

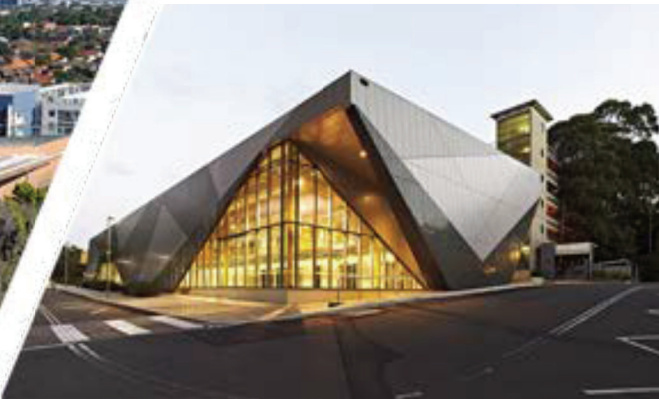


ARENA

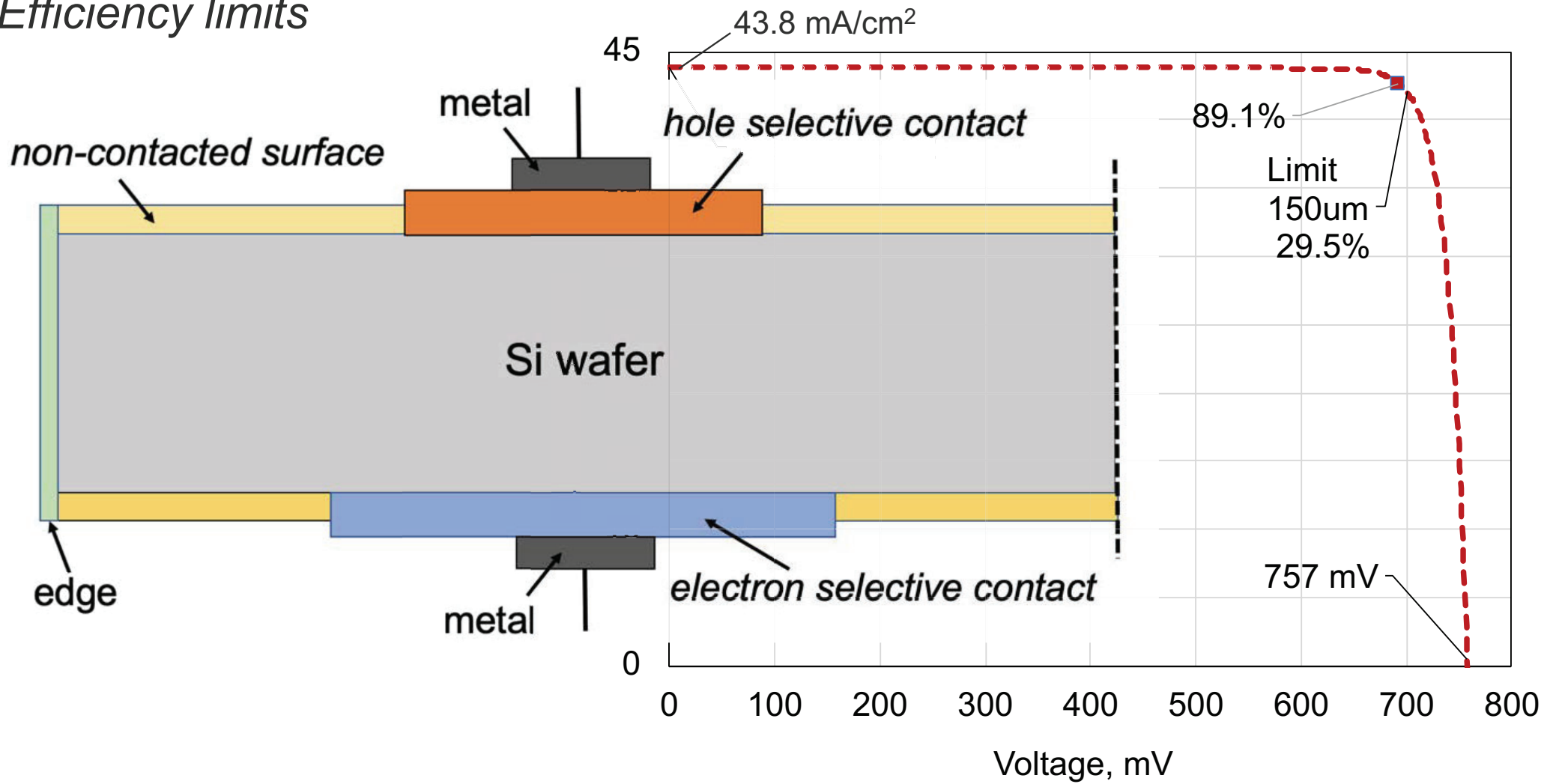


Efficiency limits for PERC, TOPCon, HJT and IBC

Martin Green, UNSW Sydney

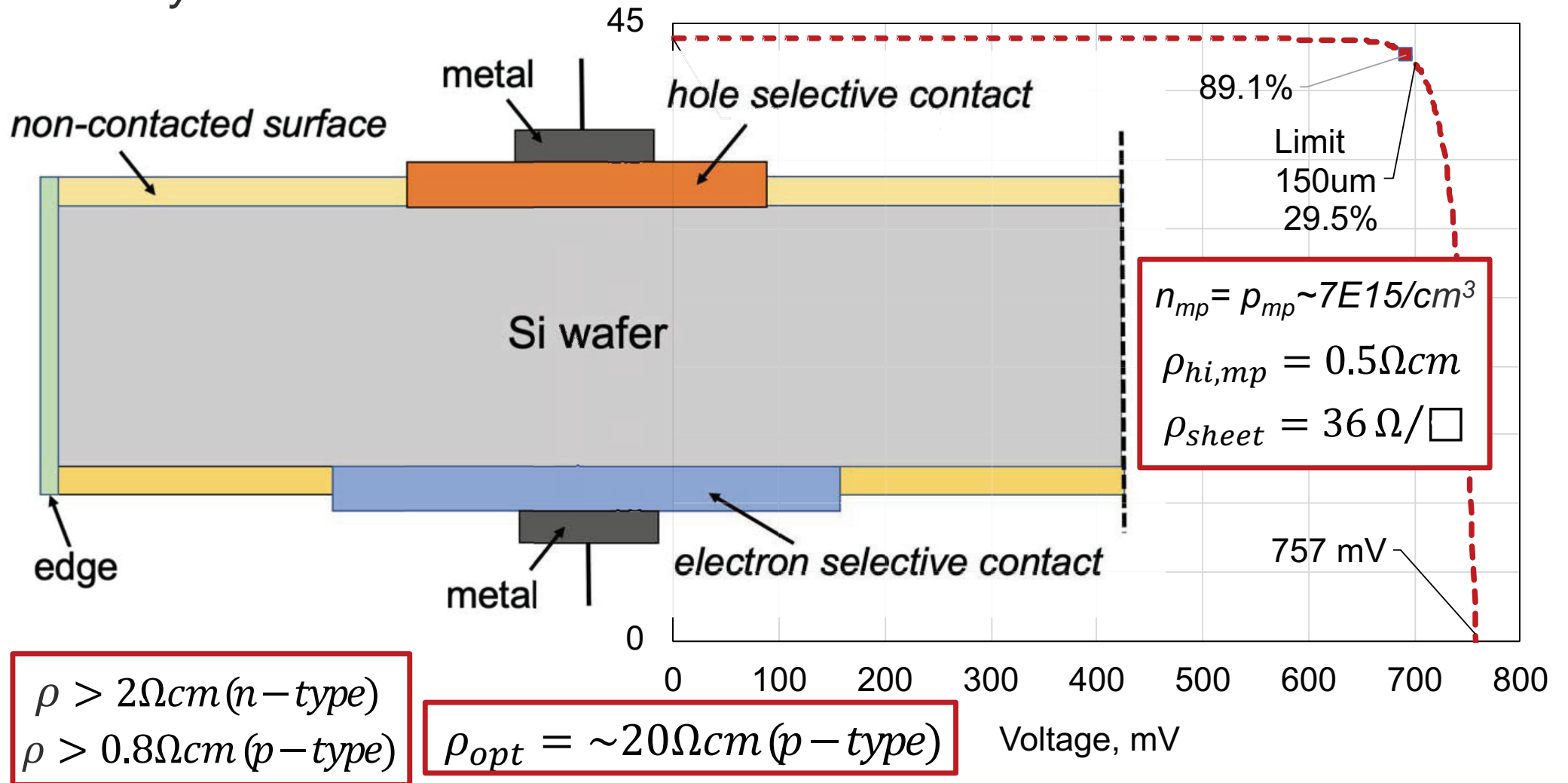


Efficiency limits



Green, IEEE ED-31, 684, 1984; Tiedje et al., ibid., 711.

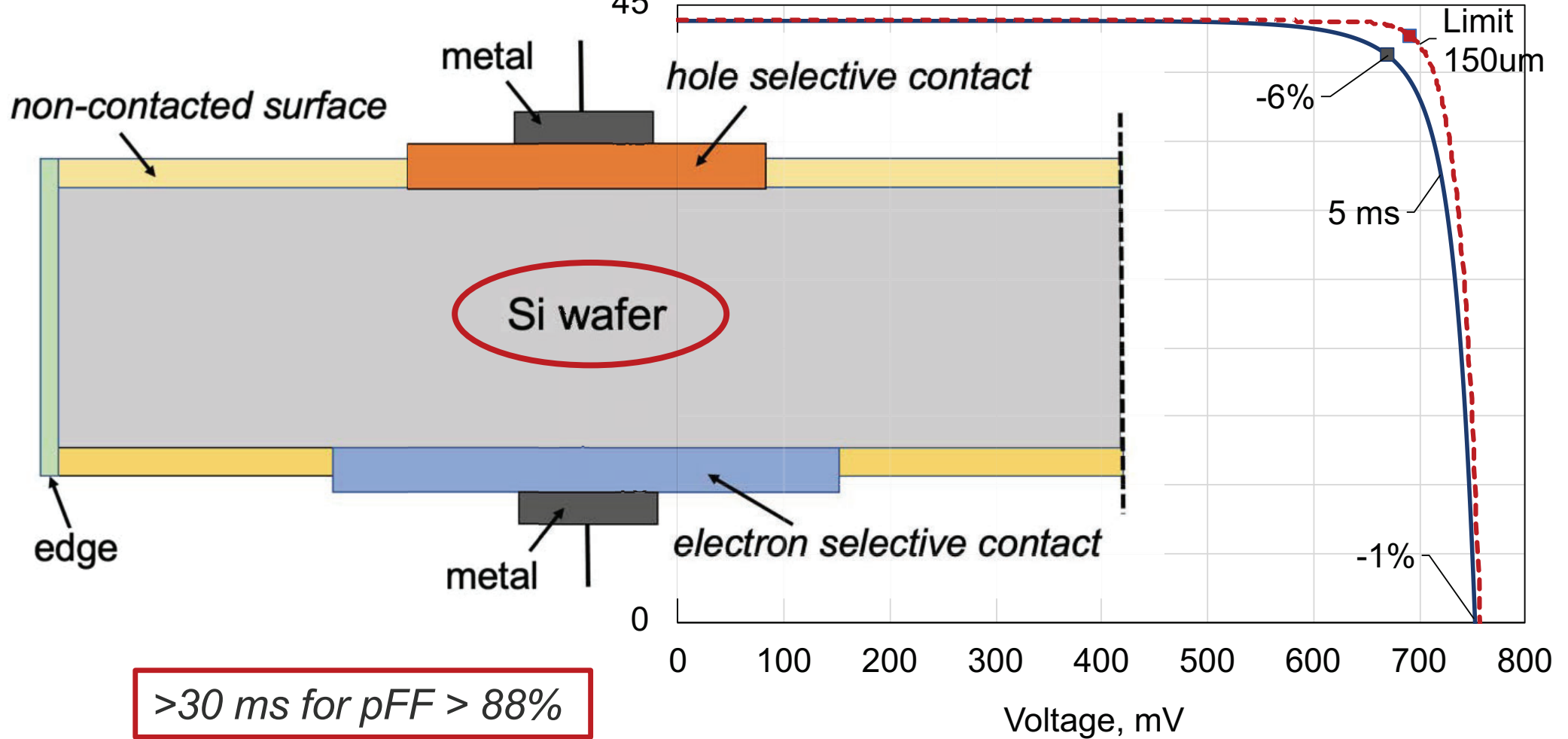
Efficiency limits



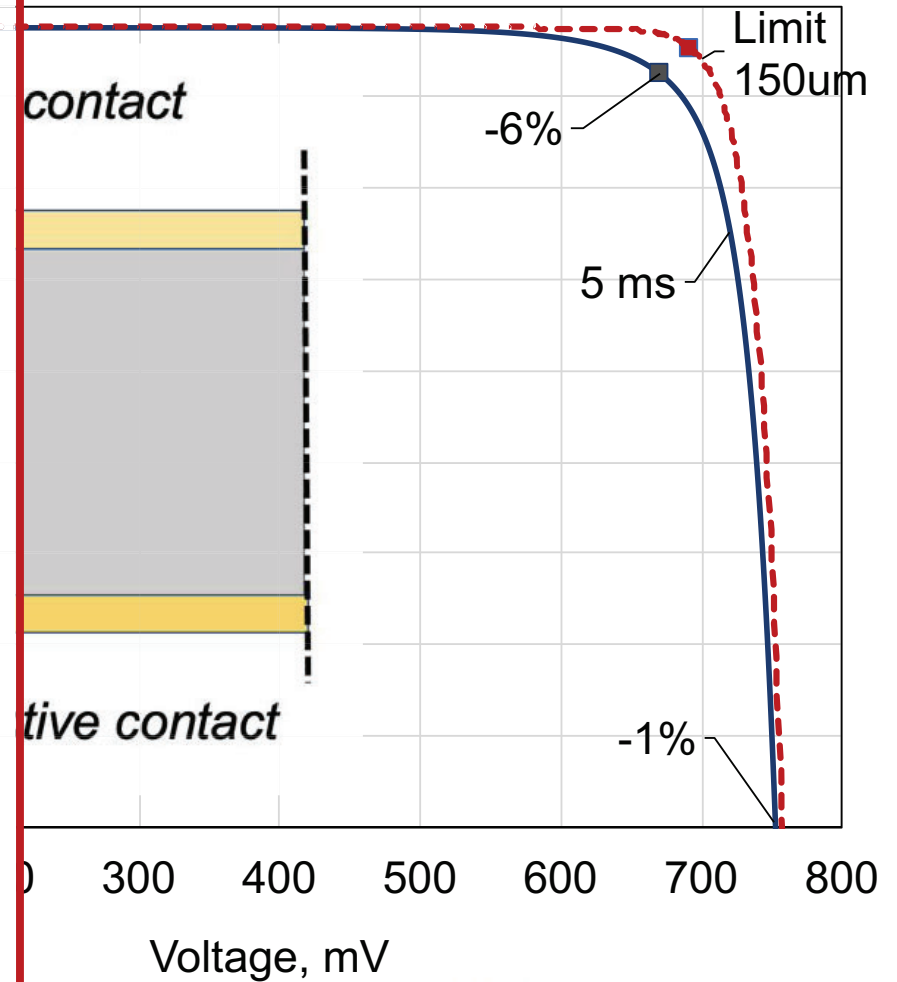
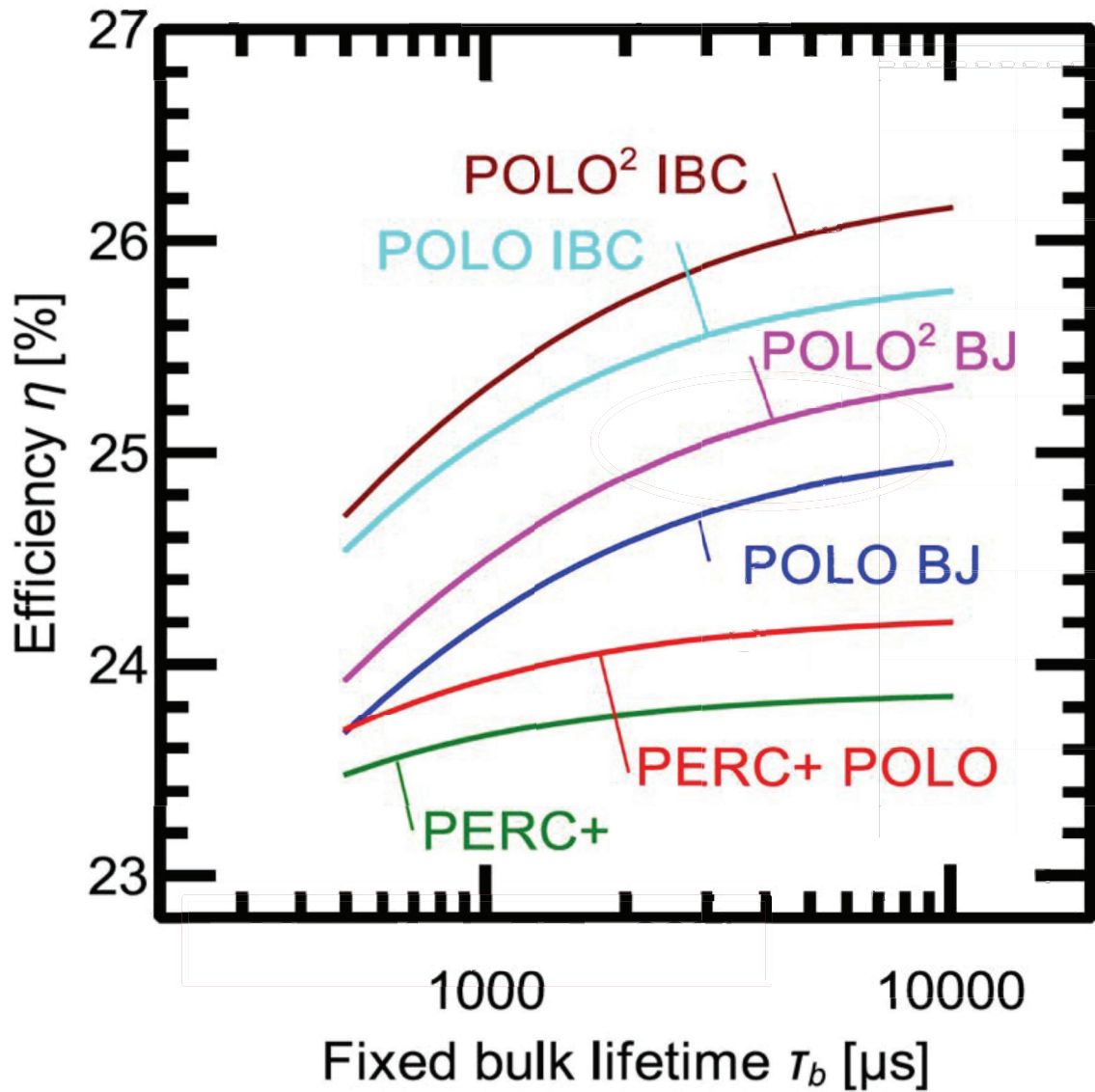
Green, IEEE ED-31, 684, 1984; Tiedje et al., ibid., 711.

Efficiency limits – wafer quality?

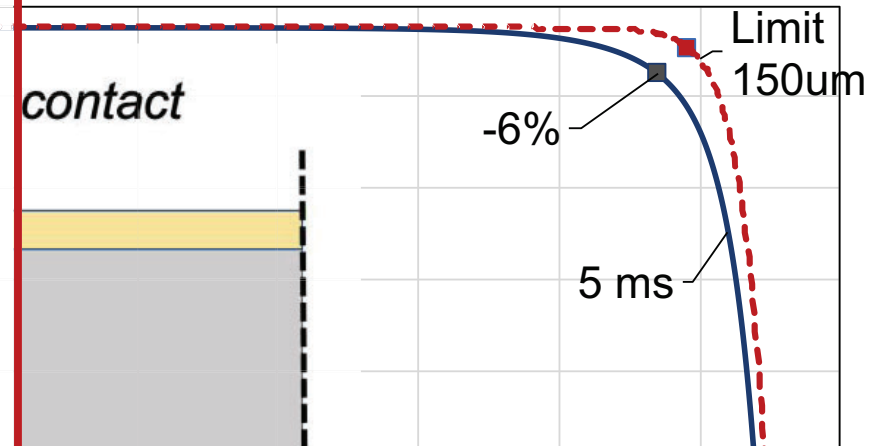
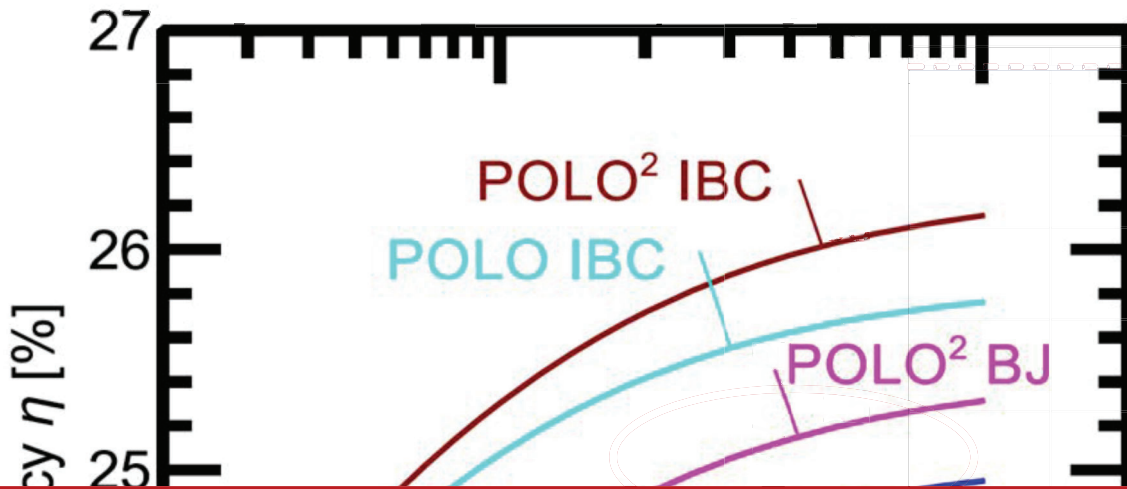
45



Green, IEEE ED-31, 684, 1984; Tiedje et al., ibid., 711.



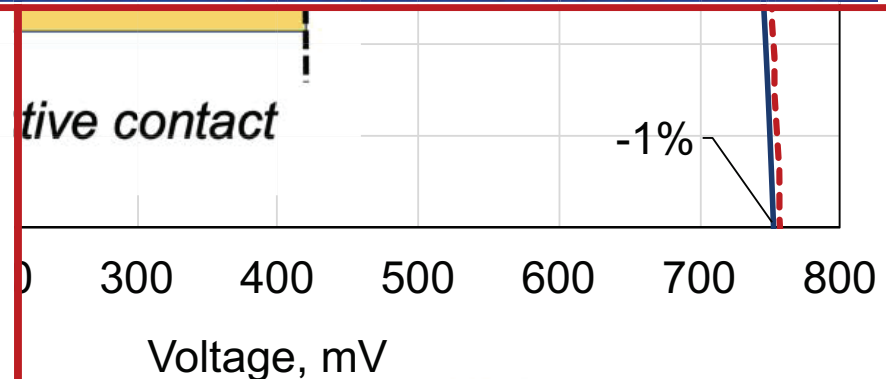
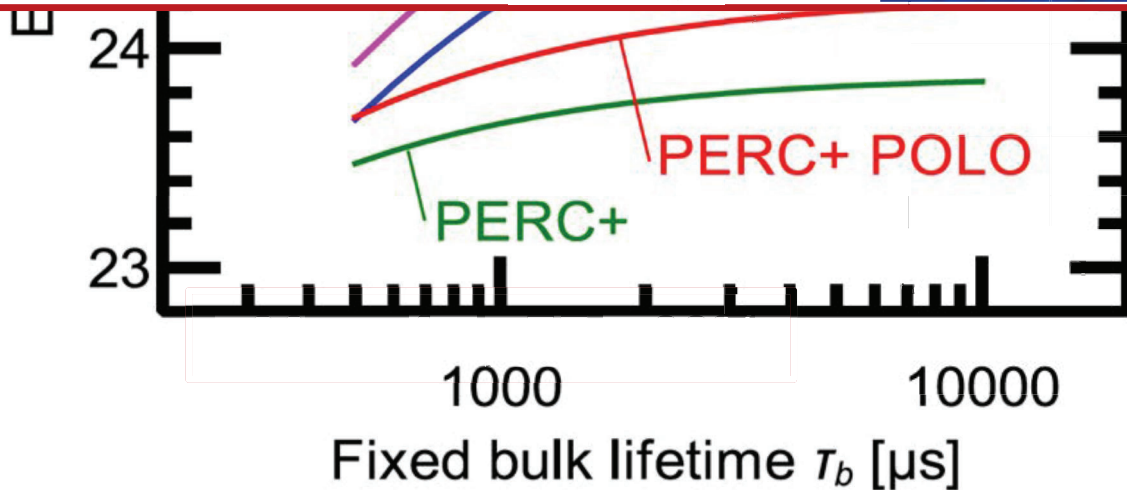
Kruse et al. (ISFH) | Scientific Reports | (2021) 11:996



■ Mass production efficiency is sensitive to wafer quality. N-type wafer spec should be controlled.

risen solar technology

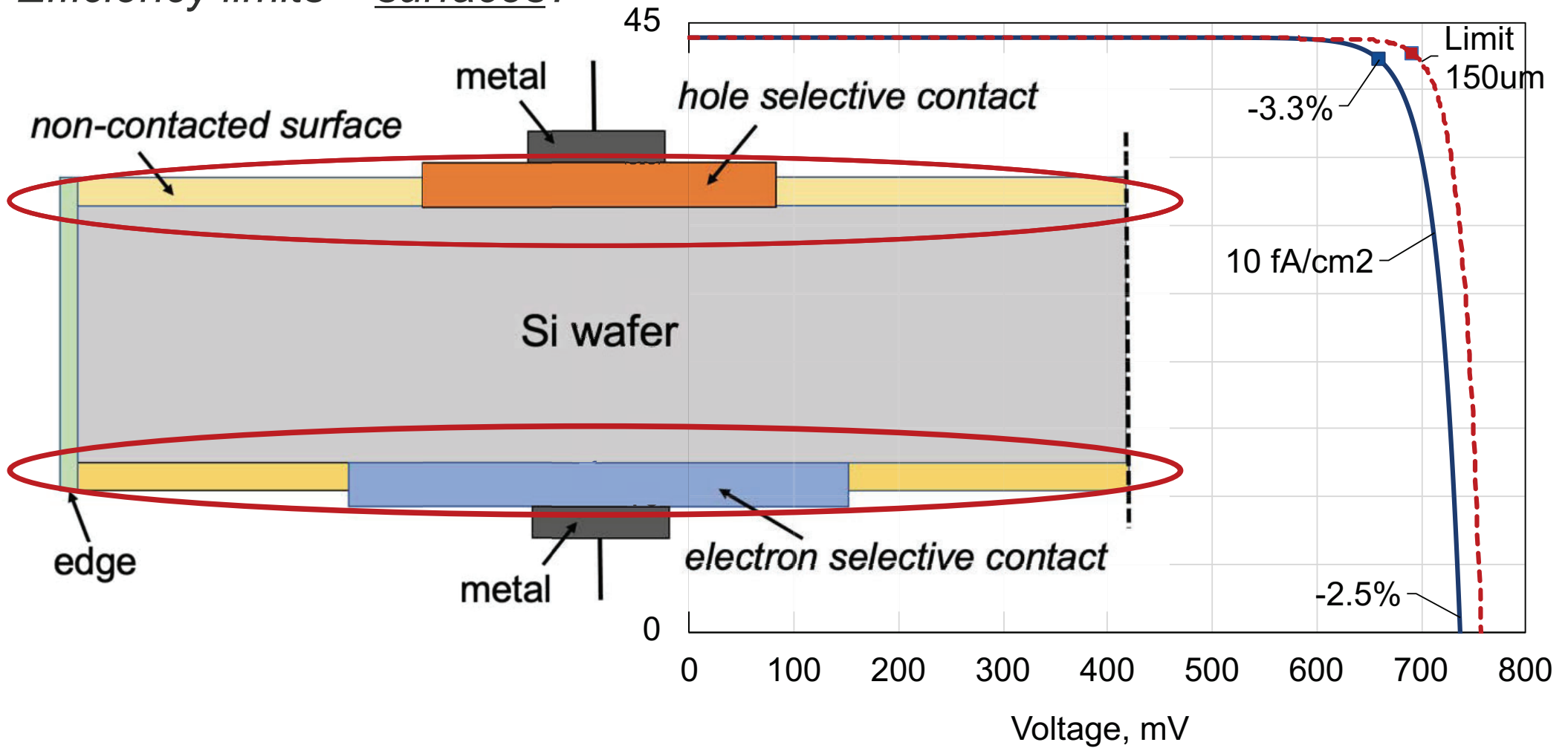
17 March 2021 | PV HeterojunctionTech Online



Kruse et al. (ISFH) | Scientific Reports | (2021) 11:996

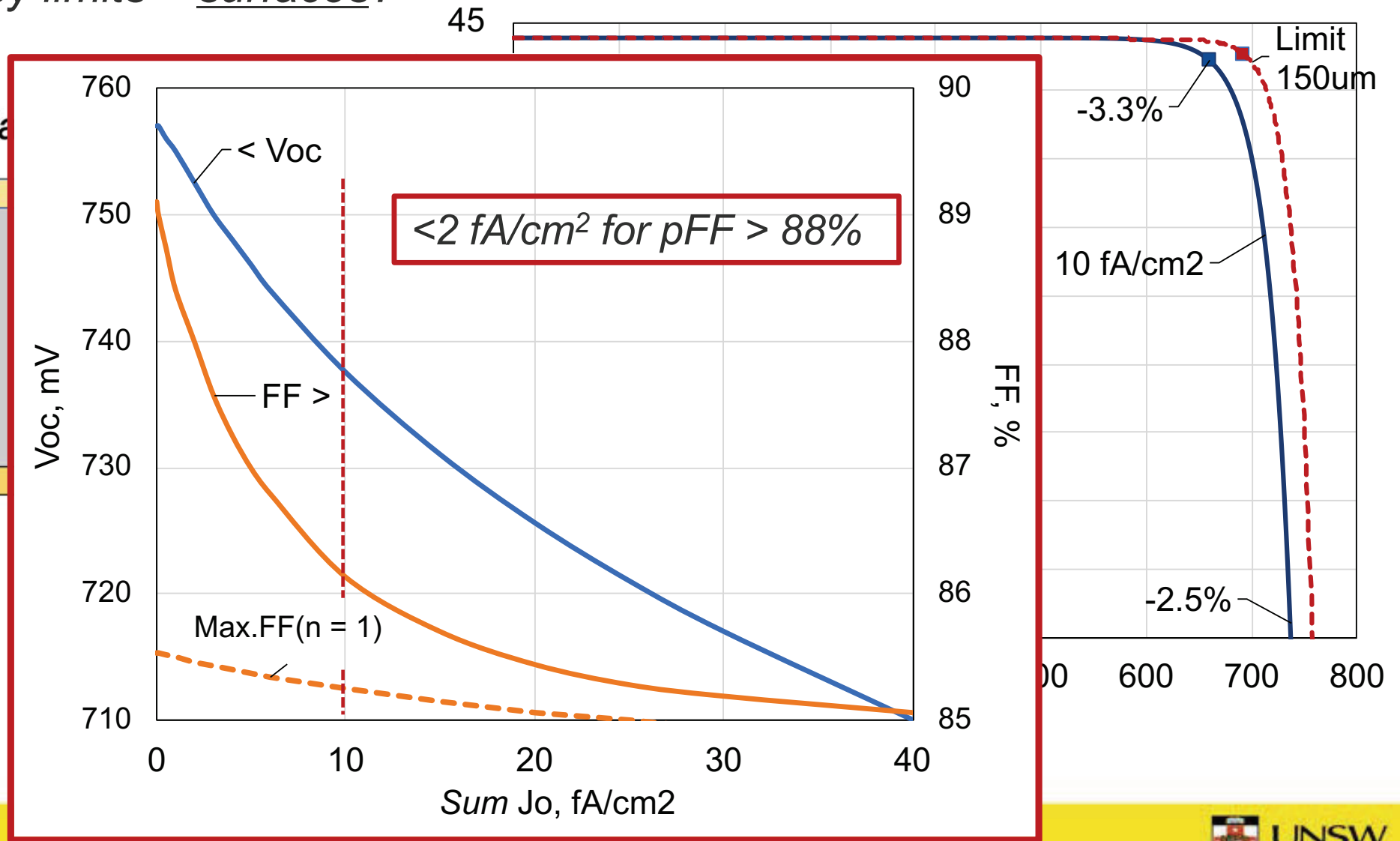
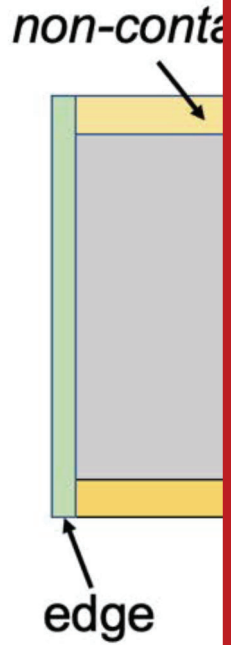


Efficiency limits – surfaces?

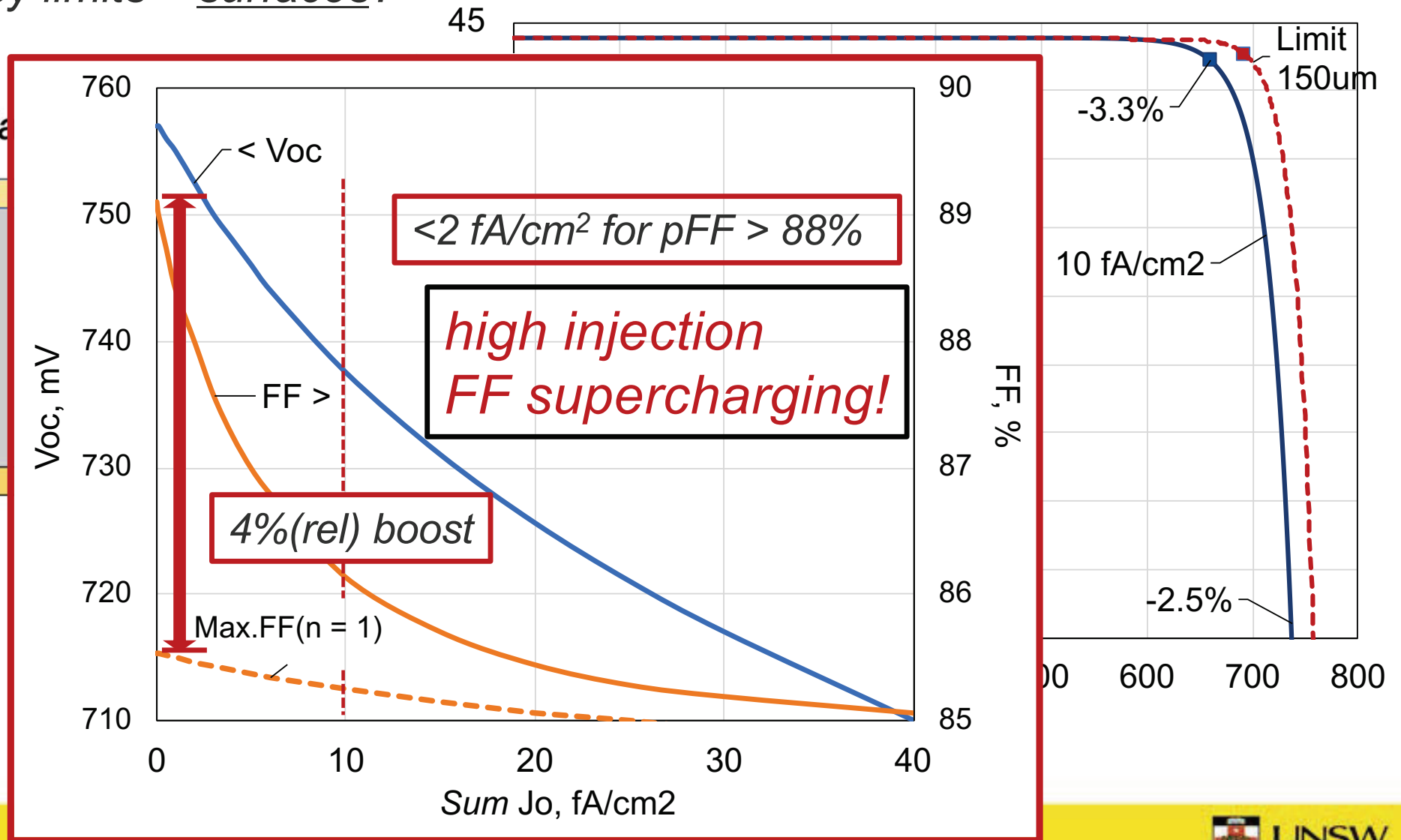
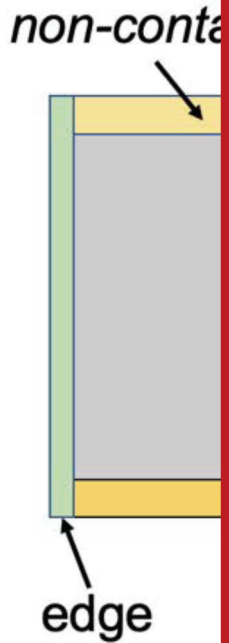


Green, IEEE ED-31, 684, 1984; Tiedje et al., *ibid.*, 711.

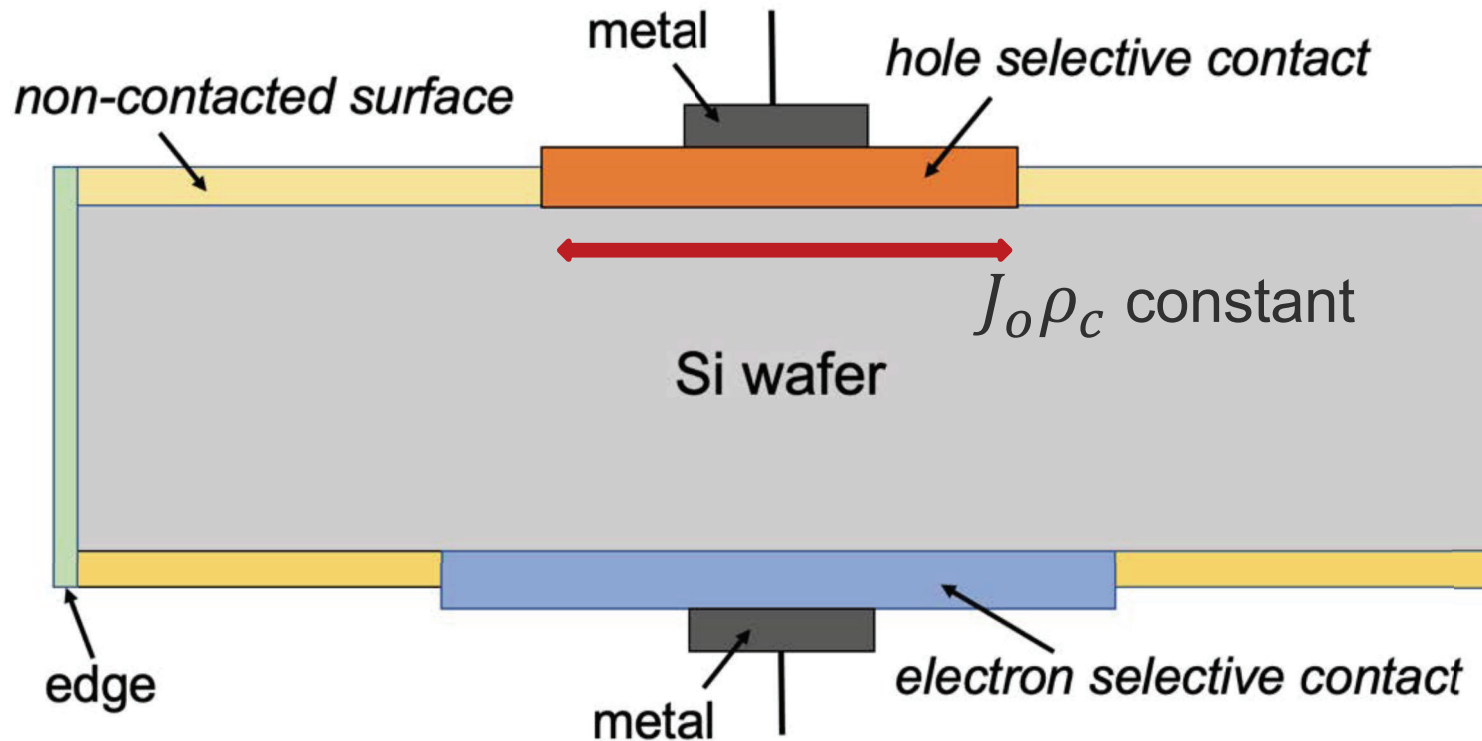
Efficiency limits – surfaces?



Efficiency limits – surfaces?



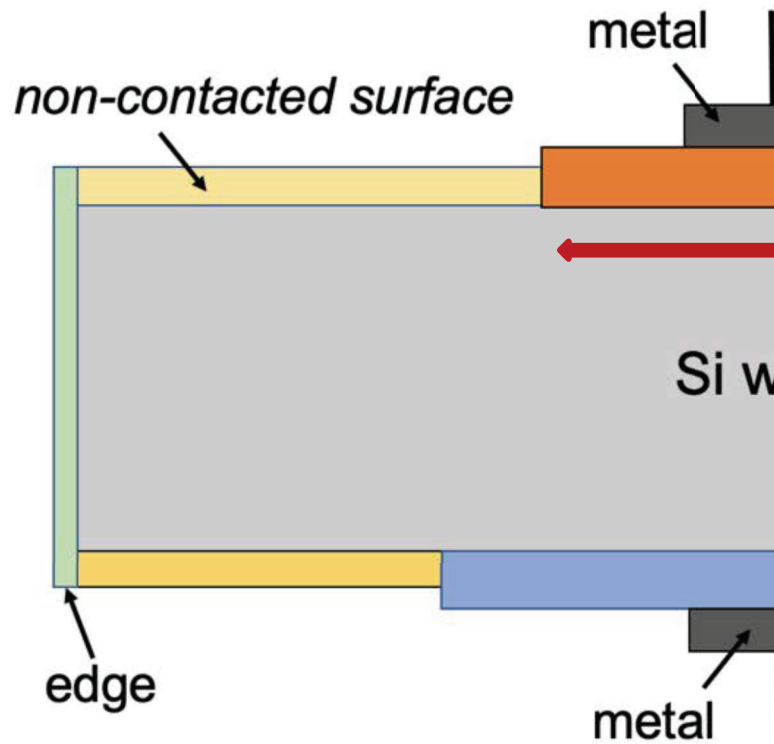
Contact selectivity S_{10}



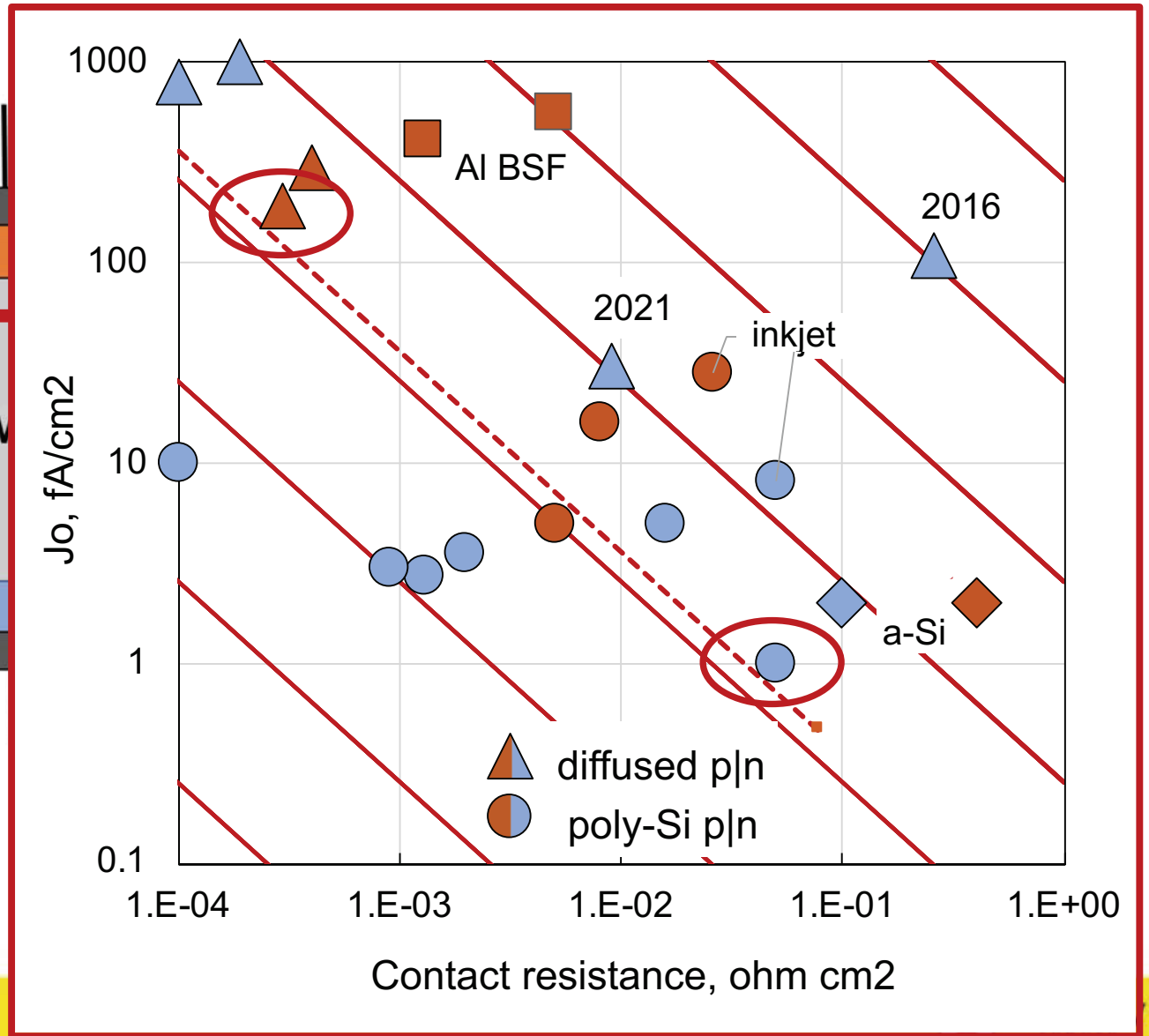
$$S_{10} = \log\left[\frac{V_{th}}{J_0\rho_c}\right]$$

$$\left(= \log\left[\frac{\text{minority carrier incremental } R}{\text{majority carrier incremental } R}\right]\Big|_{V=0}\right)$$

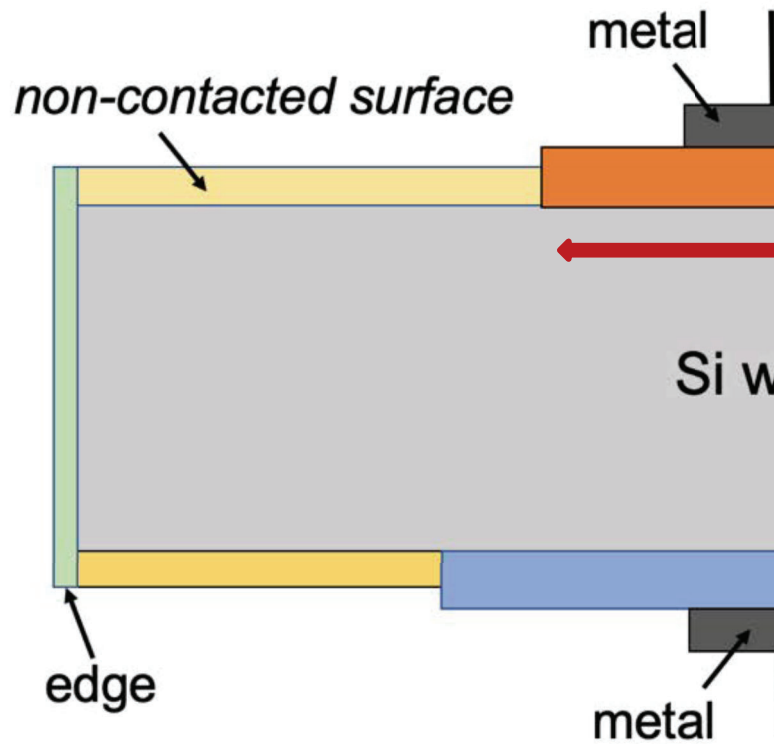
Contact selectivity S_{10}



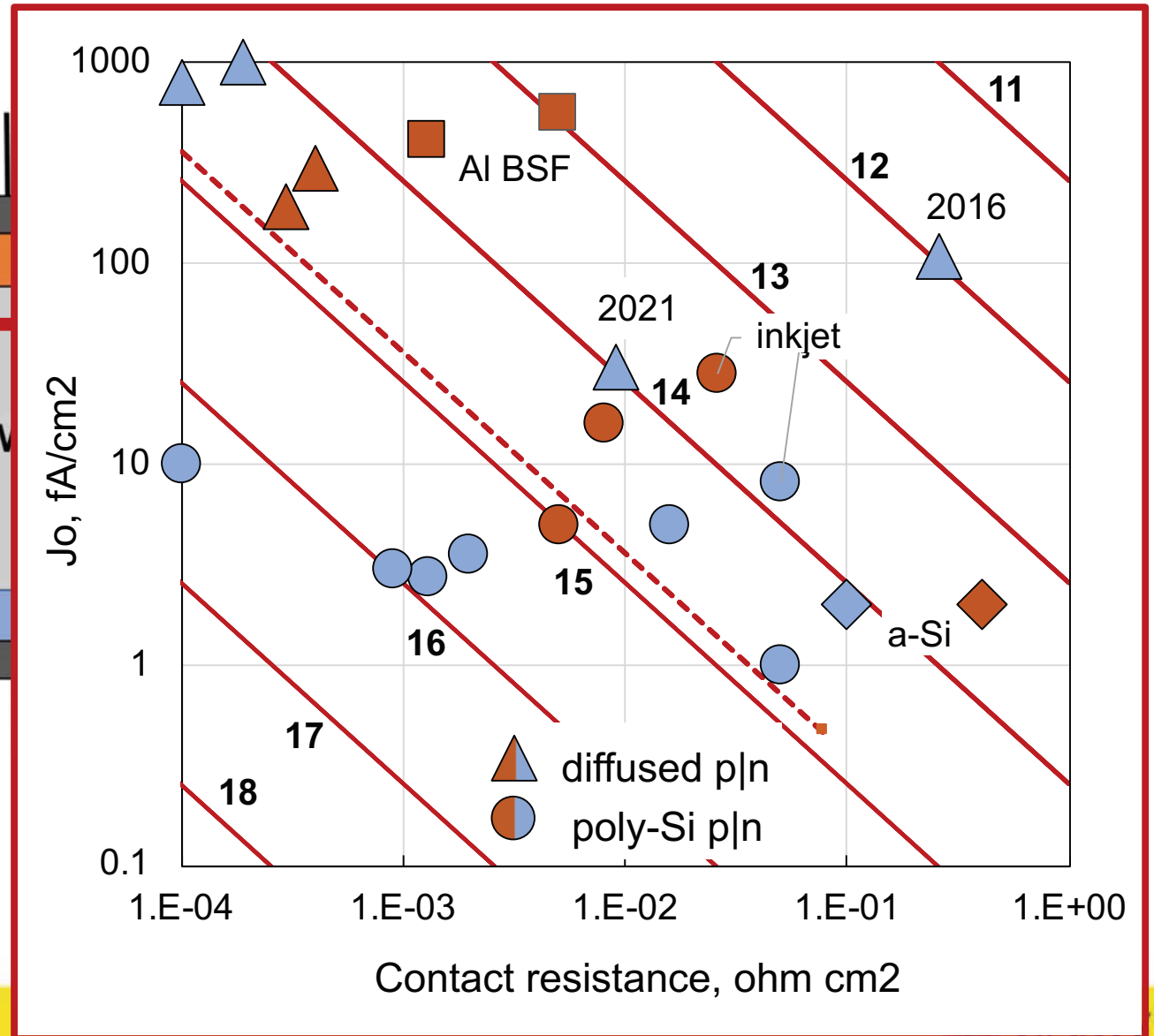
$$S_{10} = \log\left[\frac{V_{th}}{J_0 \rho_c}\right]$$



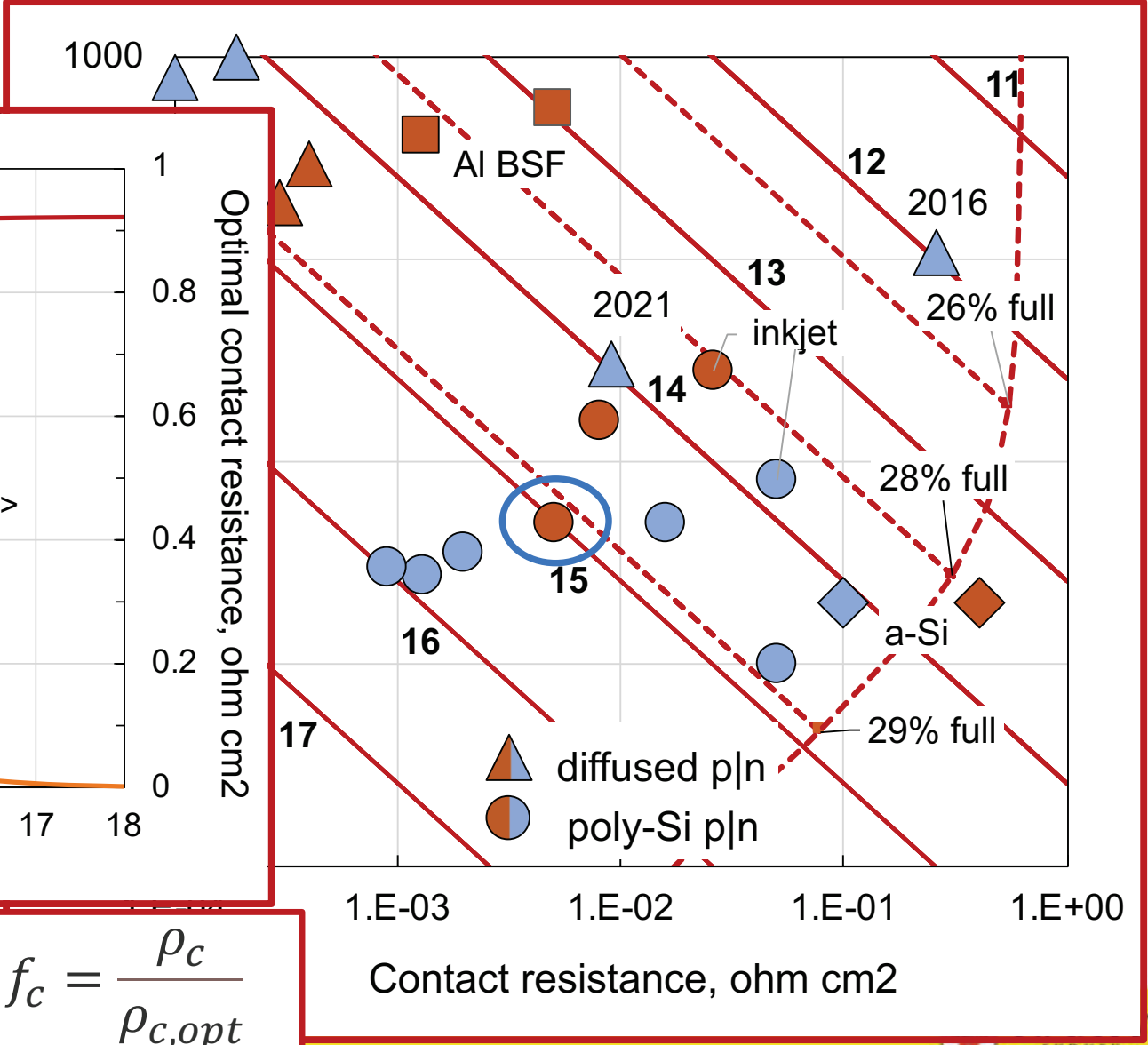
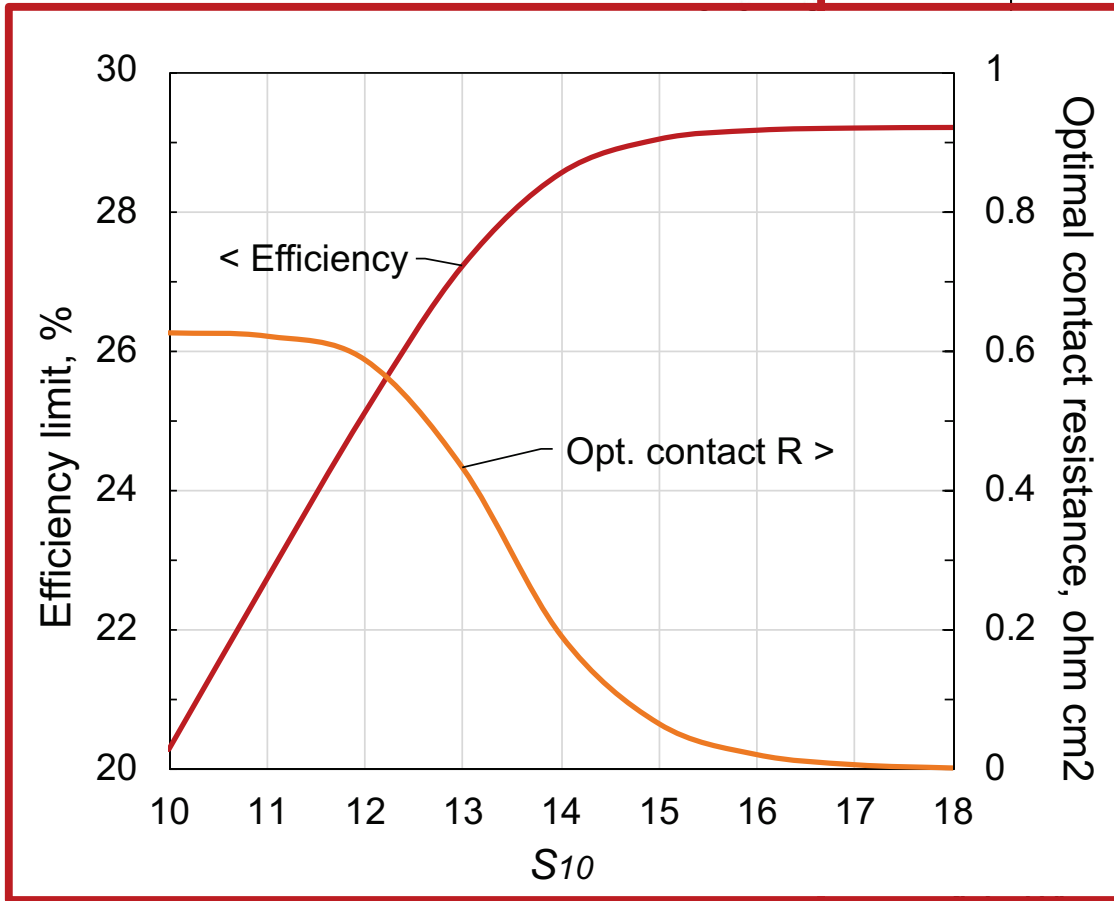
Contact selectivity S_{10}



$$S_{10} = \log\left[\frac{V_{th}}{J_0 \rho_c}\right]$$



Contact selectivity S_{10}

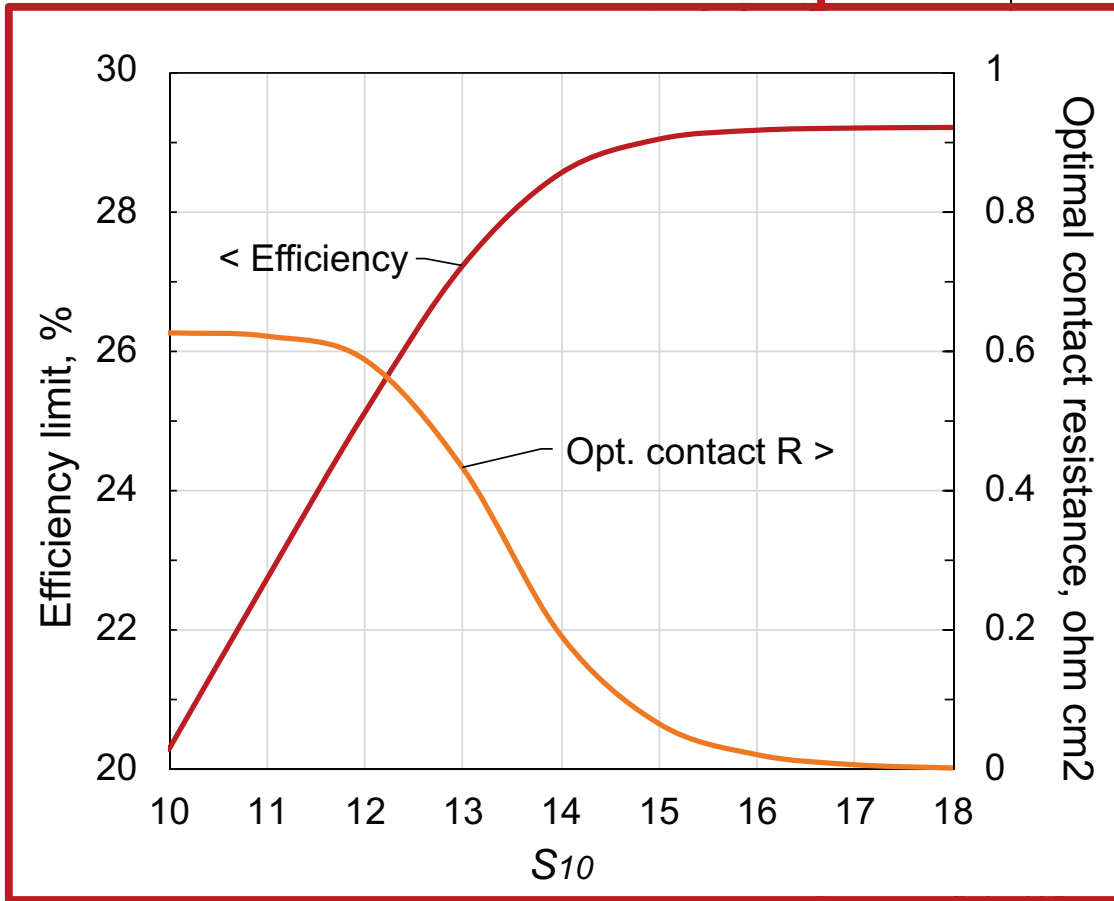


$$f_c = \frac{\rho_c}{\rho_{c,opt}}$$

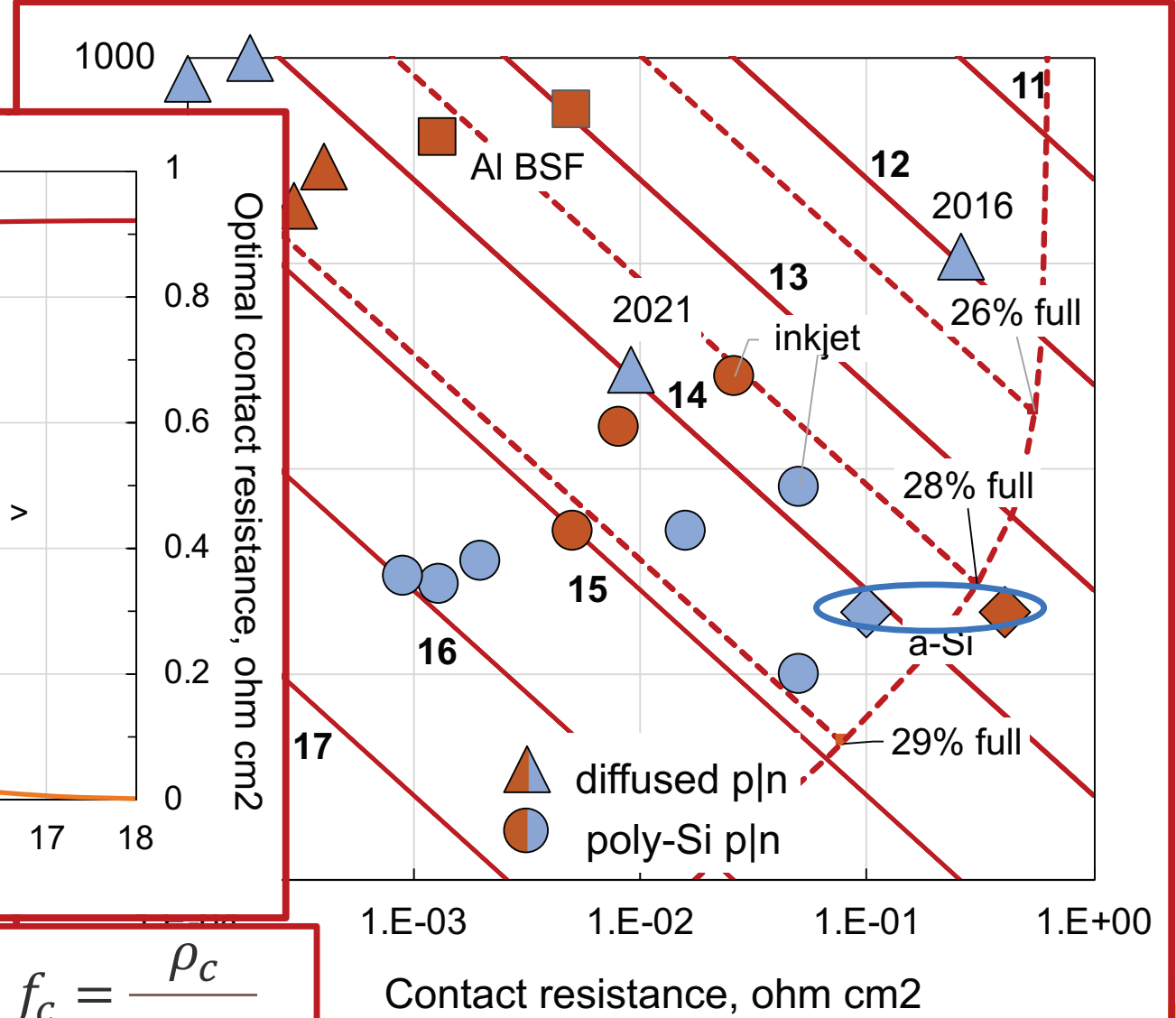
Brendel et al., 32nd EUPVSEC, 2016



Contact selectivity S_{10}



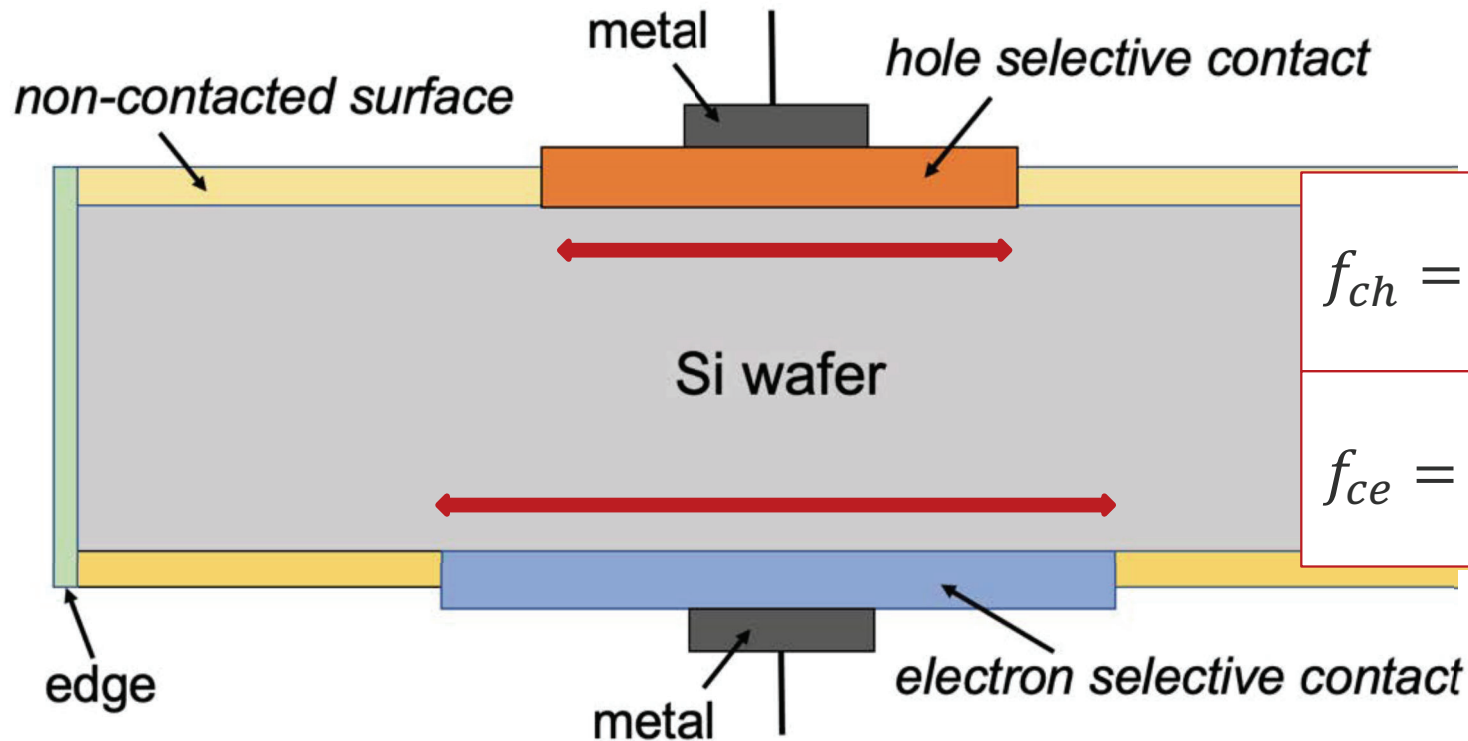
$$f_c = \frac{\rho_c}{\rho_{c,opt}}$$



Brendel et al., 32nd EUPVSEC, 2016



Electron & hole selectivity, S_{10e} & S_{10h}

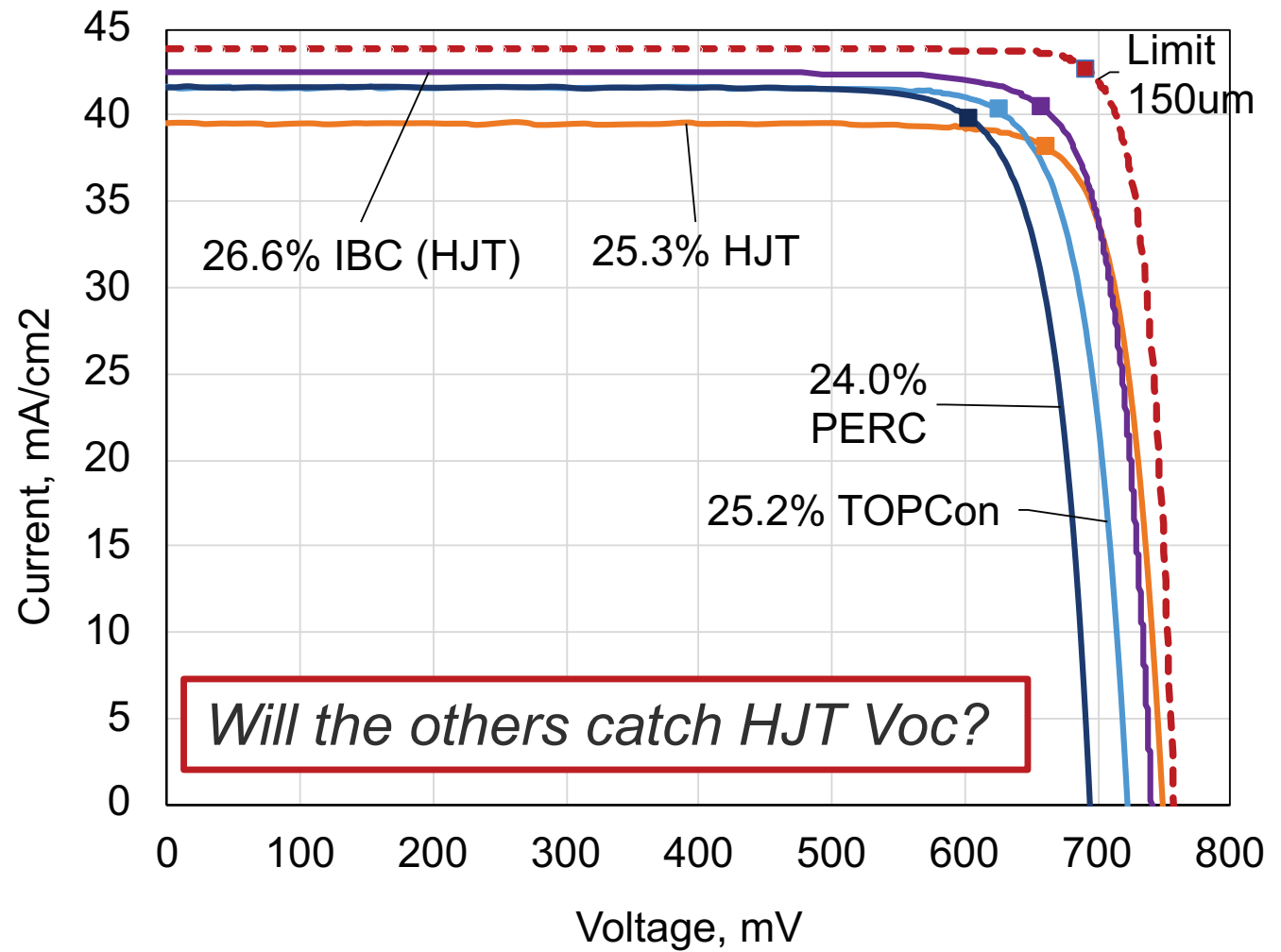
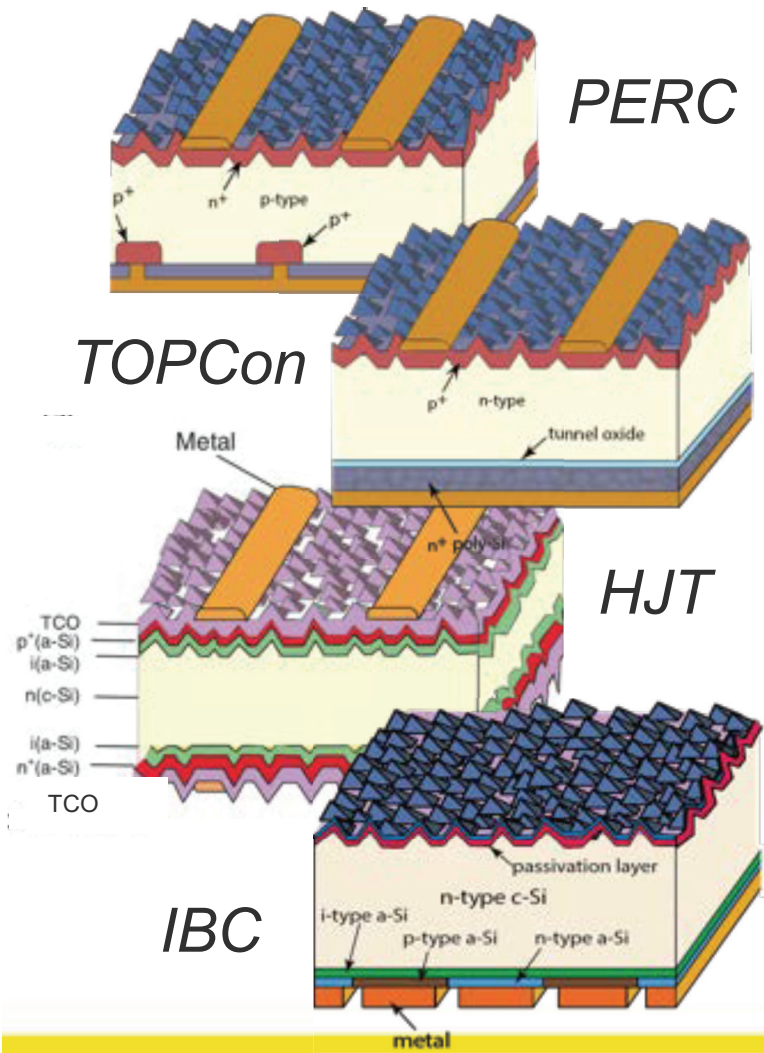


$$f_{ch} = \frac{\rho_{ch} [1 + 10^{(S_{10h} - S_{10e})/2}]}{\rho_{c,opt}}$$

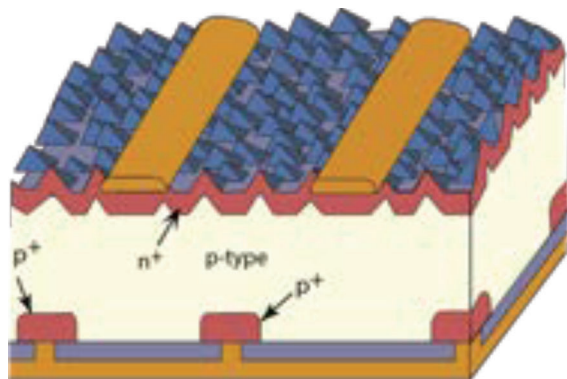
$$f_{ce} = \frac{\rho_{ce} [1 + 10^{(S_{10e} - S_{10h})/2}]}{\rho_{c,opt}}$$

$$S_{10t} = \log \left[\frac{V_{th}}{\{\sqrt{J_{oe}\rho_{ce}} + \sqrt{J_{oh}\rho_{ch}}\}^2} \right] > (S_{10min} - 10^{-(S_{10max} - S_{10min})/2})$$

The contenders

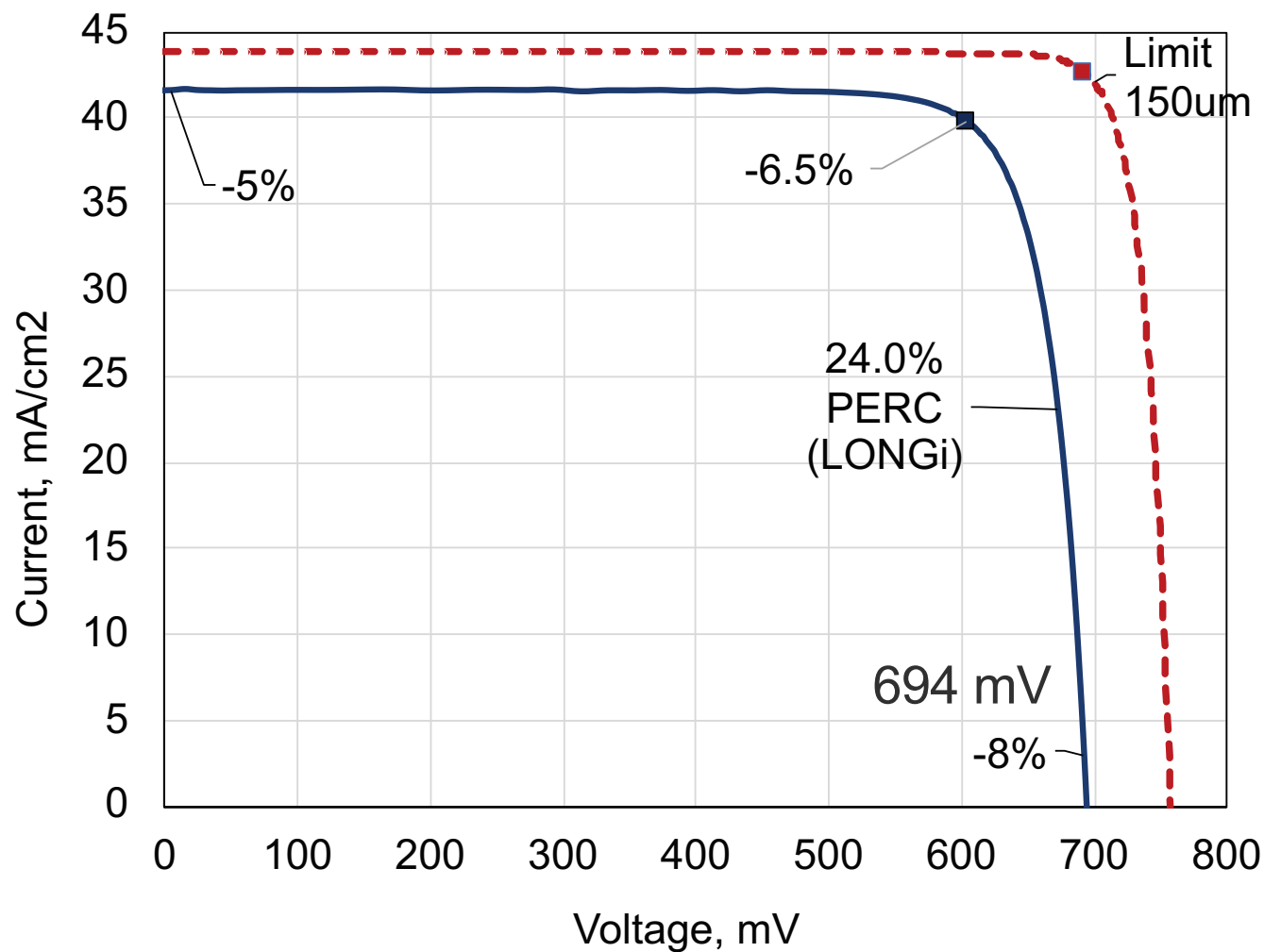


The contenders

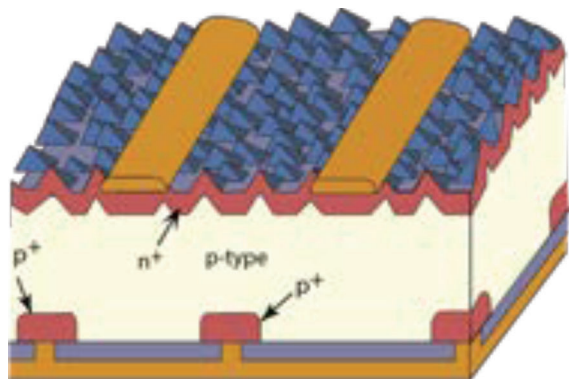


PERC

*Run out of puff?
-OR-
Just getting started?*

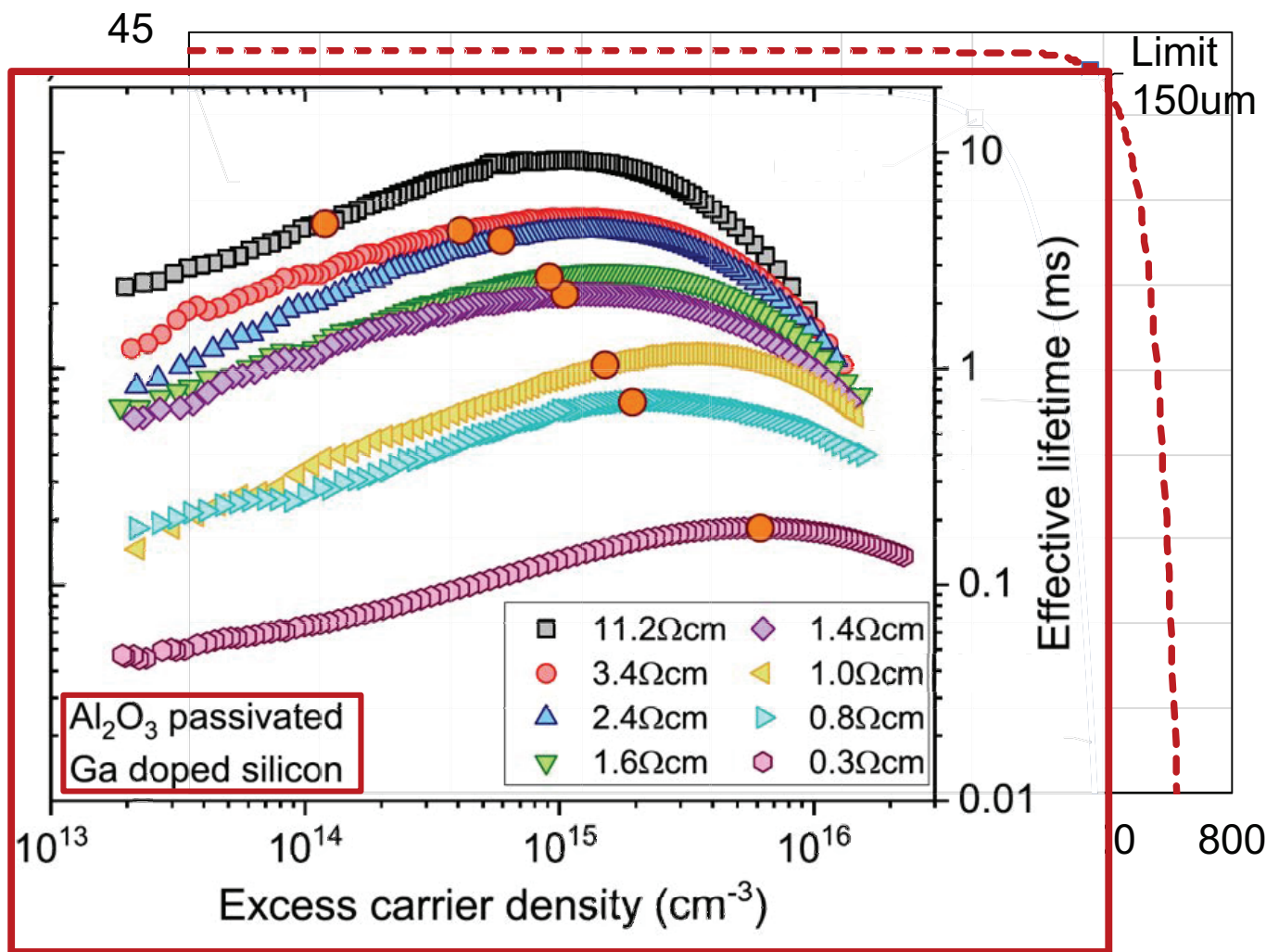


The contenders

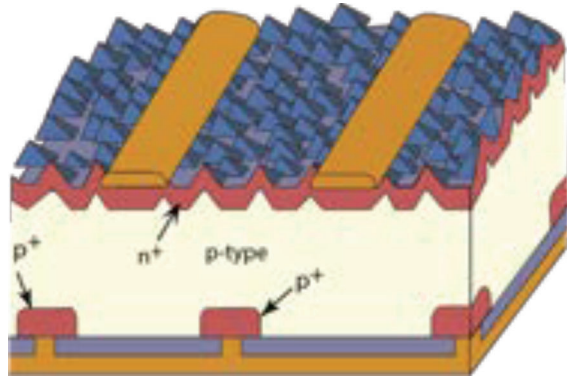


PERC

*Ga doping
- level footing n-type?*

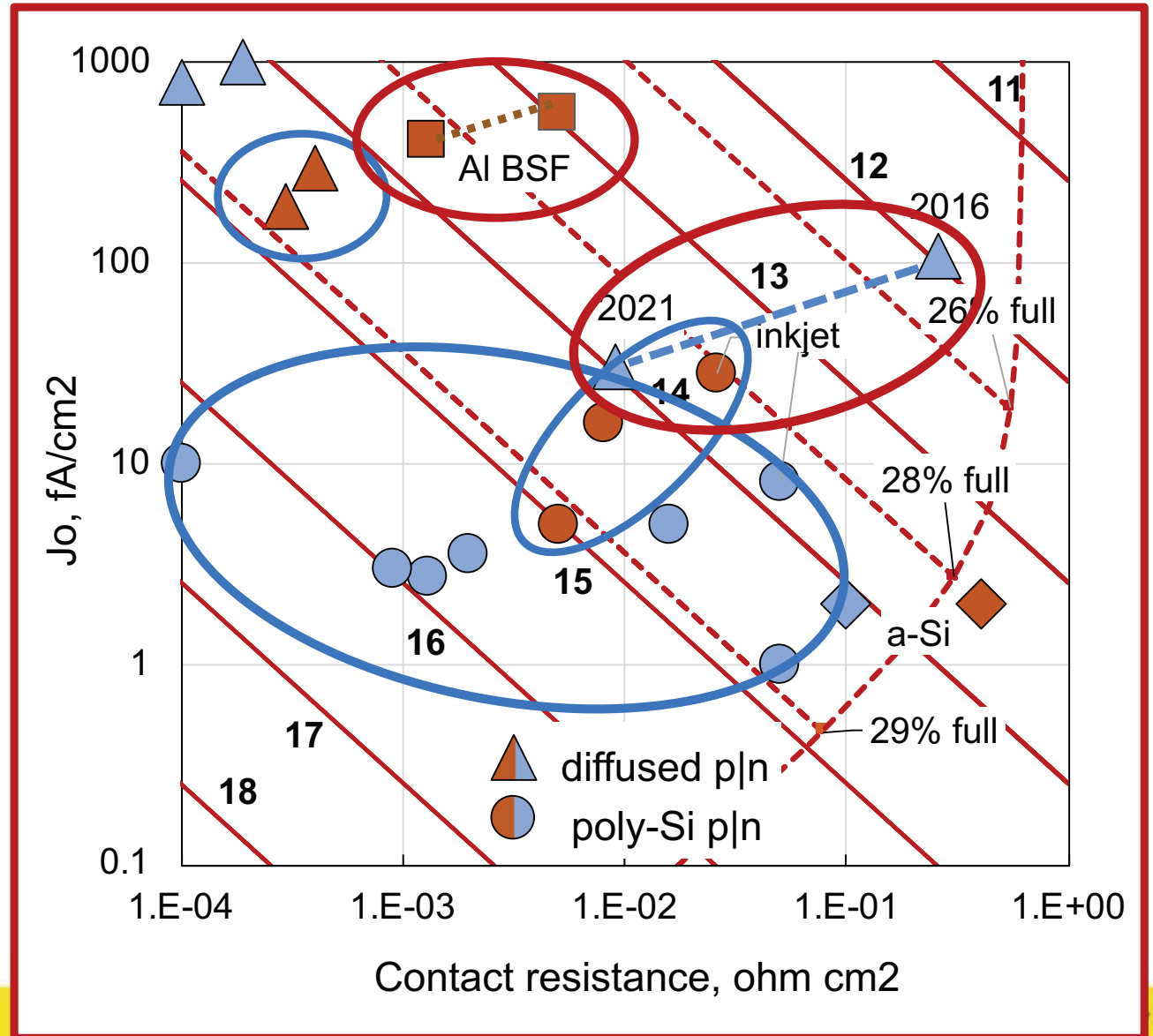


The contenders

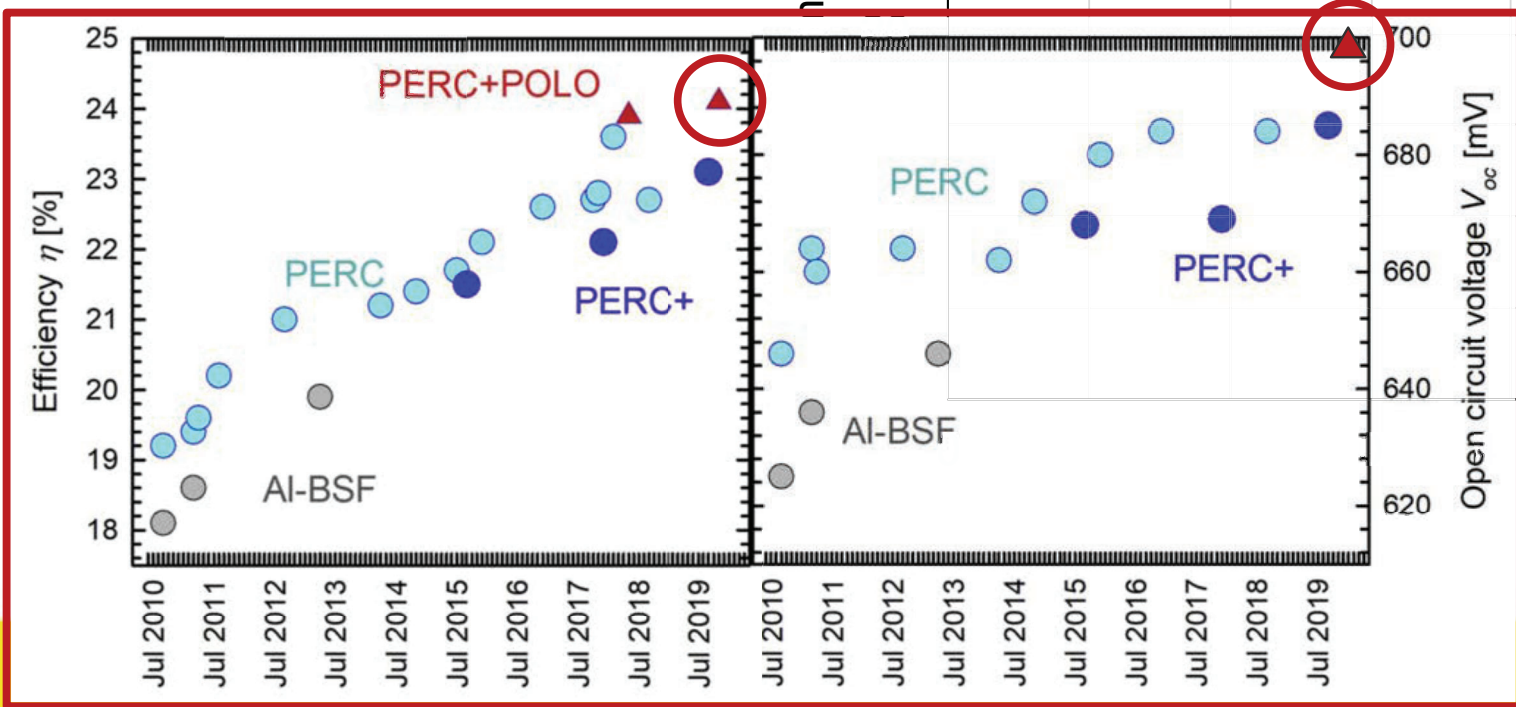
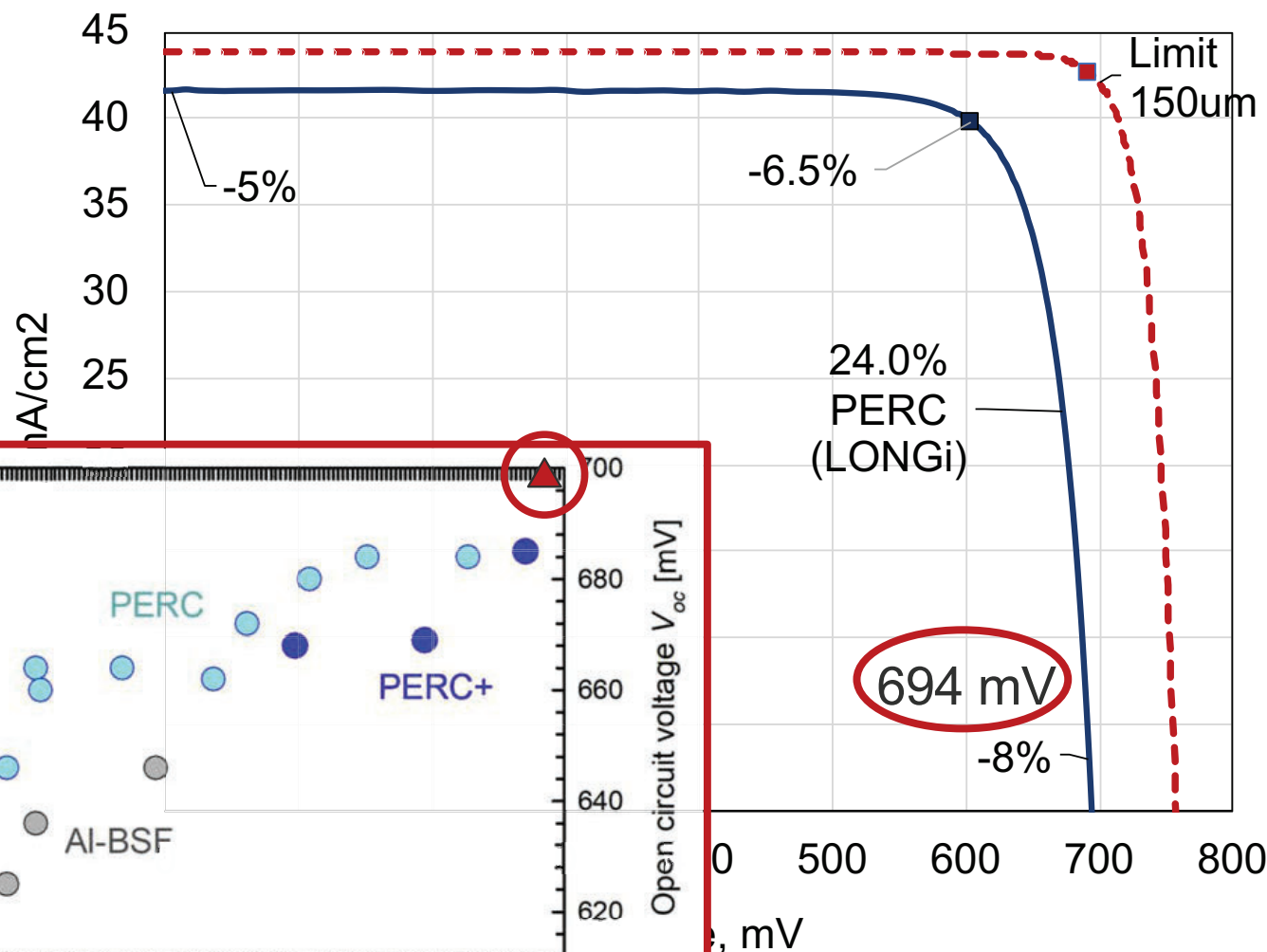
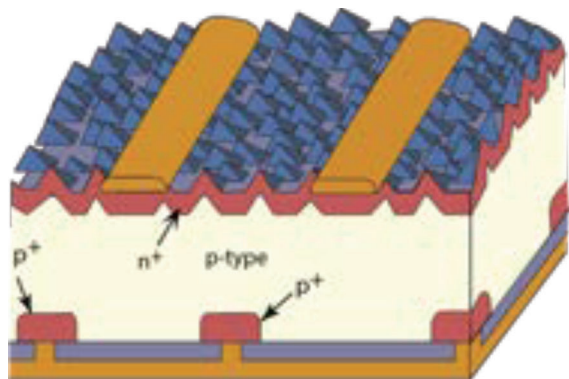


PERC

Alternative contacting?



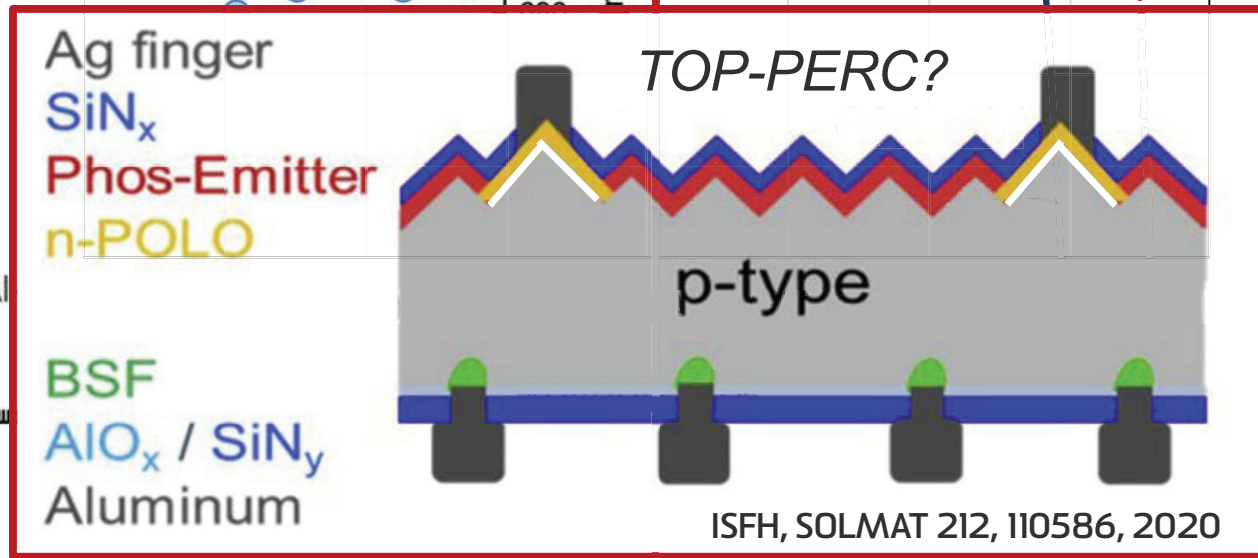
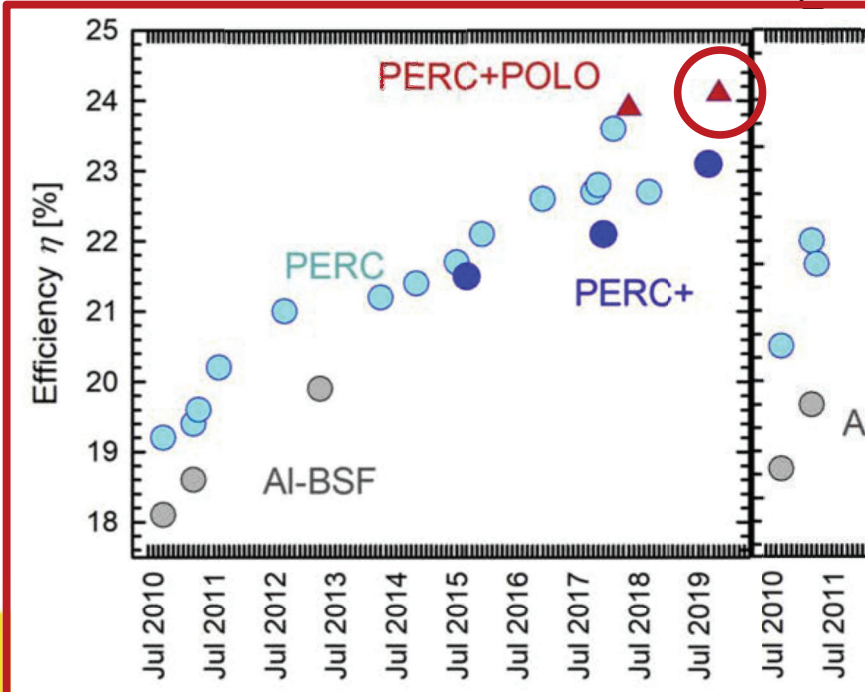
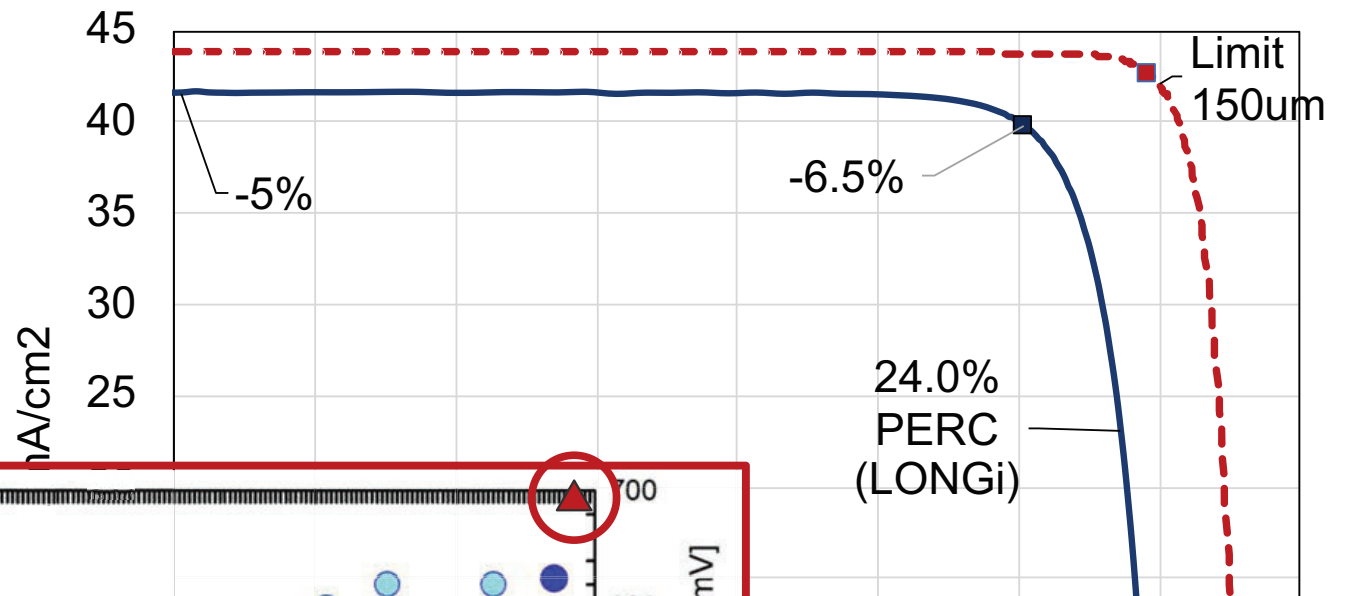
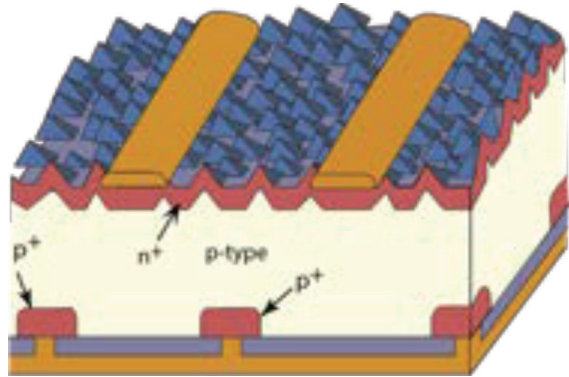
The contenders



ISFH, SOLMAT 212, 110586, 2020

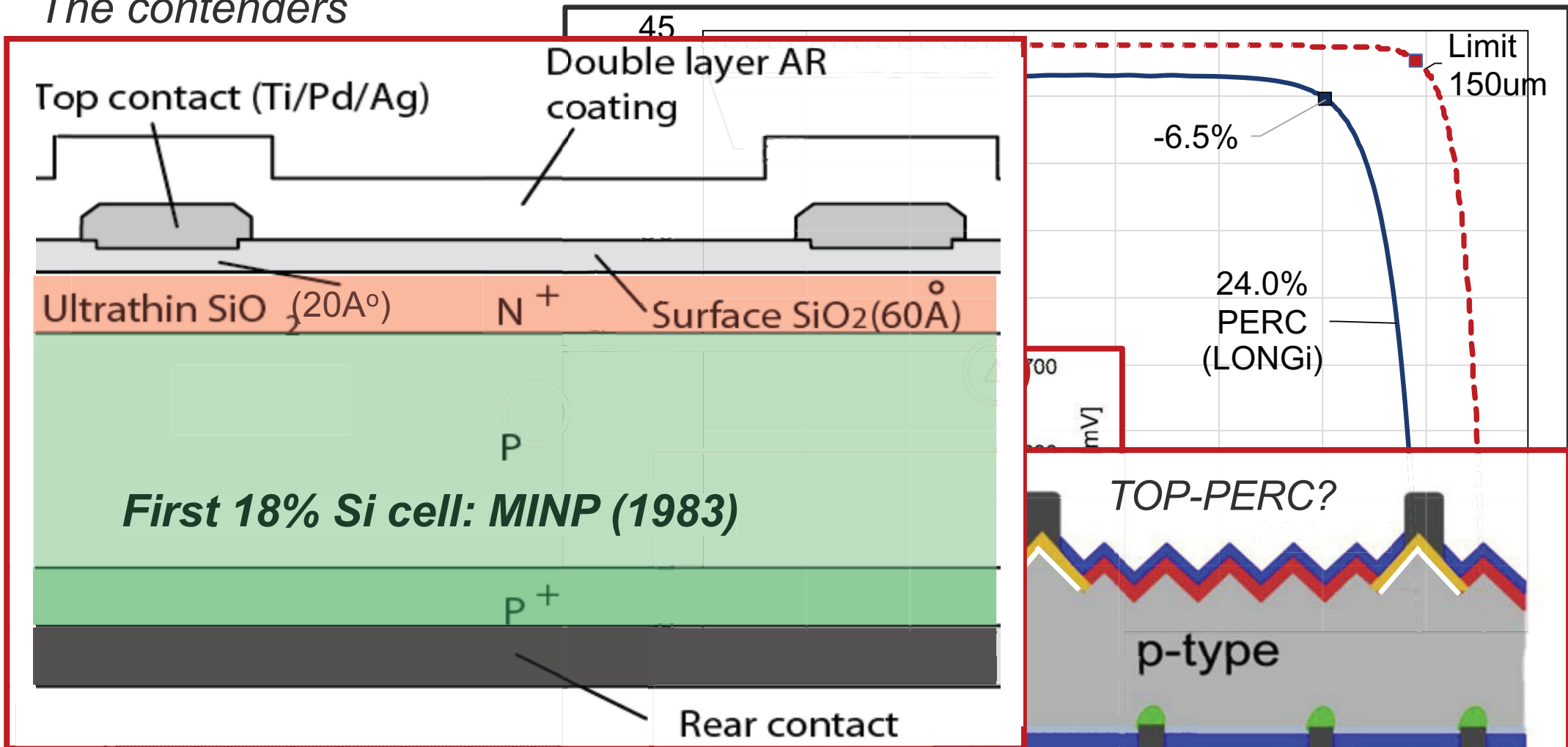


The contenders



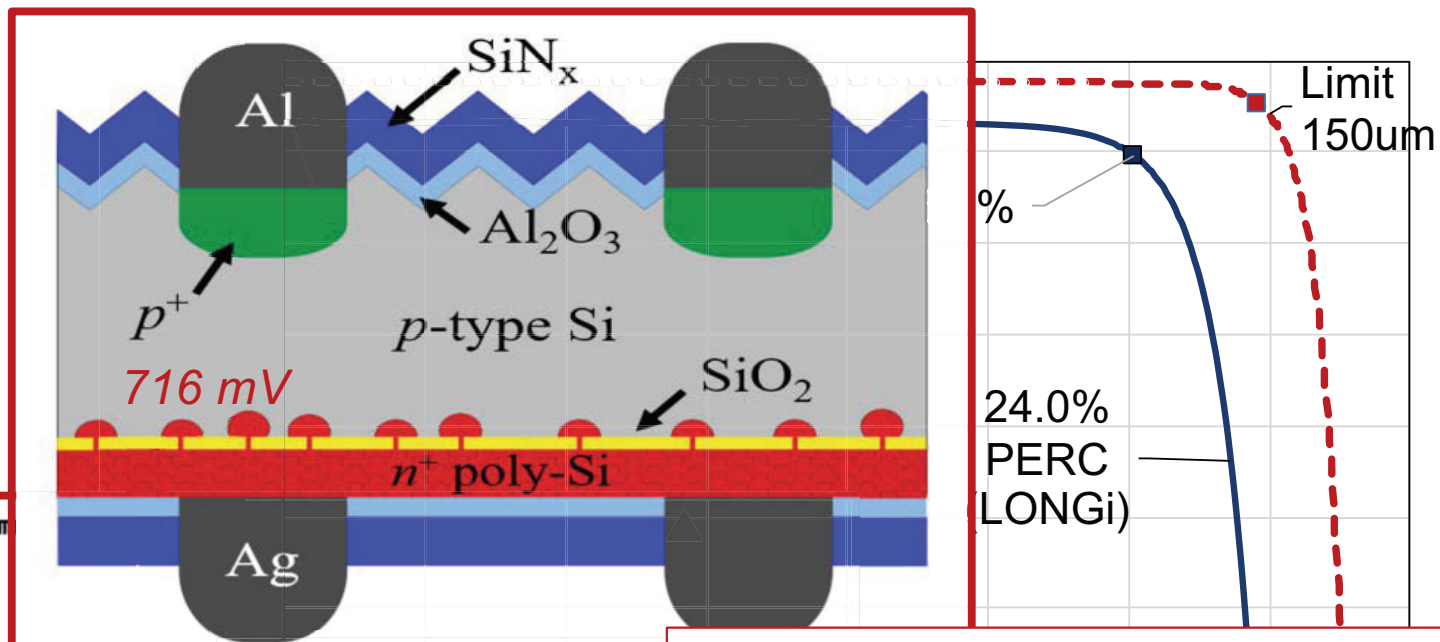
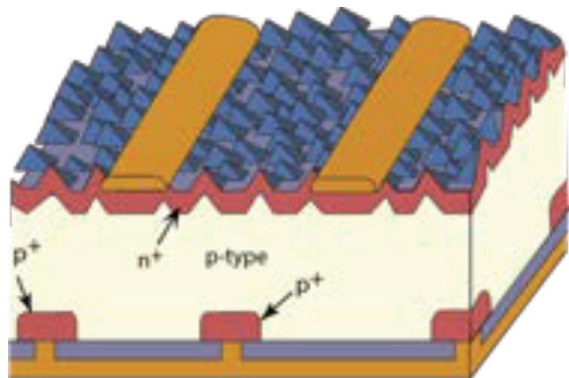
ISFH, SOLMAT 212, 110586, 2020

The contenders

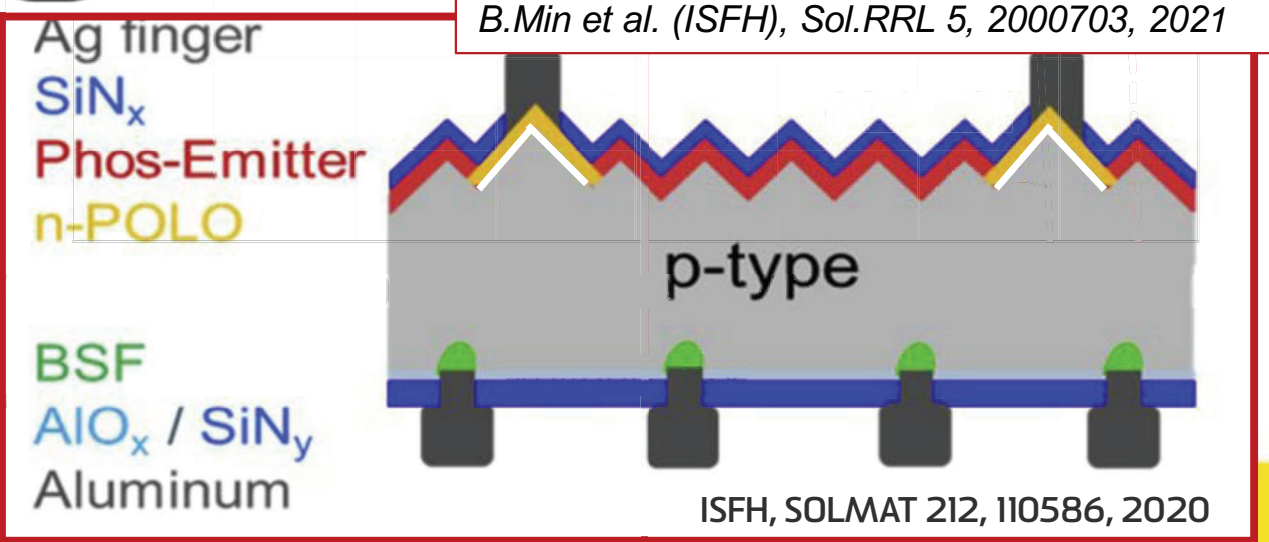
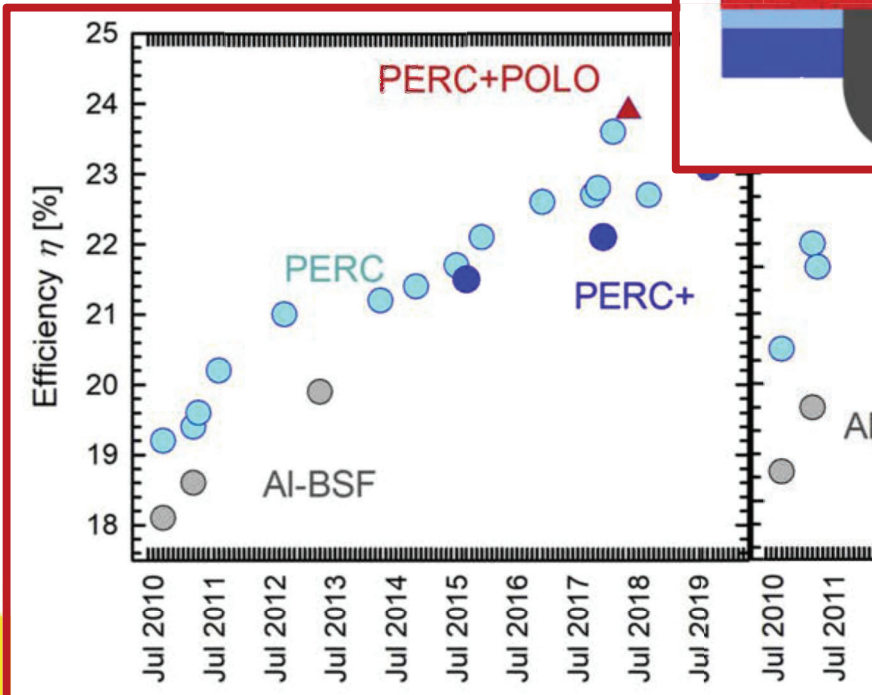


Poly-Si did not start with SIPOS (1984) but to make MIS contacts screen-printing compatible (1981) Green & Blakers, Solar Cells 8, 3 (1983); Green, "High Efficiency Si Solar Cells", TransTech, 1986.

The contenders

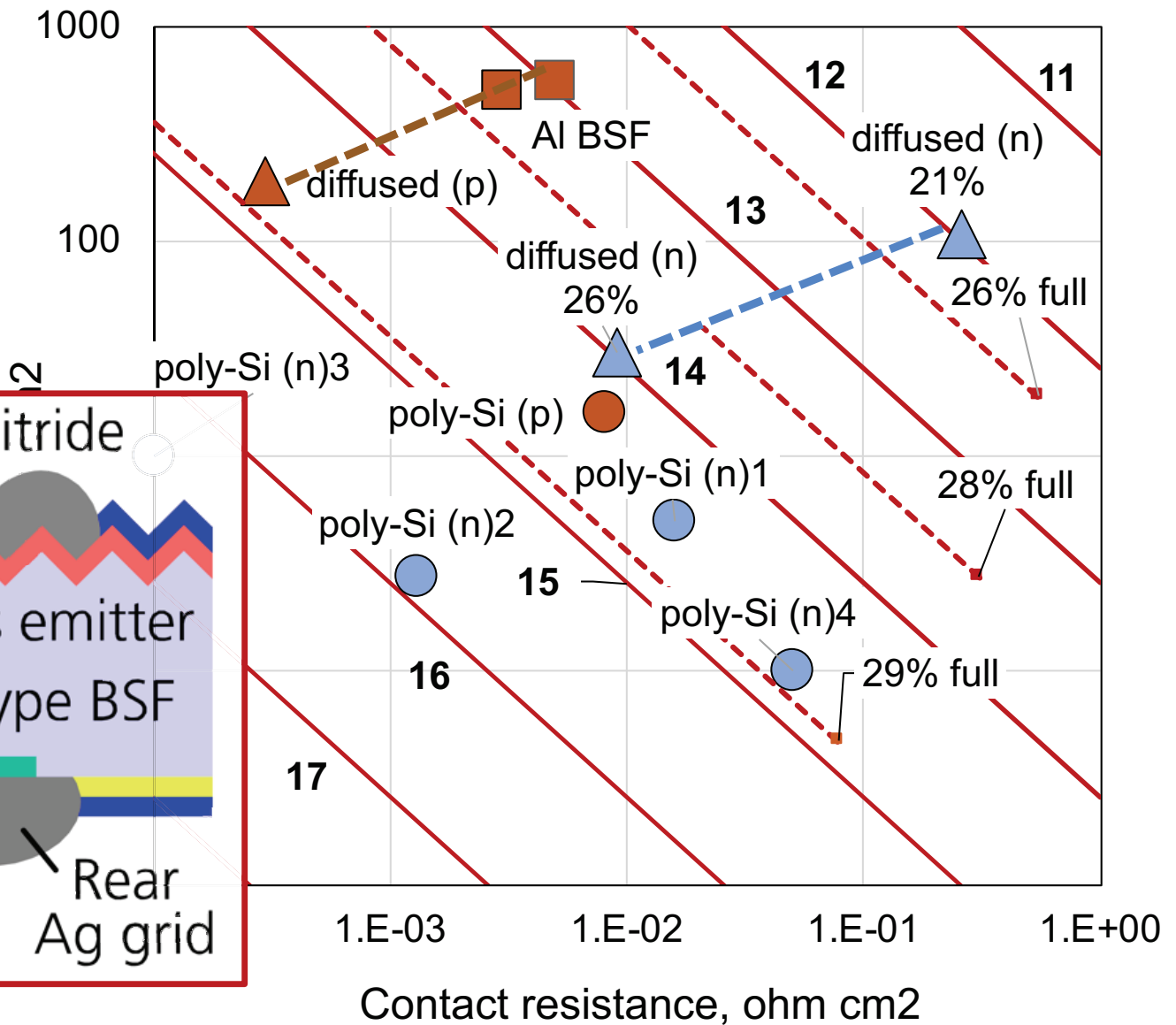
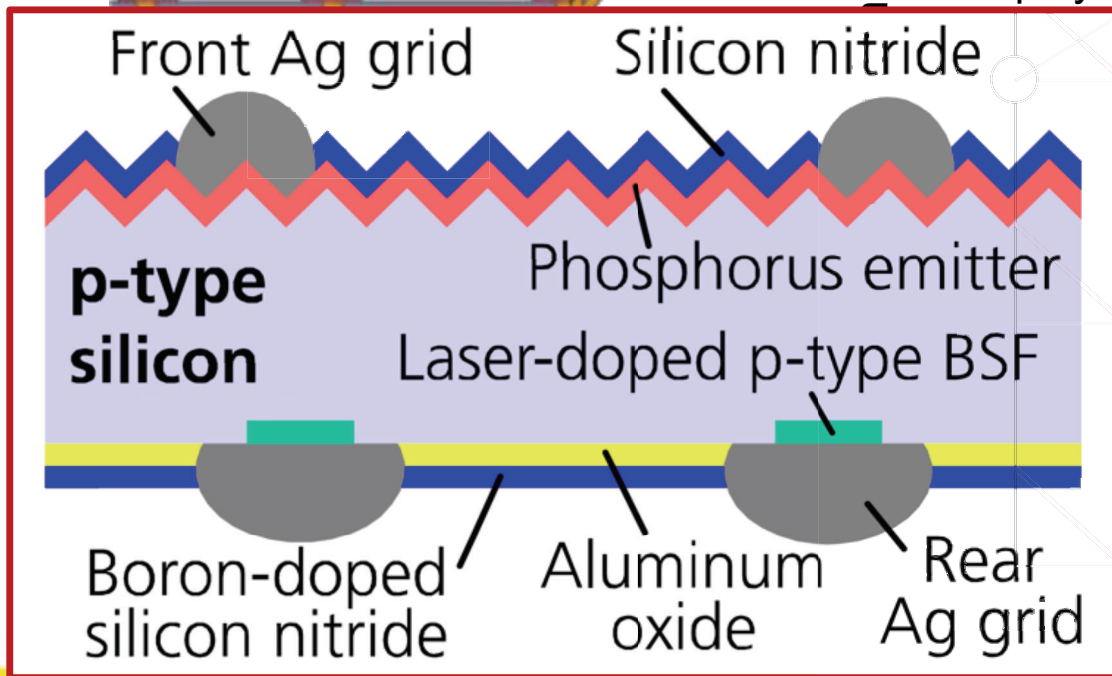
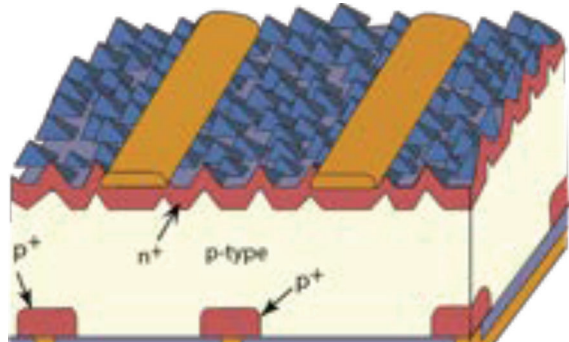


B.Min et al. (ISFH), Sol.RRL 5, 2000703, 2021



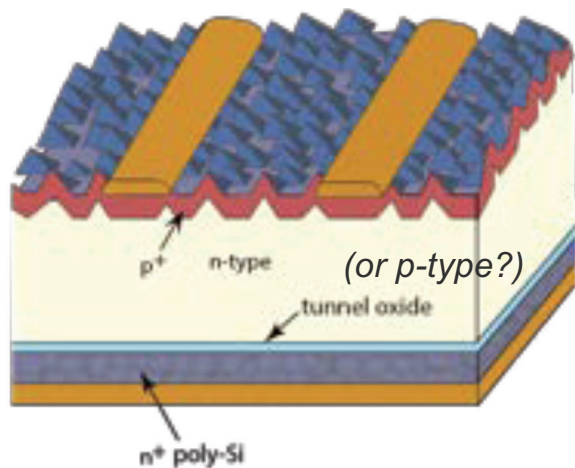
ISFH, SOLMAT 212, 110586, 2020

The contenders



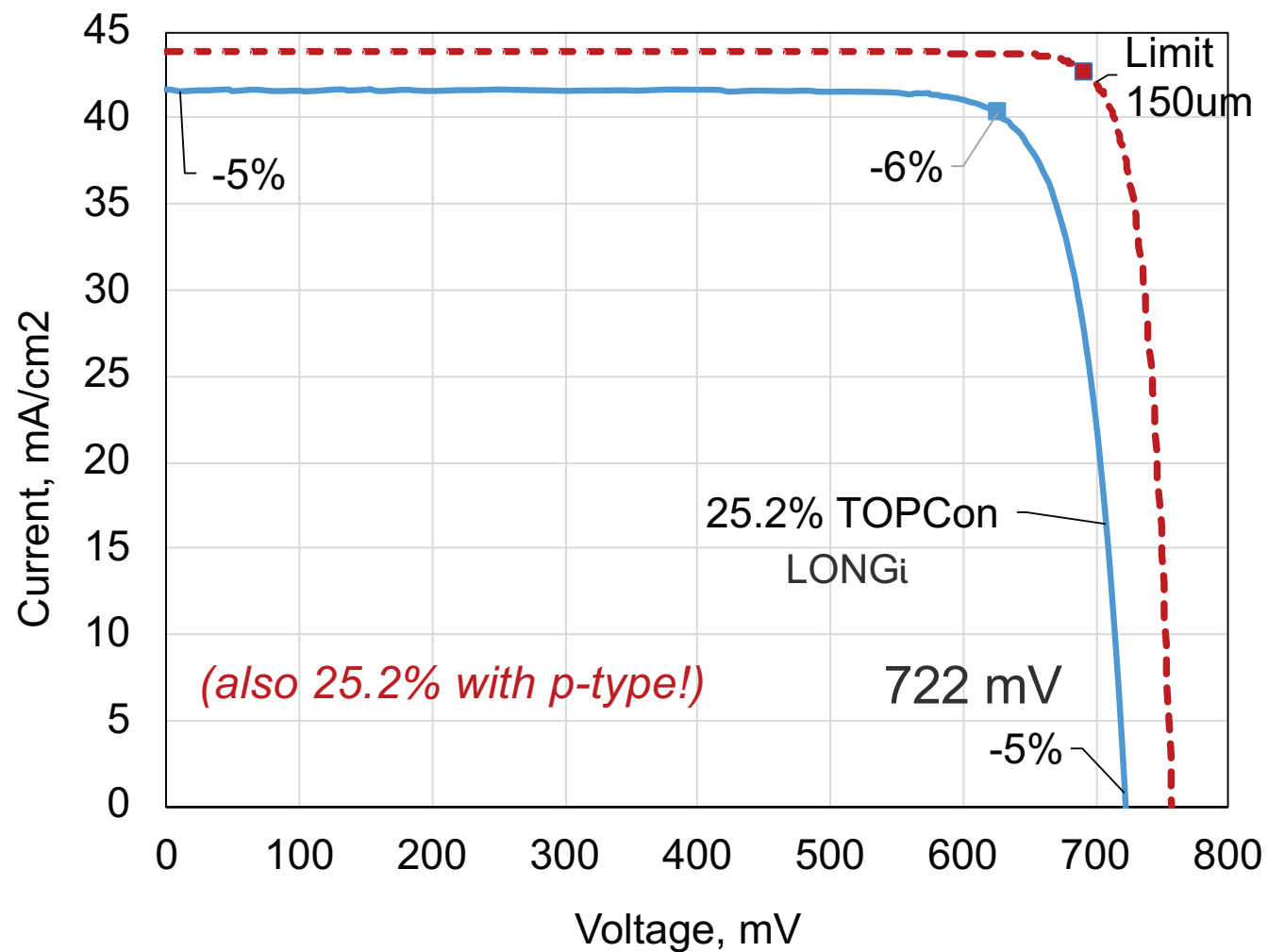
Lohmüller et al.(ISE), IEEE 7th WCPEC, 3727 (2018)

The contenders

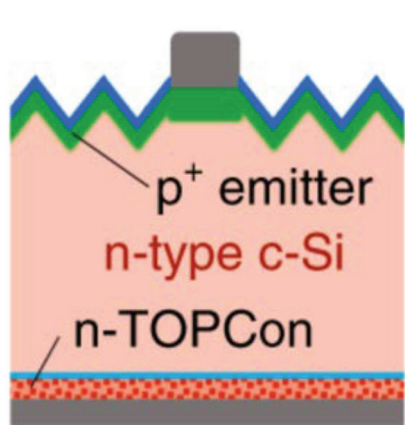


TOPCon

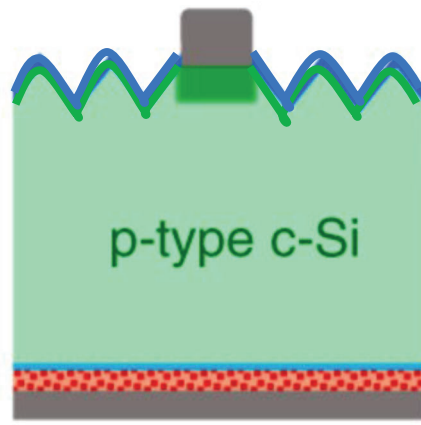
n- or p-type?



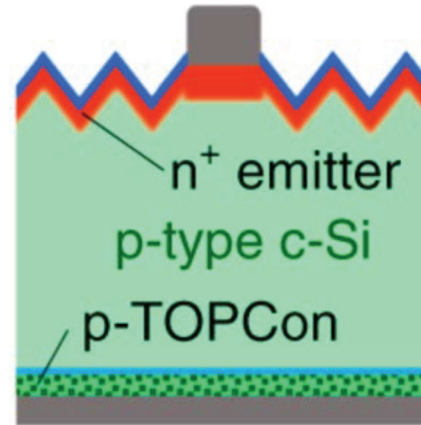
The contenders (TOPCon + diffused emitter)



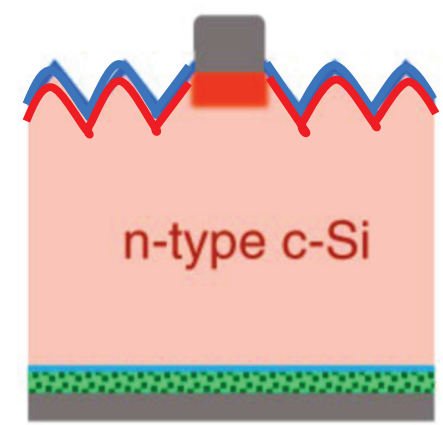
FJ



BJ



FJ



BJ

Exp. 25.8%

1 Ωcm , 300 Ω/\square

Exp. 26.0% (25.5%)

1 Ωcm (10 Ωcm), 16.5 $\text{k}\Omega/\square$

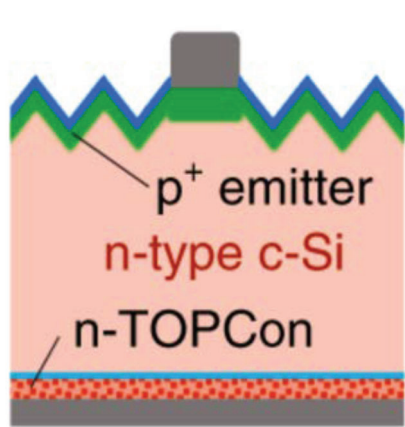
Richter et al. (ISE)

NATURE ENERGY | VOL 6 | APRIL 2021 | 429-438 |

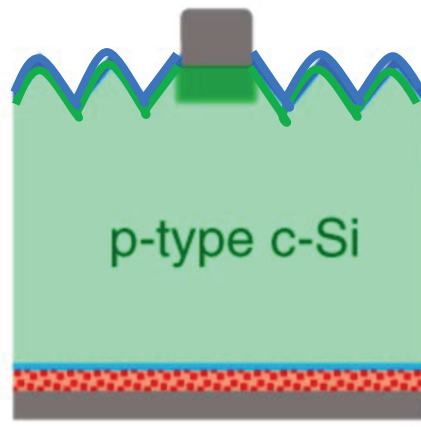
 p-type  n-type



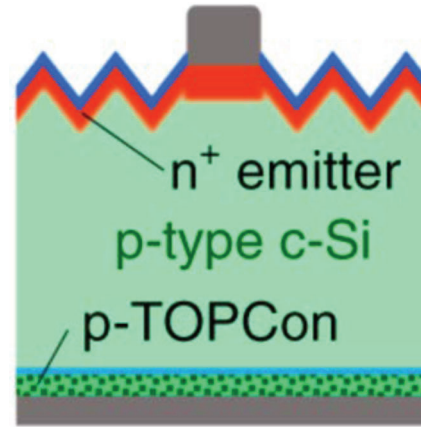
The contenders (TOPCon + diffused emitter)



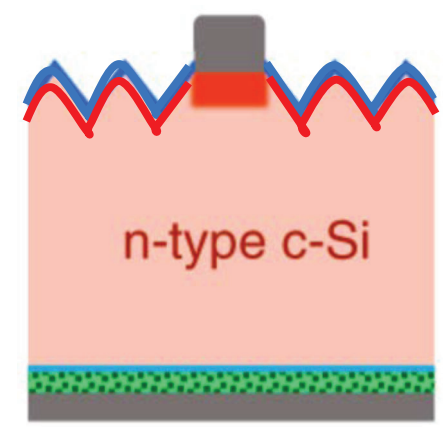
FJ



BJ



FJ



BJ

26.4 - 26.7%

$\rho_{sheet} \sim 700 \Omega/\square$

$\rho_{bulk} = 3 - 40 \Omega cm$

Exp. 25.8%

1 Ωcm , 300 Ω/\square

Exp. 26.0% (25.5%)

1 Ωcm (10 Ωcm), 16.5 $k\Omega/\square$

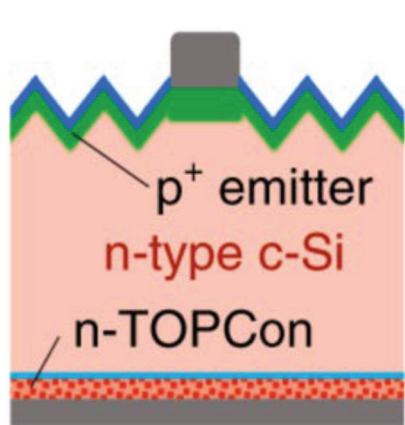
Richter et al. (ISE)

NATURE ENERGY | VOL 6 | APRIL 2021 | 429-438 |

 p-type  n-type



The contenders (TOPCon + diffused emitter)



FJ

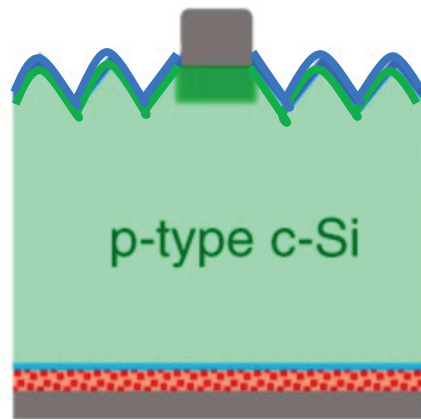
26.4 - 26.7%

$$\rho_{sheet} \sim 700 \Omega/\square$$

$$\rho_{bulk} = 3 - 40 \Omega cm$$

Exp. 25.8%

1 Ωcm , 300 Ω/\square



BJ

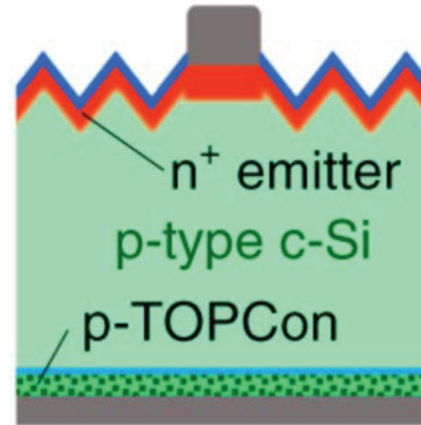
26.6 - 26.8%

$$\rho_{sheet} \sim 1,000 \Omega/\square$$

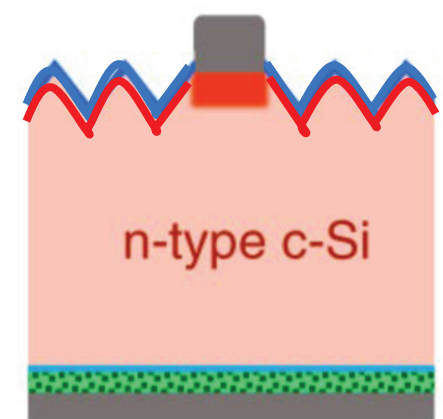
$$\rho_{bulk} = 1 - 10 \Omega cm$$

Exp. 26.0% (25.5%)

1 Ωcm (10 Ωcm), 16.5 $k\Omega/\square$



FJ



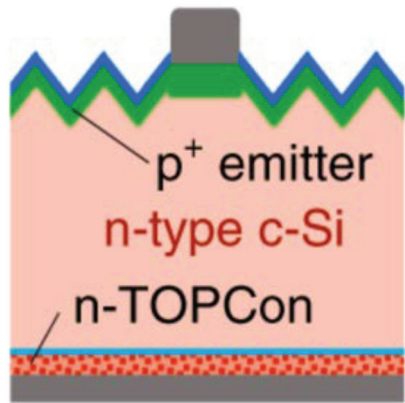
BJ

Richter et al. (ISE)

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 p-type  n-type

The contenders (TOPCon + diffused emitter)



FJ

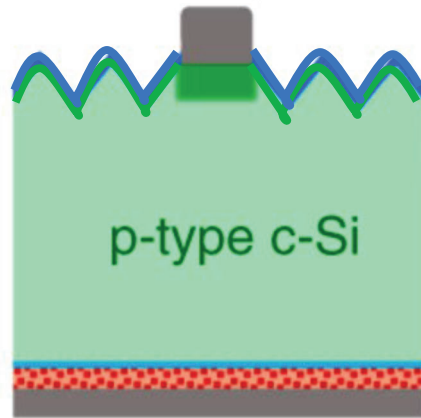
26.4 - 26.7%

$$\rho_{sheet} \sim 700 \Omega/\square$$

$$\rho_{bulk} = 3 - 40 \Omega cm$$

Exp. 25.8%

1 Ωcm , 300 Ω/\square



BJ

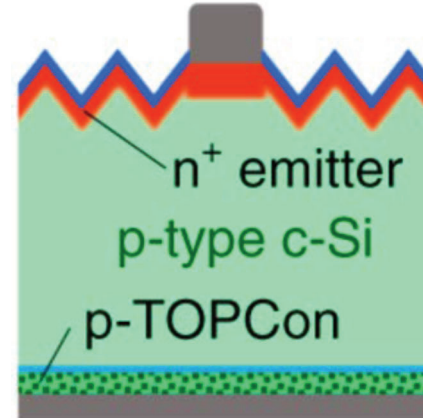
26.6 - 26.8%

$$\rho_{sheet} \sim 1,000 \Omega/\square$$

$$\rho_{bulk} = 1 - 10 \Omega cm$$

Exp. 26.0% (25.5%)

1 Ωcm (10 Ωcm), 16.5 $k\Omega/\square$

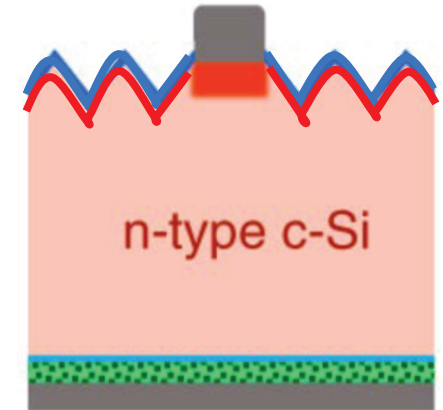


FJ

26.5 - 26.8%??

$$\rho_{sheet} > 300 \Omega/\square$$

$$\rho_{bulk} > 3 \Omega cm$$



BJ

26.6 - 26.8%??

$$\rho_{sheet} \sim 1,000 \Omega/\square$$

$$\rho_{bulk} > 1.5 \Omega cm$$

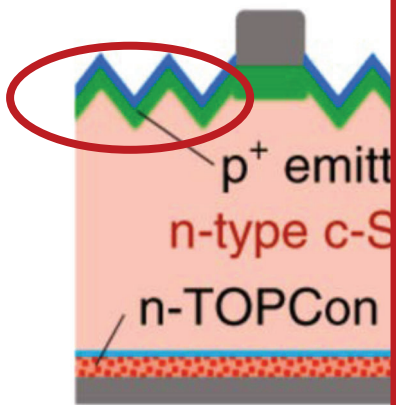
Richter et al. (ISE)

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 p-type  n-type



The contenders (TOPCon + diffused emitter)



FJ

26.4 - 26.7%

$\rho_{sheet} \sim 700 \Omega/\square$

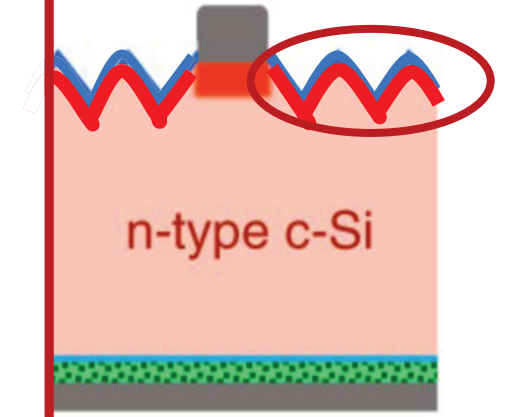
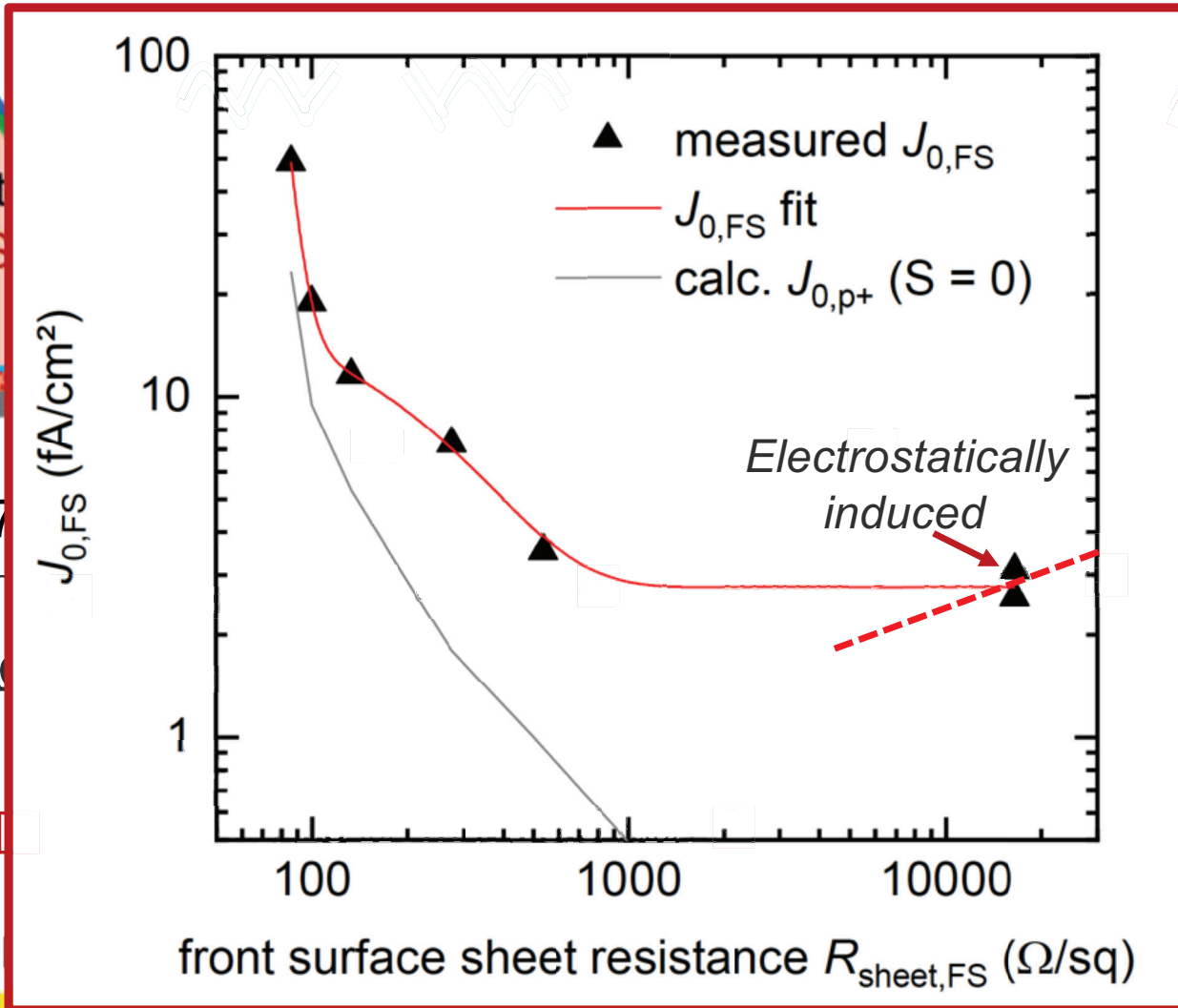
$\rho_{bulk} = 3 - 40 \Omega\text{cm}$

Exp. 25.8%

1 Ωcm , 300 Ω/\square

Richter et al. (ISE)

NATURE ENERGY | VOL 6



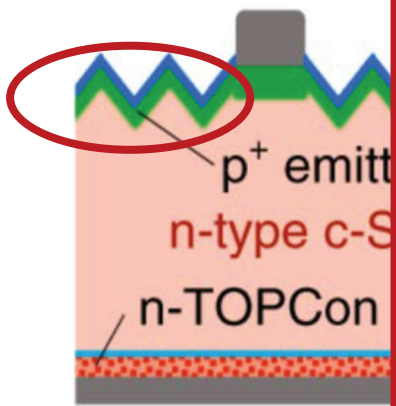
BJ

26.6 - 26.8%??

$\rho_{sheet} \sim 1,000 \Omega/\square$

$\rho_{bulk} > 1.5 \Omega\text{cm}$

The contenders (TOPCon + diffused emitter)



FJ

26.4 - 26.7%

$\rho_{sheet} \sim 700 \Omega/\square$

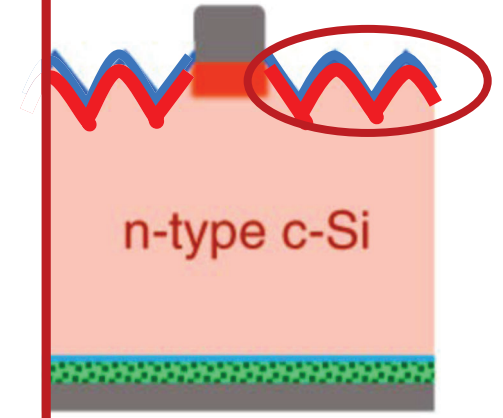
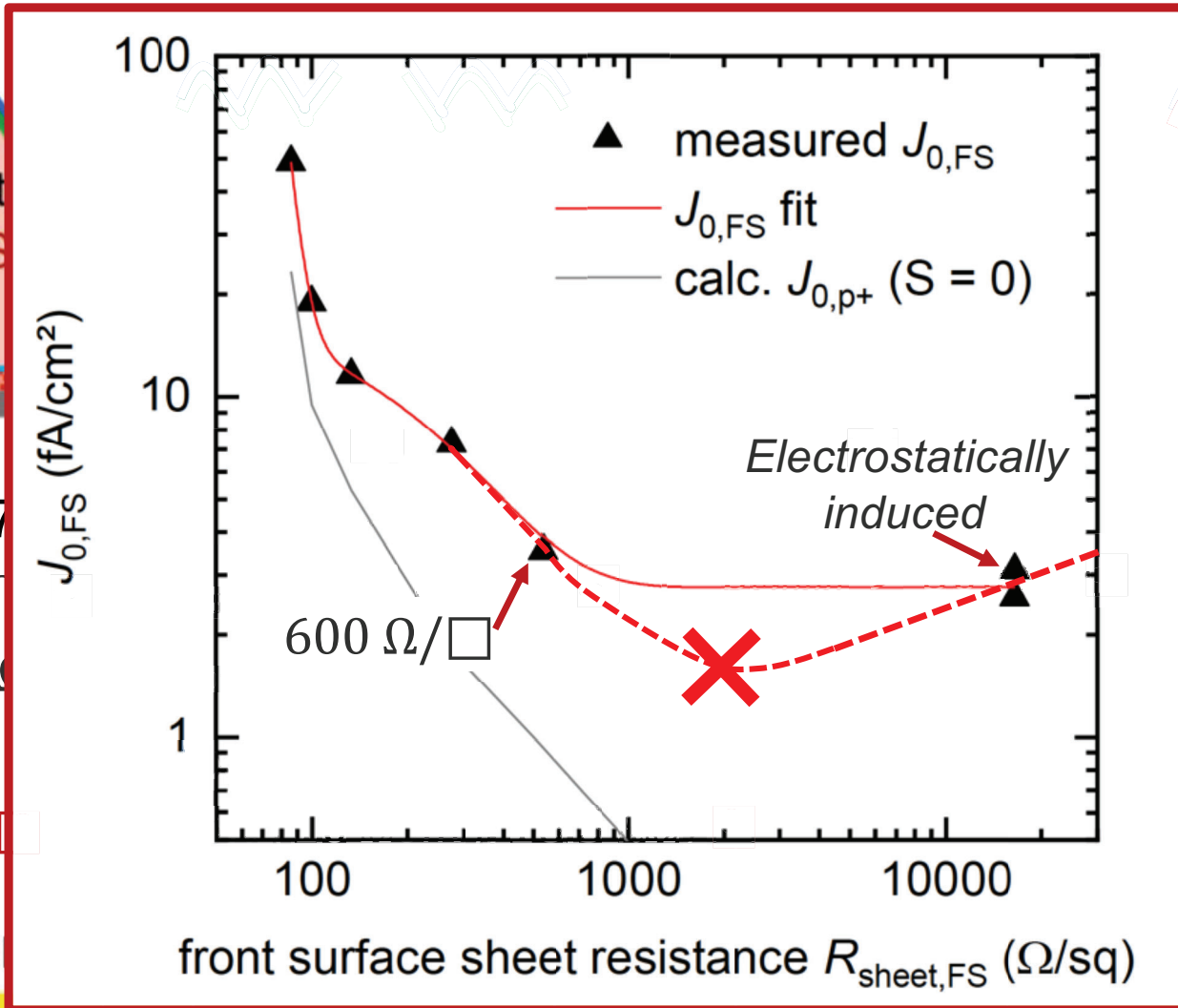
$\rho_{bulk} = 3 - 40 \Omega\text{cm}$

Exp. 25.8%

1 Ωcm , 300 Ω/\square

Richter et al. (ISE)

NATURE ENERGY | VOL 6



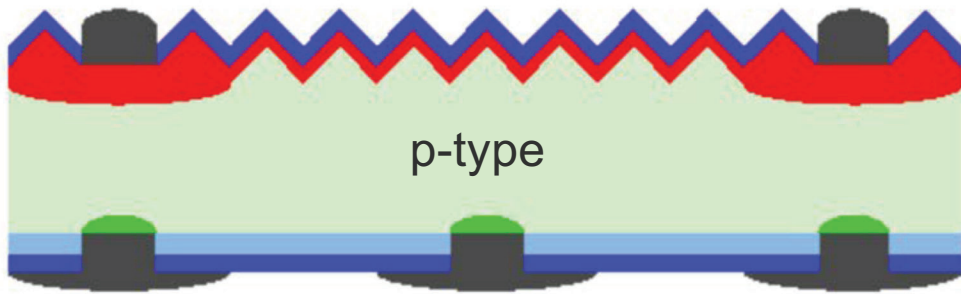
BJ

26.6 - 26.8%??

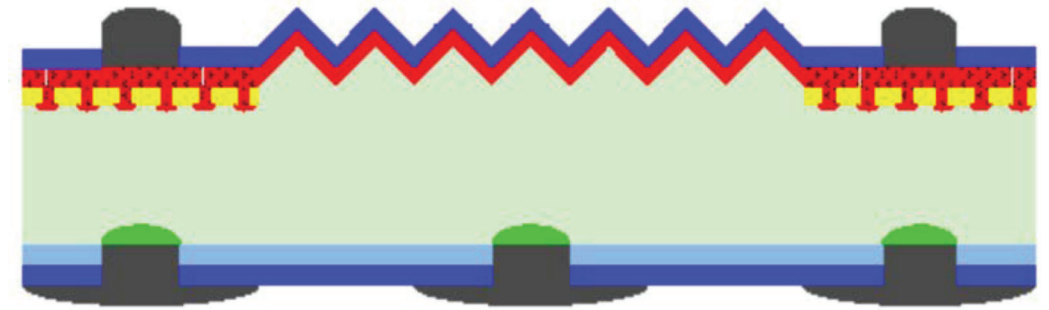
$\rho_{sheet} \sim 1,000 \Omega/\square$

$\rho_{bulk} > 1.5 \Omega\text{cm}$

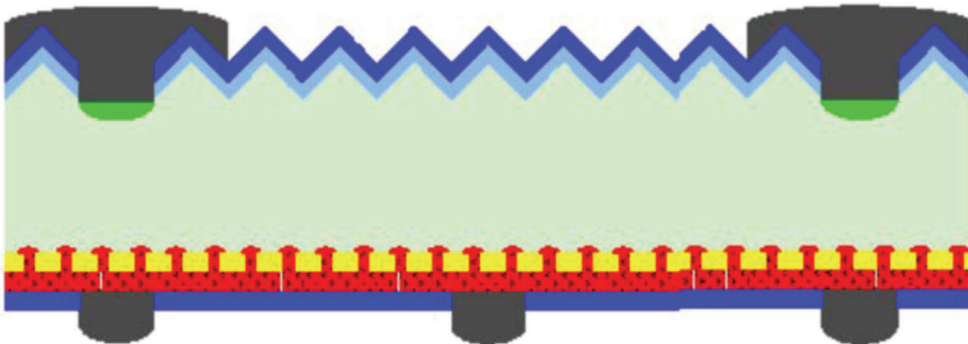
The contenders (ISFH: POLO) – the ones we've seen before!



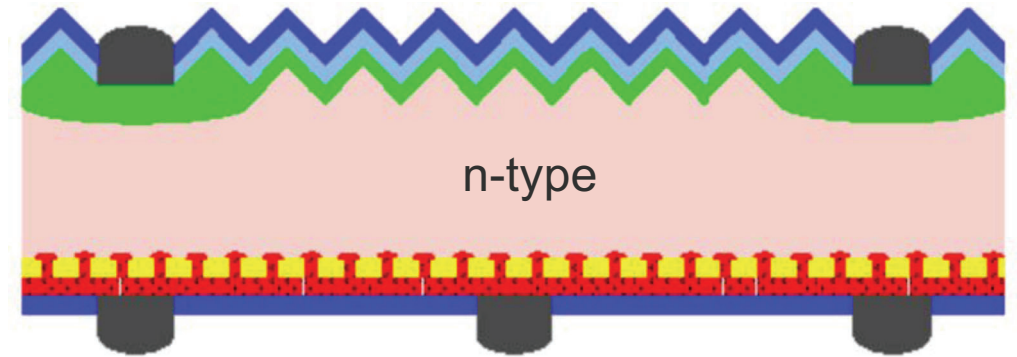
PERC: 23.7%



TOP-PERC (PERC+POLO): 24.1%



POLO BJ: 24.7%



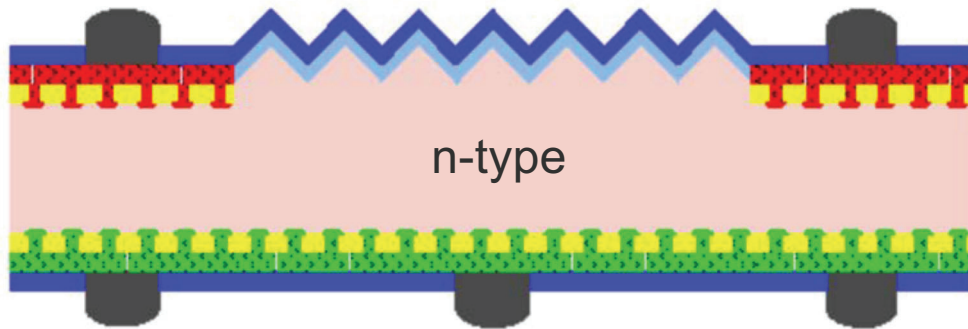
TOPCon: 24.4% (vs 26.4-26.7%)

Kruse et al. (ISFH) **Scientific Reports** | (2021) 11:996 |

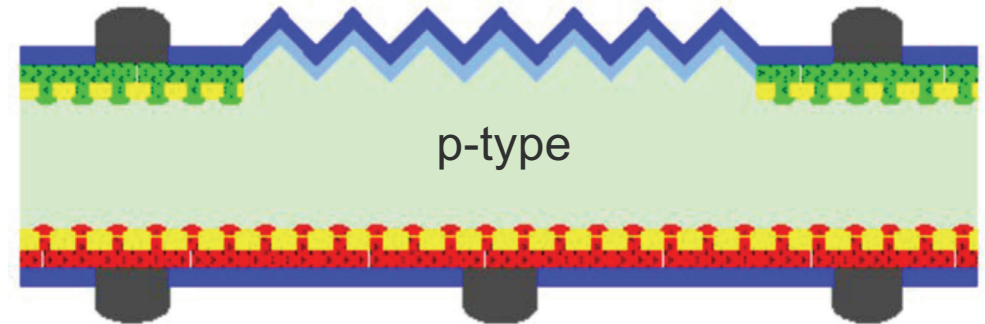
 p-type  n-type



The contenders (2 polarities poly)



POLO² BJ: 25.1% (*Tetrasun 2009*)



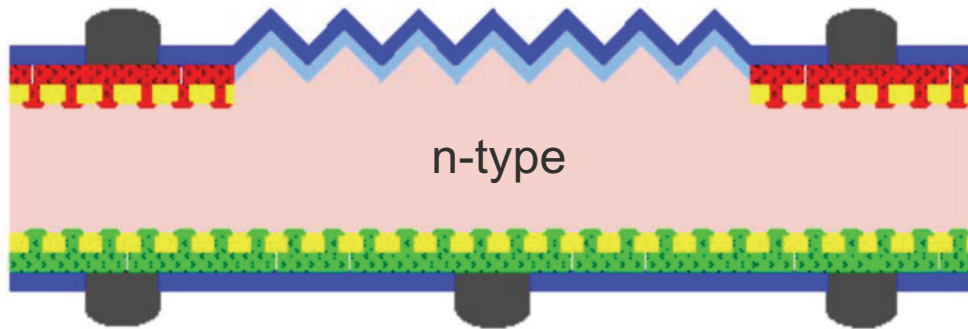
POLO² BJ: 25.0%

FJ?

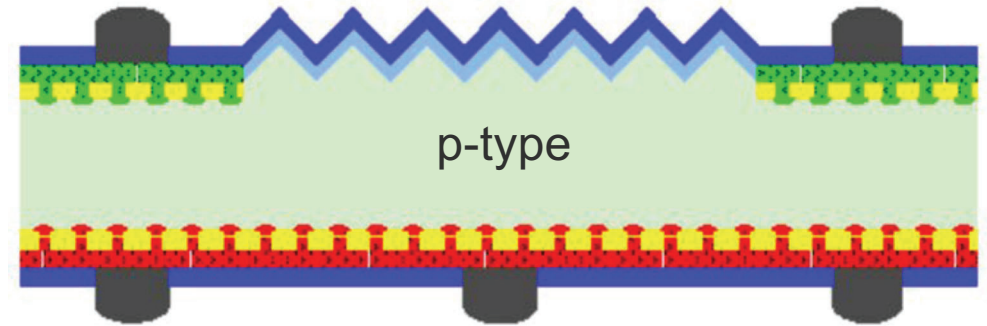
Kruse et al. (ISFH) **Scientific Reports** | (2021) 11:996 |

 p-type  n-type

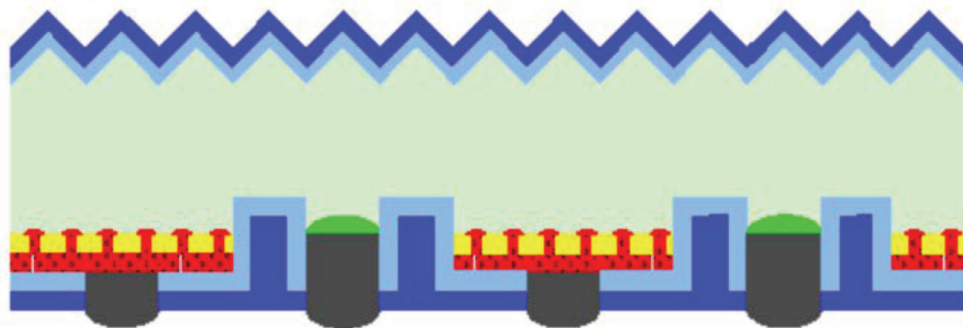
The contenders (2 polarities poly)



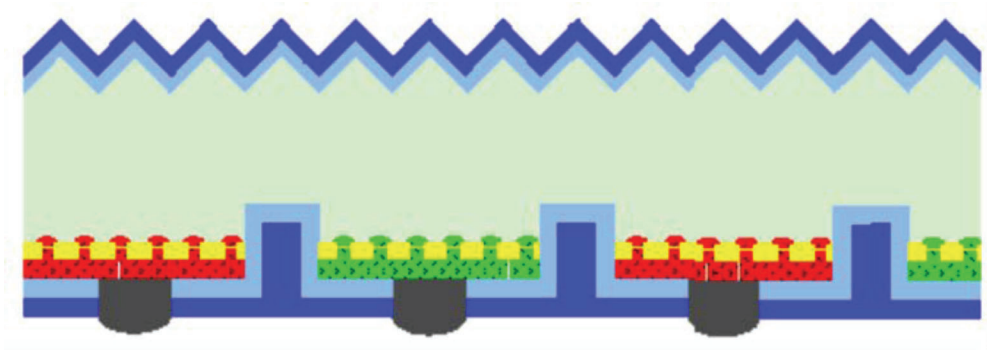
POLO² BJ: 25.1% (*Tetrasun 2009*)



POLO² BJ: 25.0%



POLO IBC: 25.5%



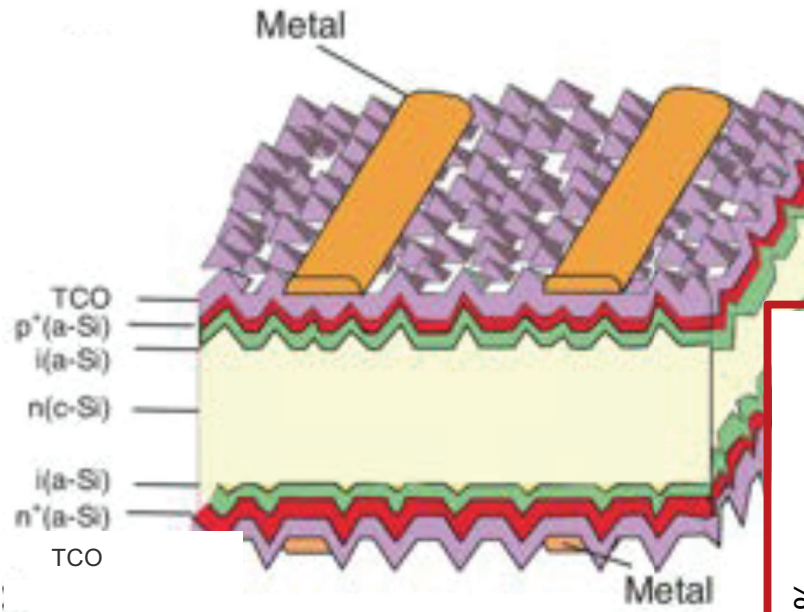
POLO² IBC: 25.9% (*SunPower*) (*Exp. 26.1%*)

Kruse et al. (ISFH) **Scientific Reports** | (2021) 11:996 |

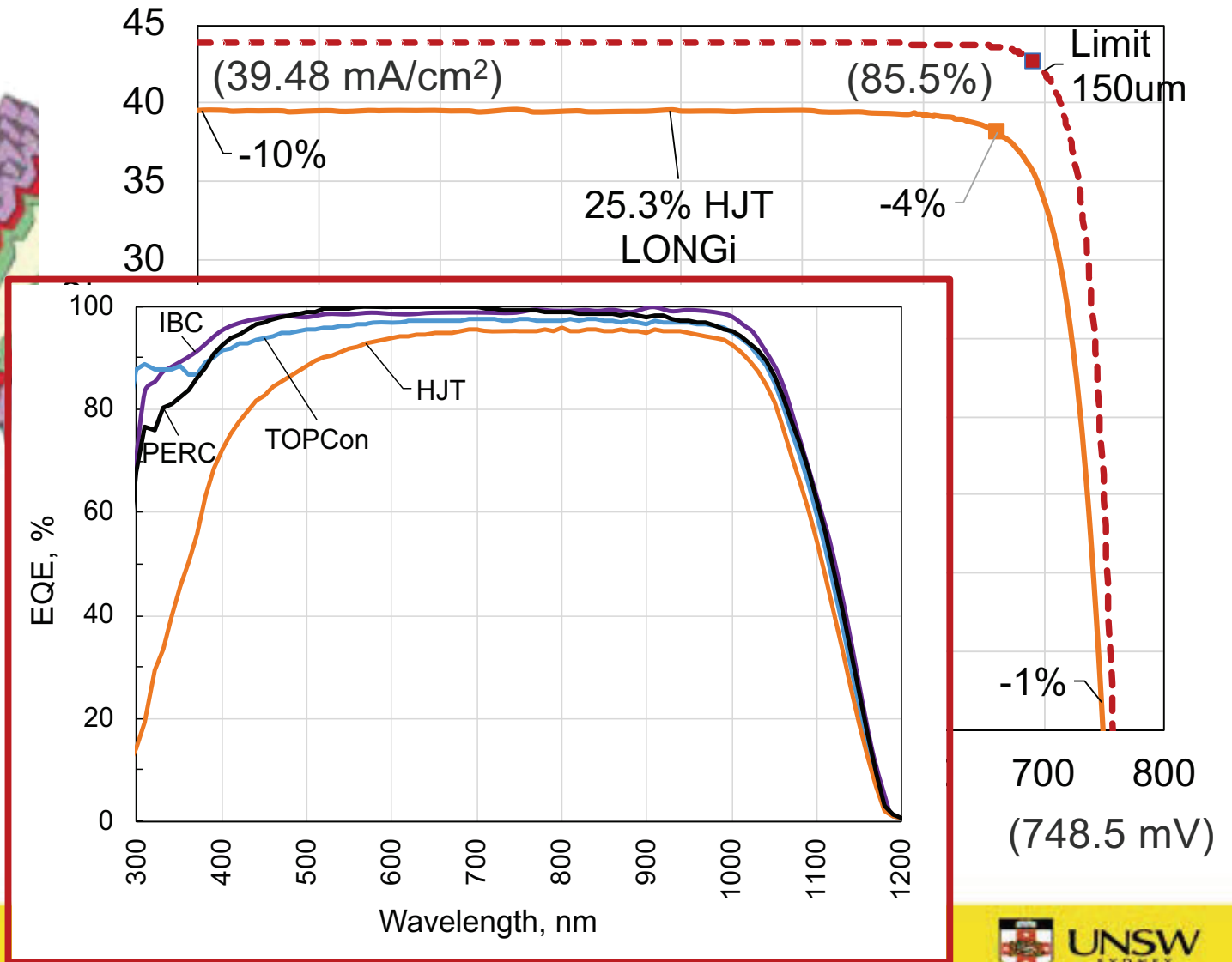
 p-type  n-type



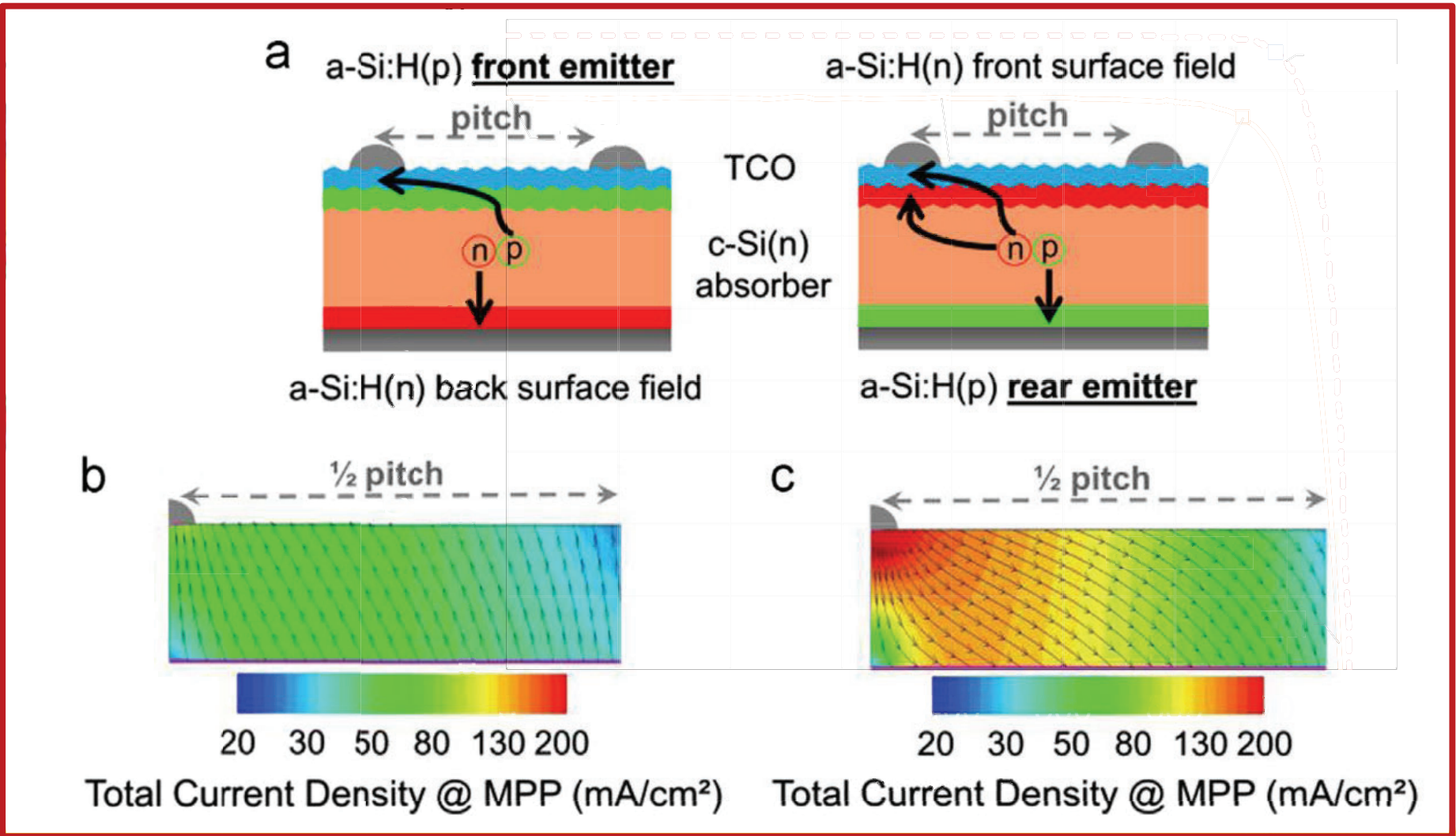
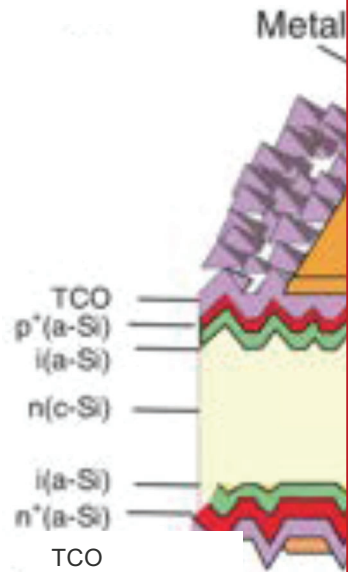
The contenders



HJT



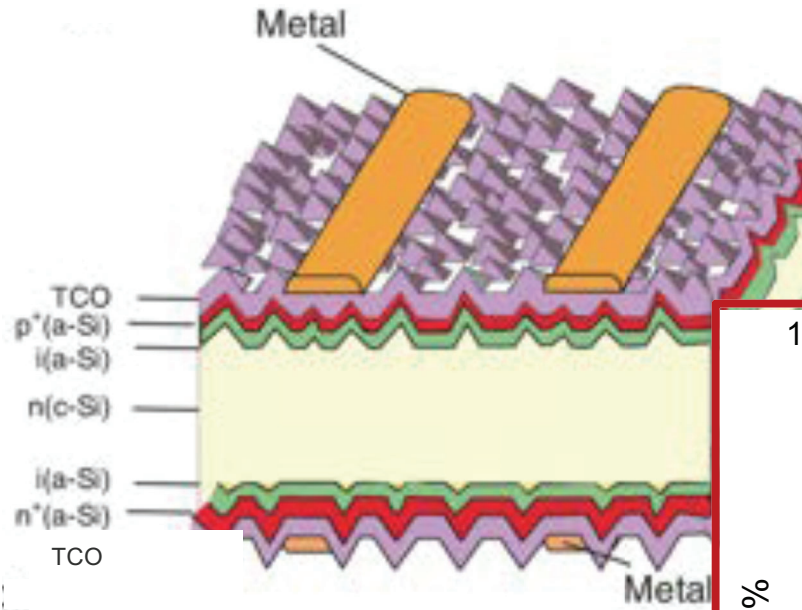
The contenders



M. Bivour et al. / Solar Energy Materials & Solar Cells 122 (2014) 120–129

p-type
 n-type

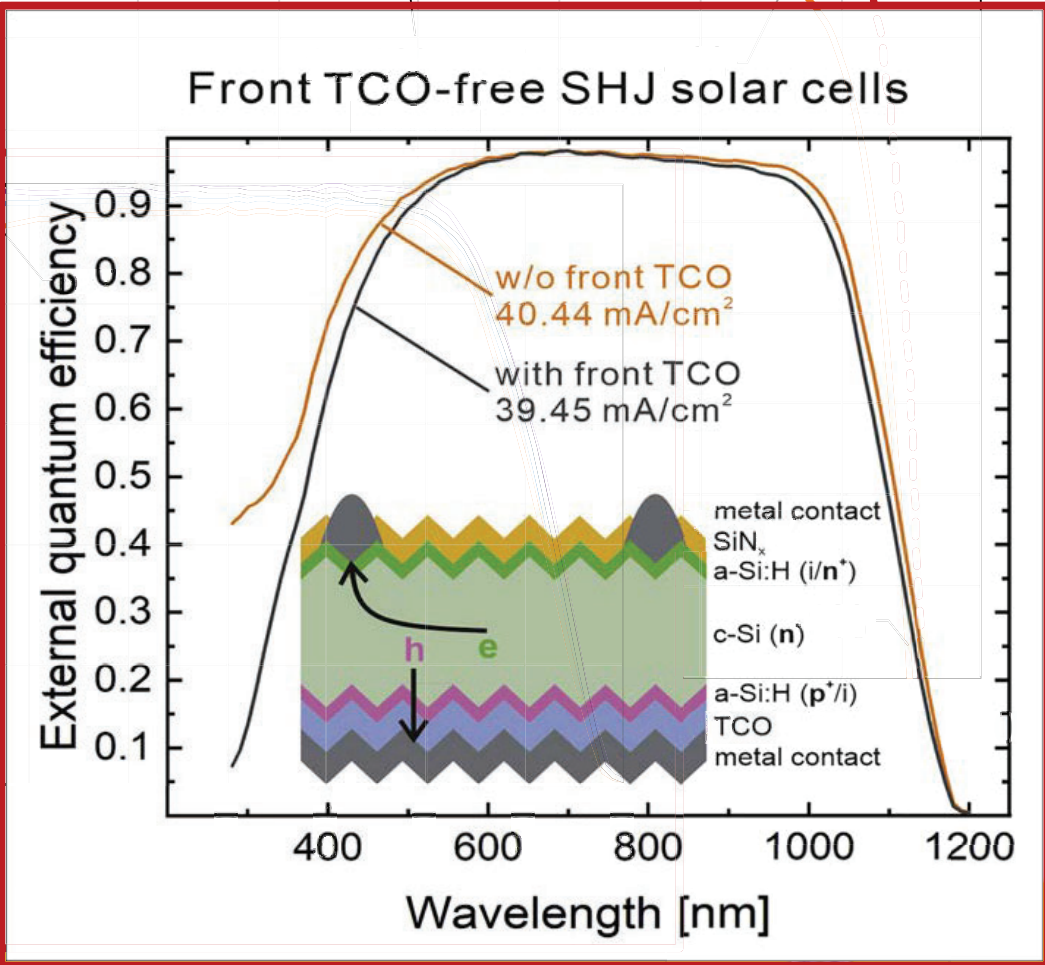
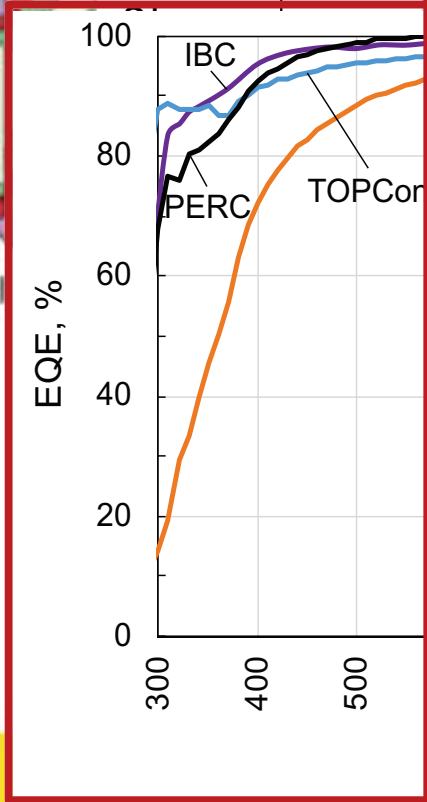
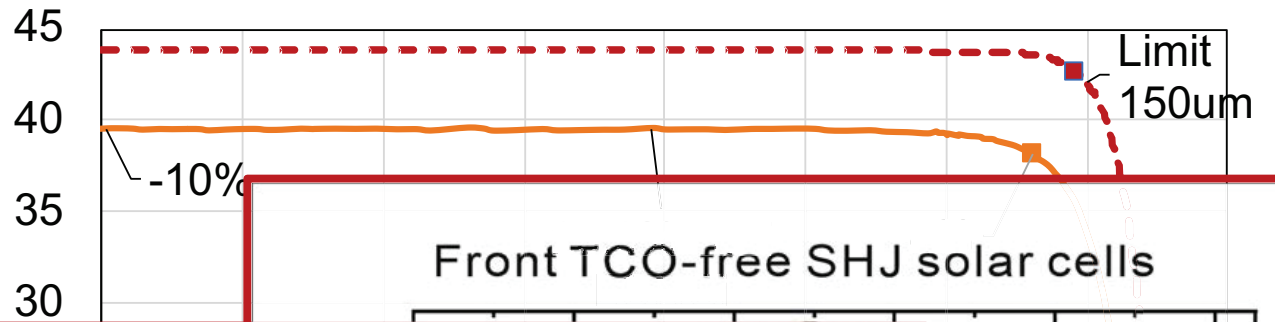
The contenders



HJT

Is a-Si now needed over whole top surface?

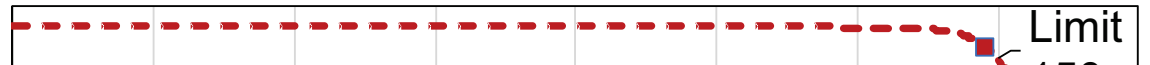
Li et al, Joule 5, 16 June 2021, p.1535



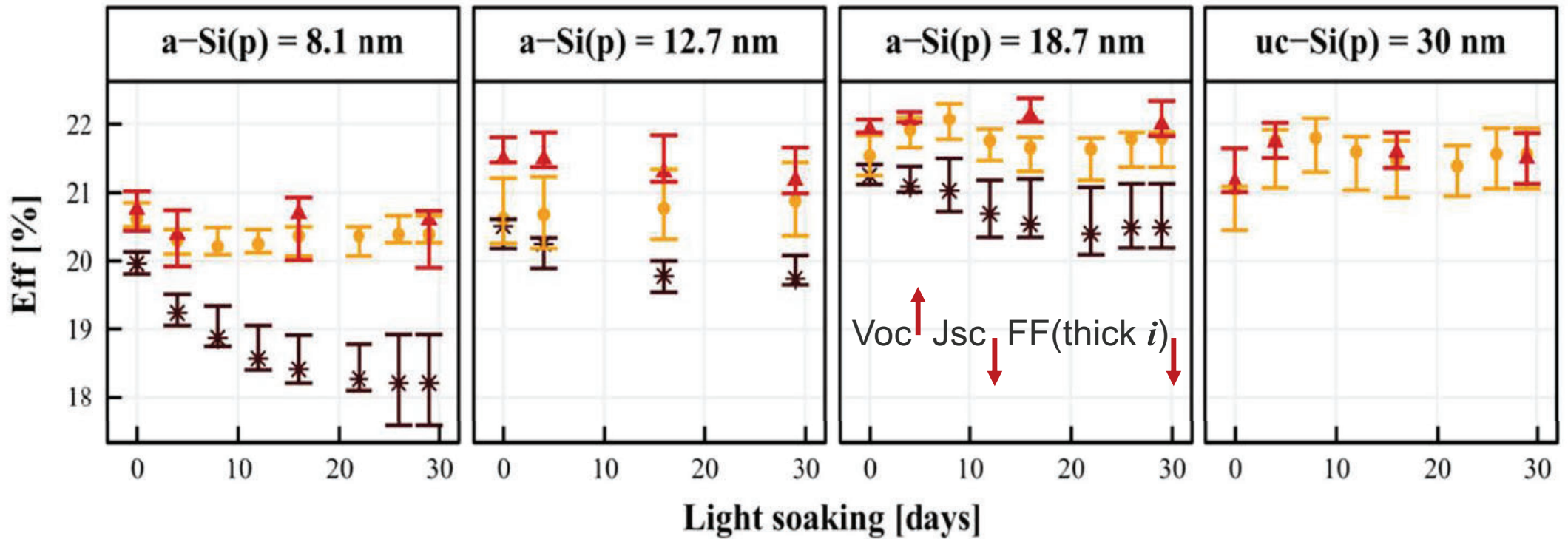
The contenders

45

Metal



(i) layer [nm] ● 7.2 ▲ 9.2 * 13.8

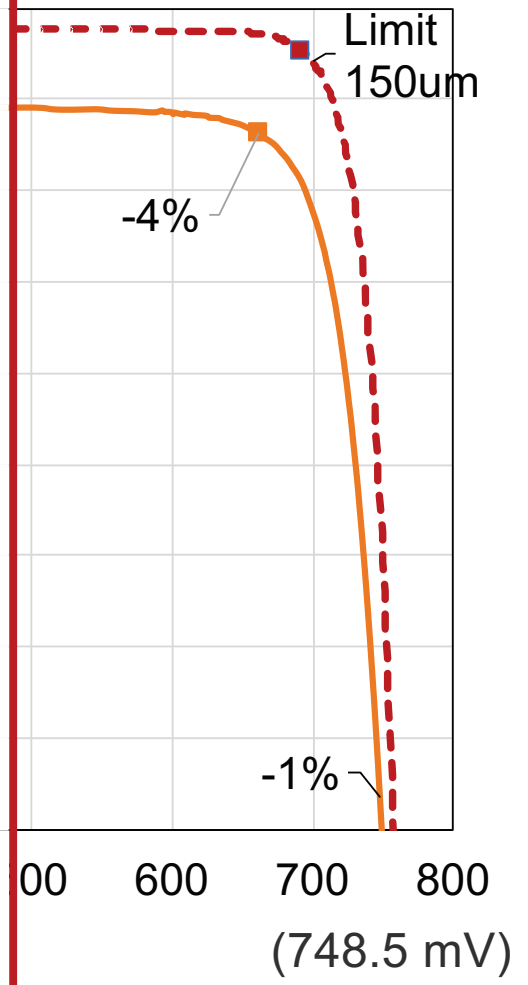
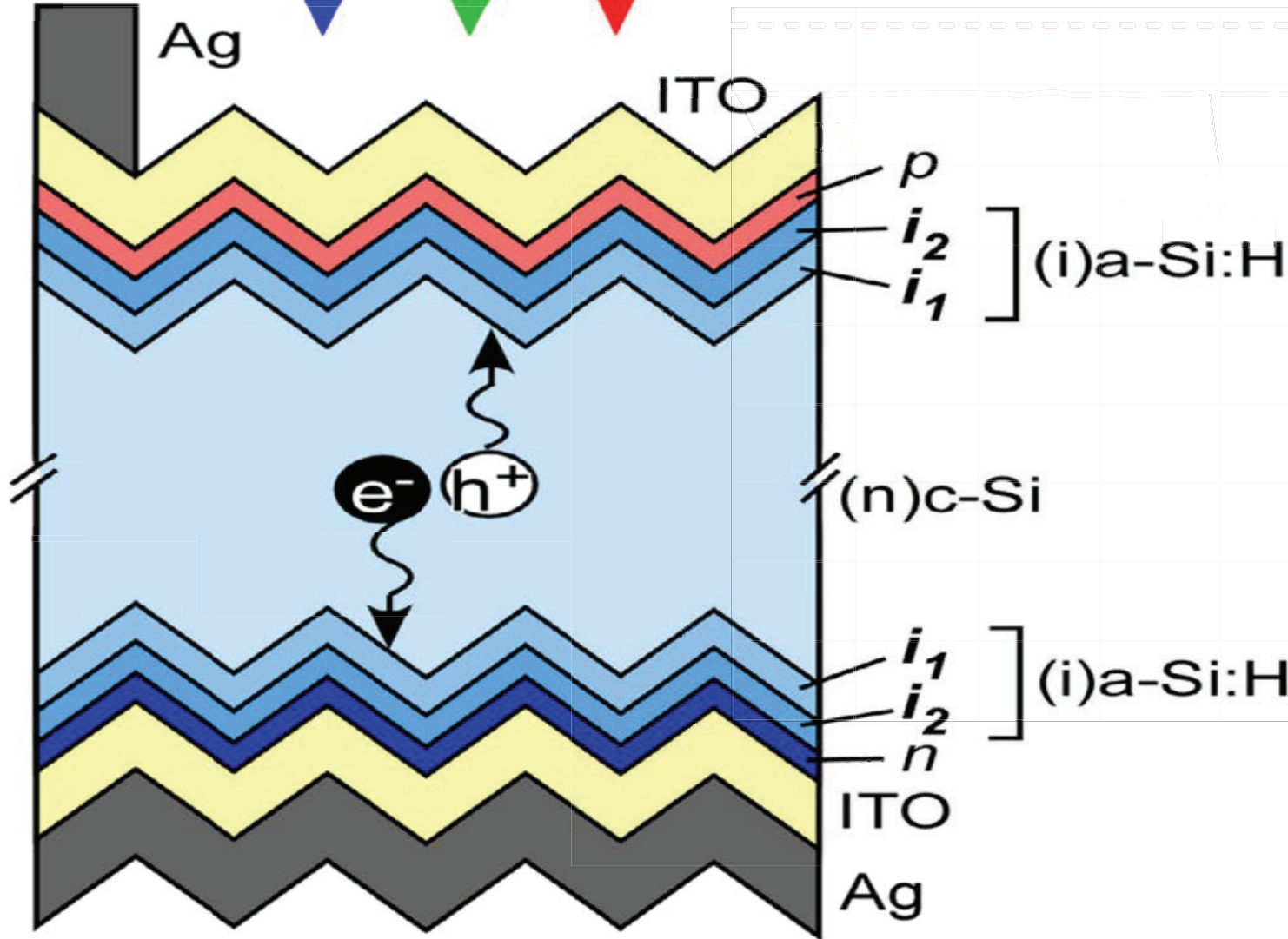


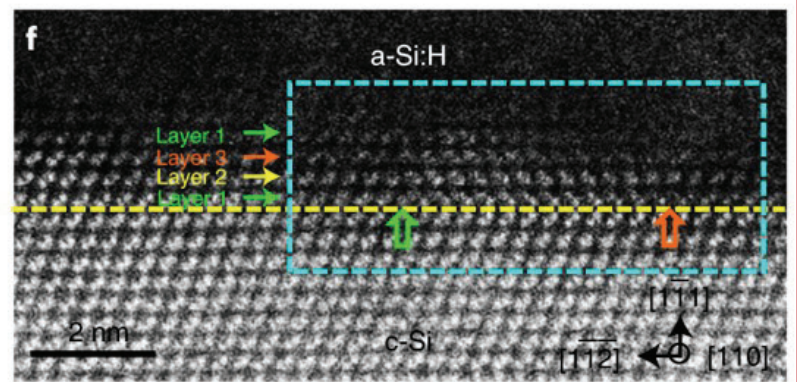
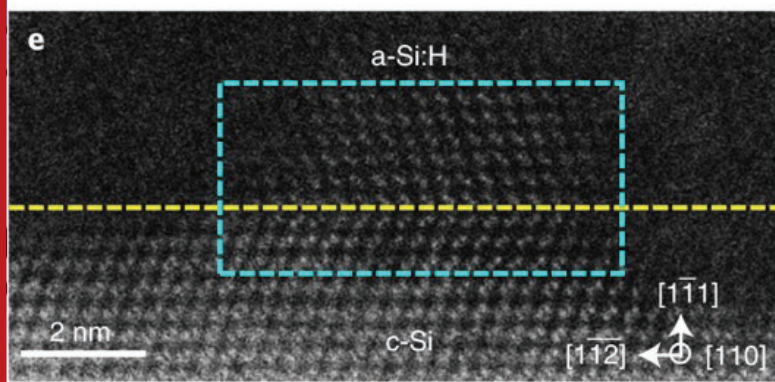
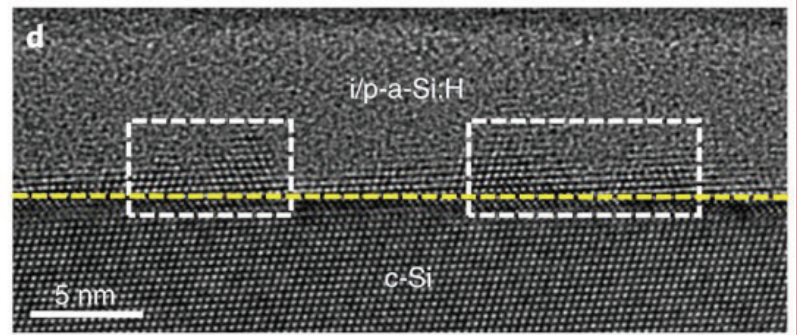
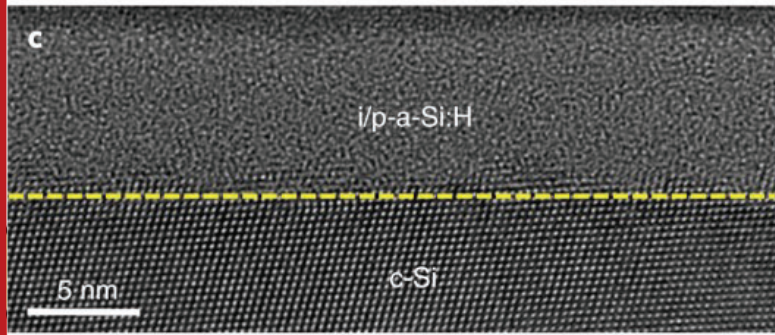
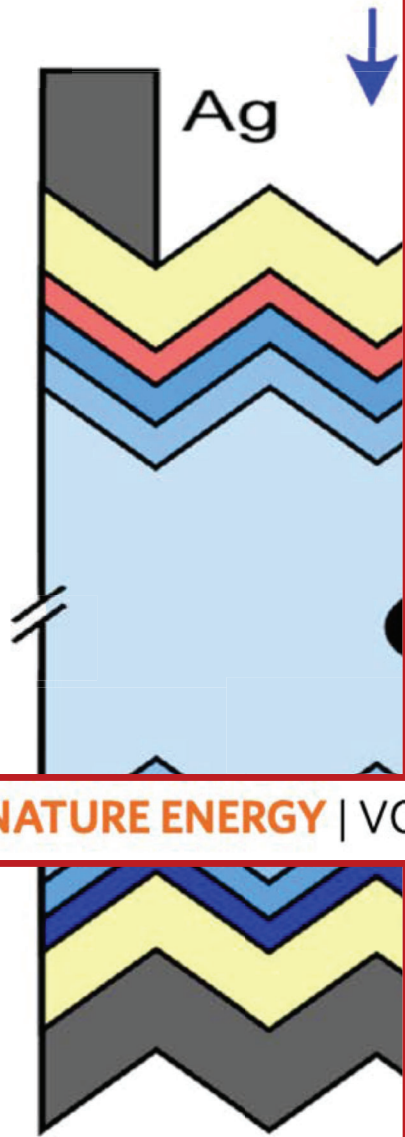
Cattin et al. (EPFL et al.), IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 11, 575, MAY 2021

wavelength, nm

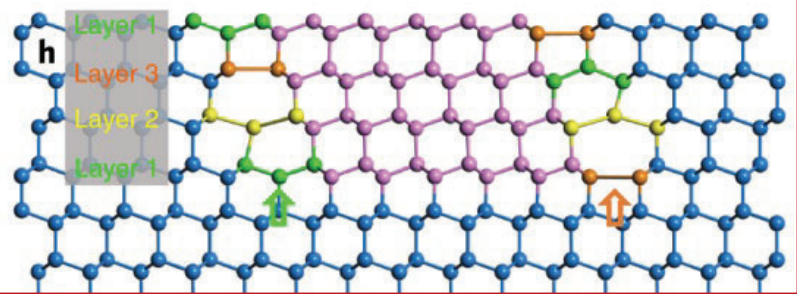
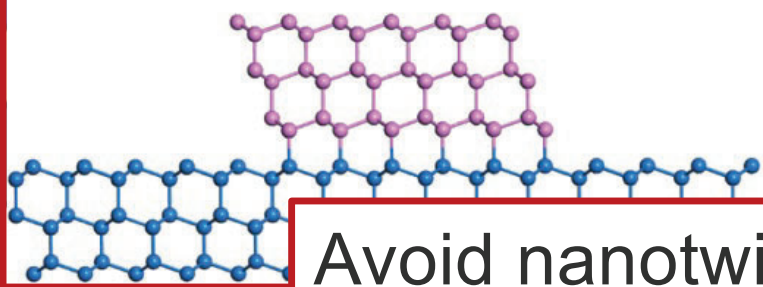


Sai et al., Phys. Status Solidi A 2021, 218, 2000743

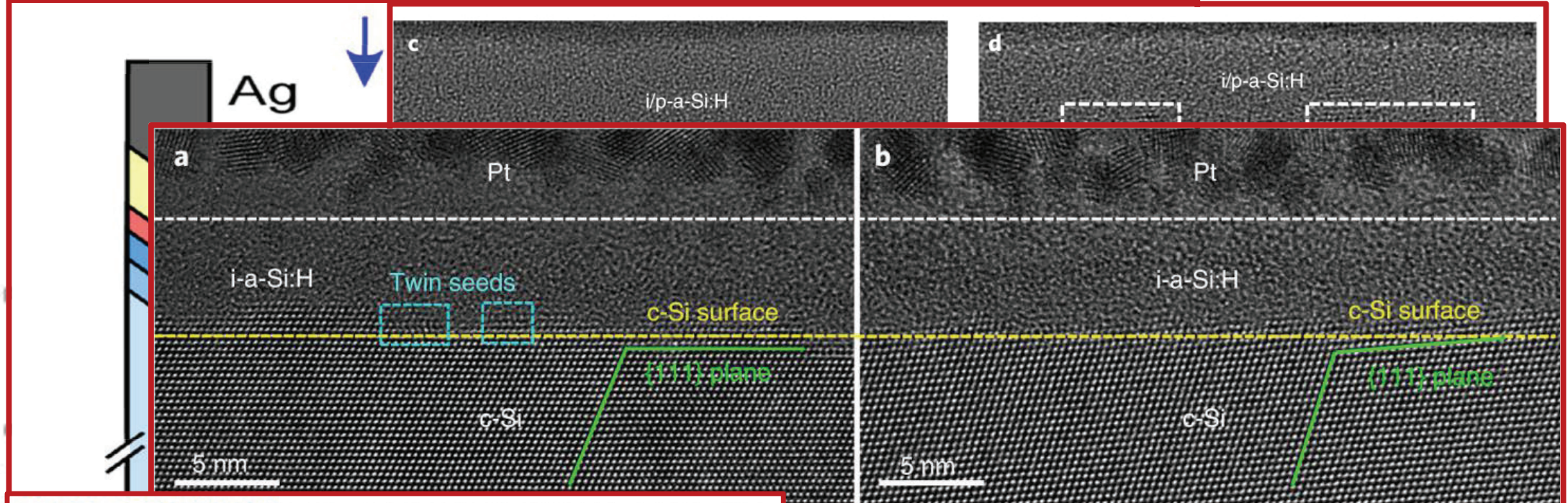




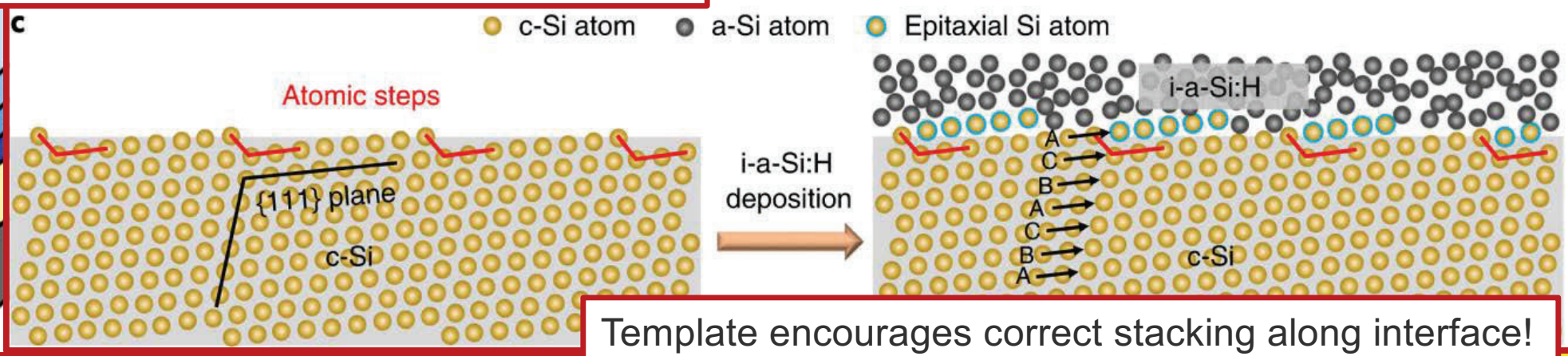
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Avoid nanotwins! (V_{oc} & FF up $>0.3\%$!)



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Template encourages correct stacking along interface!

Efficiency limits for PERC, TOPCon, HJT and IBC

All continue improving to 26% & beyond in production:

- . **better wafers:** > 30 ms lifetimes for hi-resistivity (P & Ga) → *supercharged FF*
- . **improved surfaces:** J_0 contribution < 2 fA/cm² → *supercharged FF*
- . **improved contact selectivity:** $S_{10e,h} = 15 - 16$; $S_{10t} > 15$
- . **patterning a-Si & poly-Si!**

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PERC:

- . poly-Si/oxide n-contacts, diffused p-type, rear J?

TOPCon:

- . further optimization, surface doping, 2 polarities

HJT:

- . decrease top absorption!; increase pFF towards hi-injection Auger limit

IBC:

- . poly-Si or a-Si?