July 2015
Trina Solar, press release Dec. 2015
Trina Solar, press release Dec. 2016

T. Dullweber and J. Schmidt, IEEE JPV, **6**, 1366 (2016)

PERC+ efficiency potential



η_{front} > 23%

- selective emitter
- narrow Ag fingers
- improved surface passivation

η_{rear} > 20% (85% bifaciality)

- narrow Al fingers
- improved AR properties

T. Dullweber and J. Schmidt, IEEE JPV, **6**, 1366 (2016)

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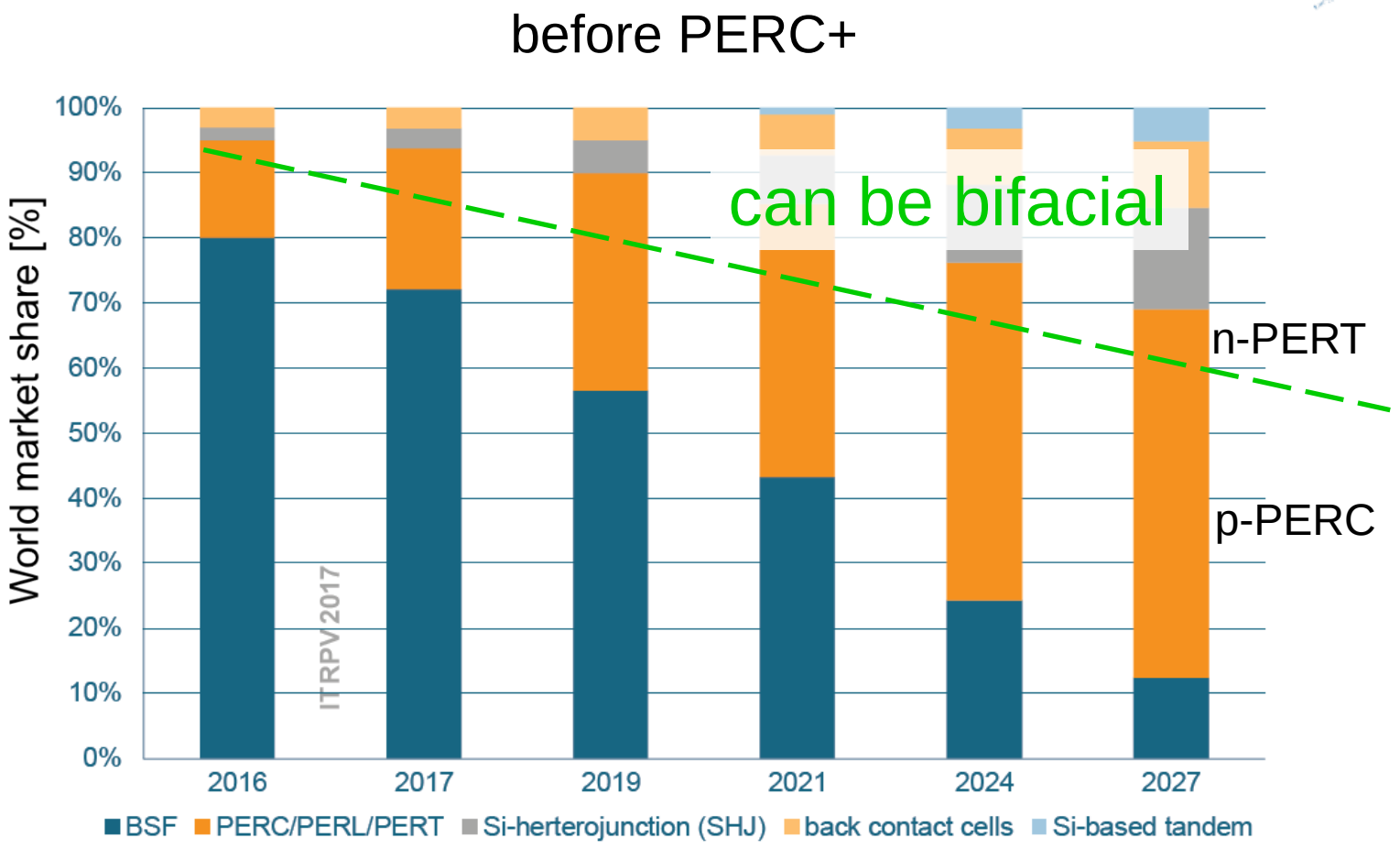
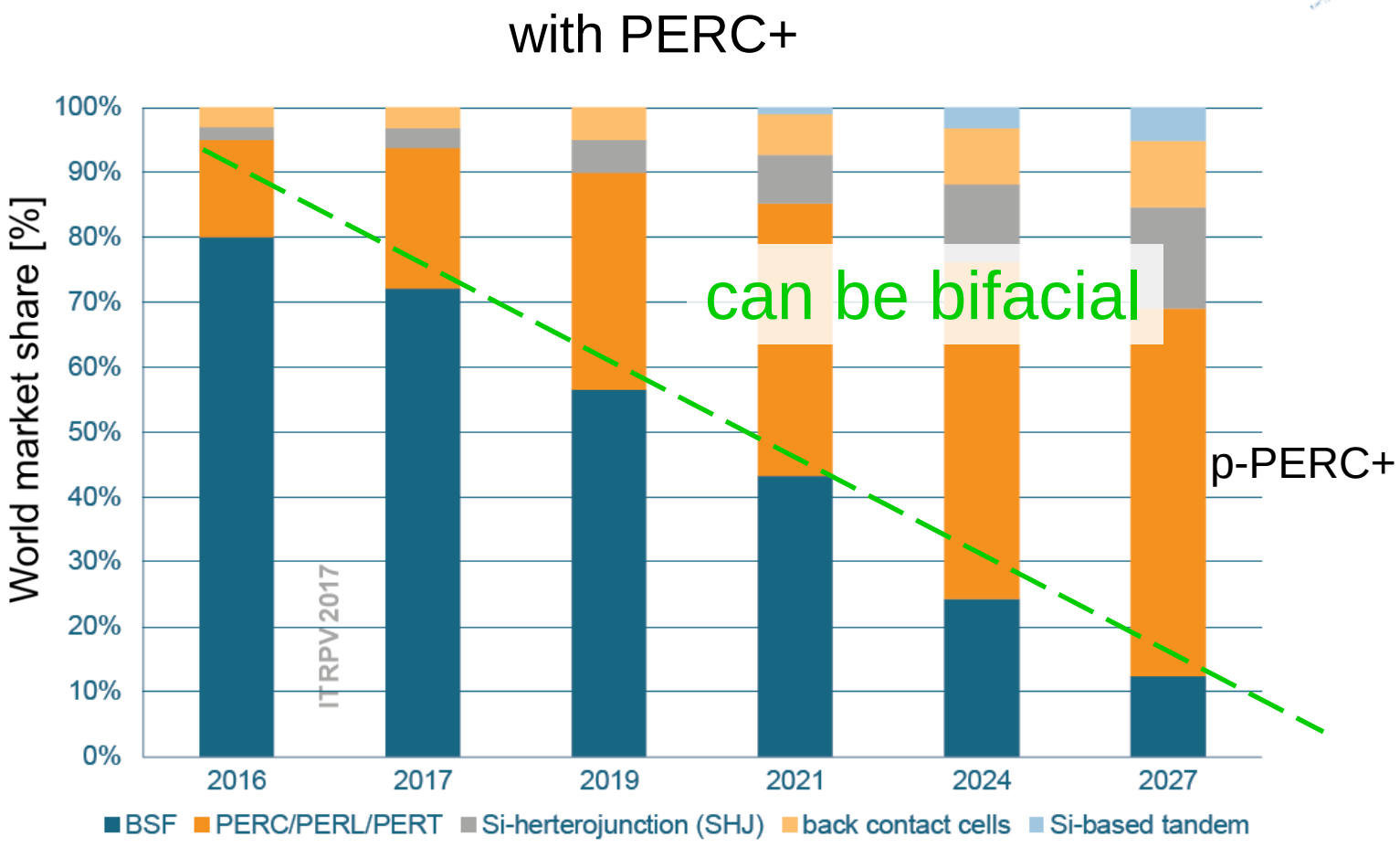
Conclusions



Data from ITRPV roadmap, March 2017

Conclusions



Data from ITRPV roadmap, March 2017

Conclusions

- PERC+ cells are attractive for monofacial and bifacial applications with η_{front} up to 22.1% and η_{rear} up to 17.2%
- Leading solar cell manufacturers are evaluating / producing PERC+ cells. Commercial PERC+ modules available from 4 companies
- PERC+ module with Smart Wire Connection Technology reduces Ag paste to 55 mg and increases bifaciality to 83%
- Evolutionary PERC improvements will increase PERC+ η_{front} > 23% and η_{rear} > 20% in next few years

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Acknowledgements

- Funding was partly provided by the German Federal Ministry for Economic Affairs and Energy under contract number 032577C (HELENE).

Federal Ministry for Economic Affairs and Energy

- Toyal for providing the Al paste

Toyal Toyo Aluminium K.K.

- Meyer Burger for supporting SWCT set up

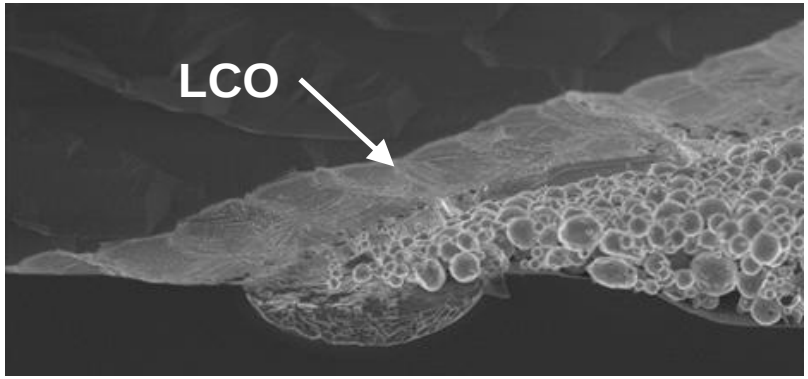
MEYER BURGER

Leibniz Universität Hannover

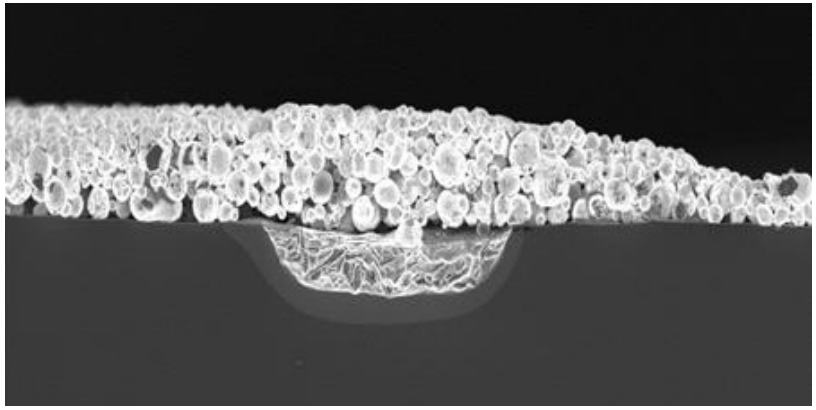
Challenges with PERC+

Aligning Al fingers to laser contact openings (LCO)

Bad example (2015)



Good example (2016)



- Misalignment forms open Si surface -> high recombination
- Al screen print to LCO align. tolerance < ± 30 µm
- Requires cameras in screen printer for aligned printing
- Requires high precision screens and lasers

Industrial introduction of PERC+

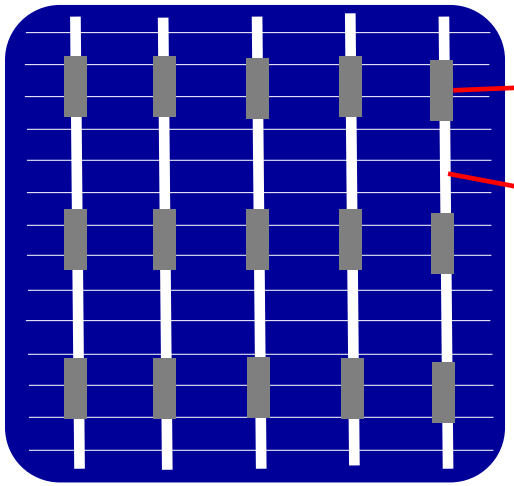
Ranking[1]	Company	PERC status	PERC+ status
1	JinkoSolar	production	in evaluation
2	Trina Solar	production	pilot production
3	Canadian Solar	production	not published
4	Hanwha Q-Cells	production	in evaluation
5	JA Solar	production	in evaluation

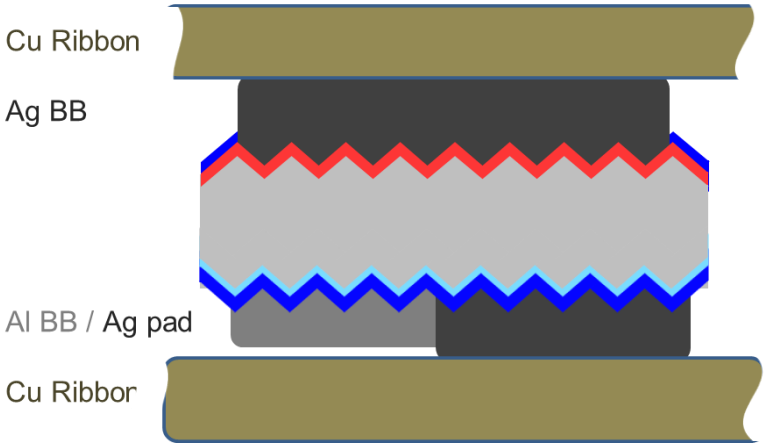
- 4 of 5 largest solar cell producers are evaluating / producing PERC+ cells based on their PERC mass production
- 5 largest solar cell manufacturers account for approx. 25 GWp production capacity / 30% market share

[1] https://www.pv-tech.org/editors-blog/top-10-solar-module-suppliers-in-2016

Commercial PERC+ modules

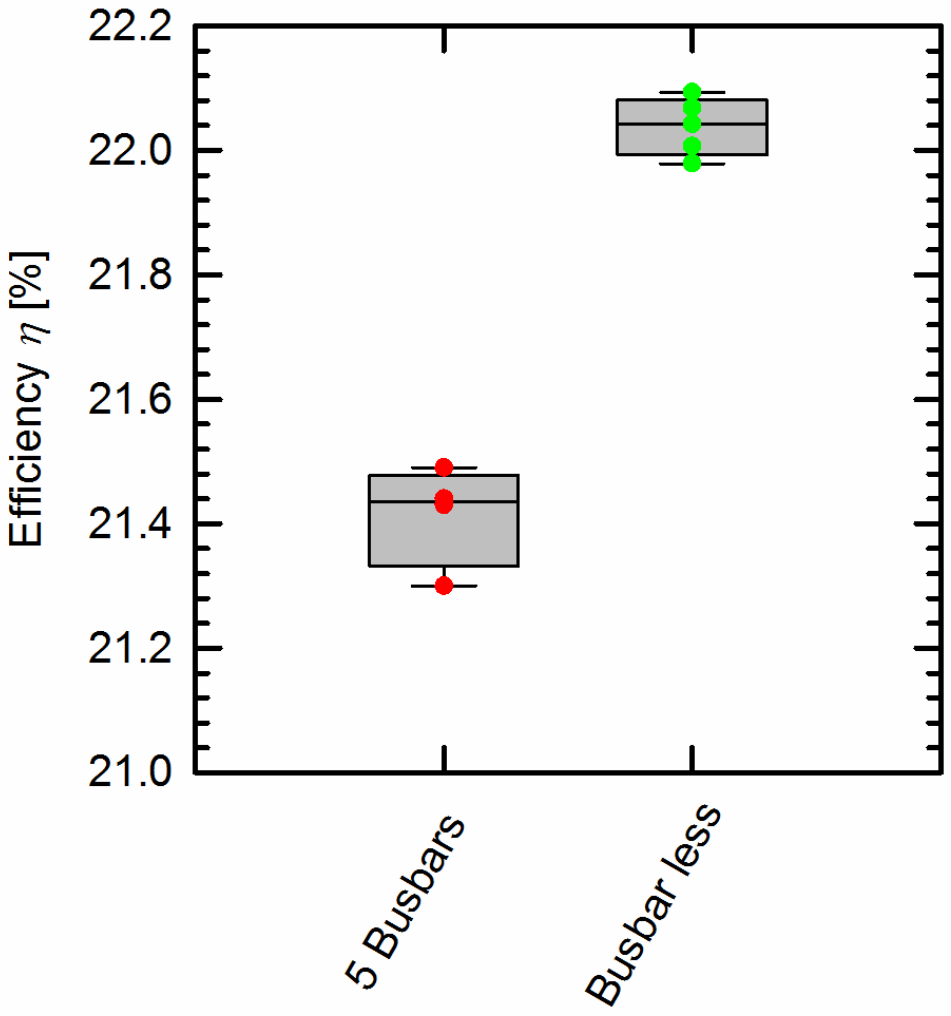
Bifacial PERC+ modules with conventional stringing technology





Bisun module from SolarWorld

22.1 % PERC+ cell at ISFH



Improvements in Ag screen print, rear design, IV tester calibration:

- 5BB η_{front} up to 21.5%
- noBB η_{front} up to **22.1%**
- 0.6% increase due to missing BB shadowing and improved rear passivation
- Measured with PASAN IV tester at ISFH

PERC+ large scale installations

Neo Solar Power, Taiwan[1]

- 2 MWp Glory Bifi roof installation
- Currently under construction

Trina Solar, China[2]

- 20 MWp Duomax power plant
- Under construction on sandy gound with high albedo

[1] https://www.pv-tech.org/news/nsp-to-construct-first-commercial-rooftop-system-using-its-bifacial-solar-m
[2] http://www.trinasolar.com/en-uk/resources/newsroom/mon-05012017-1500

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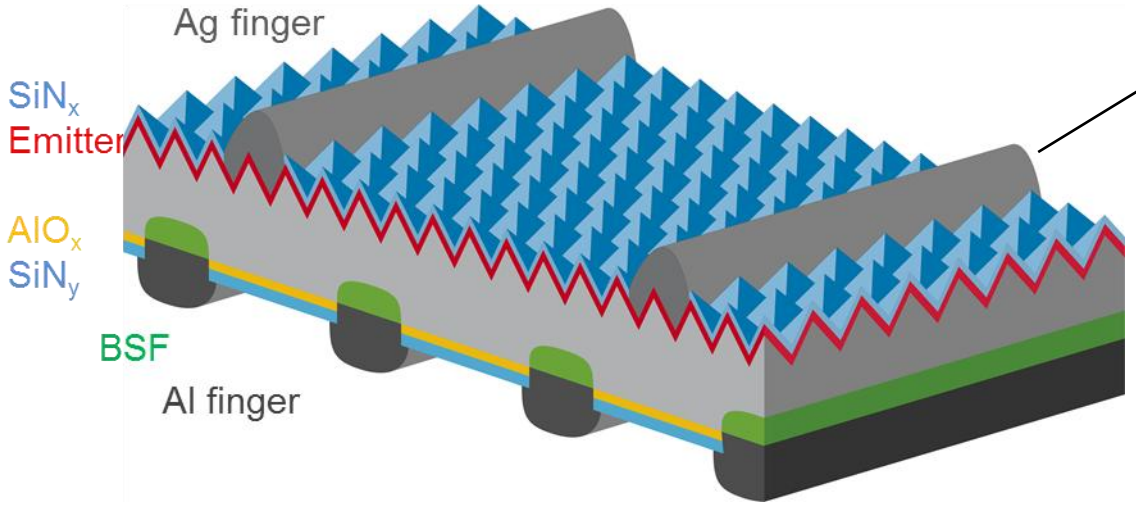
PERC+ solar cell process



55 mg Ag paste per
BB-less PERC+ cell

- “No BB“ PERC+ cells without busbars for smart wire module
- “5 BB“ PERC+ cells with 5 busbar design as reference

T. Dullweber et al., 33rd EUPVSEC (2017), in press