Beyond 26% silicon solar cells in mass production:

poly-Si or a-Si contacts?

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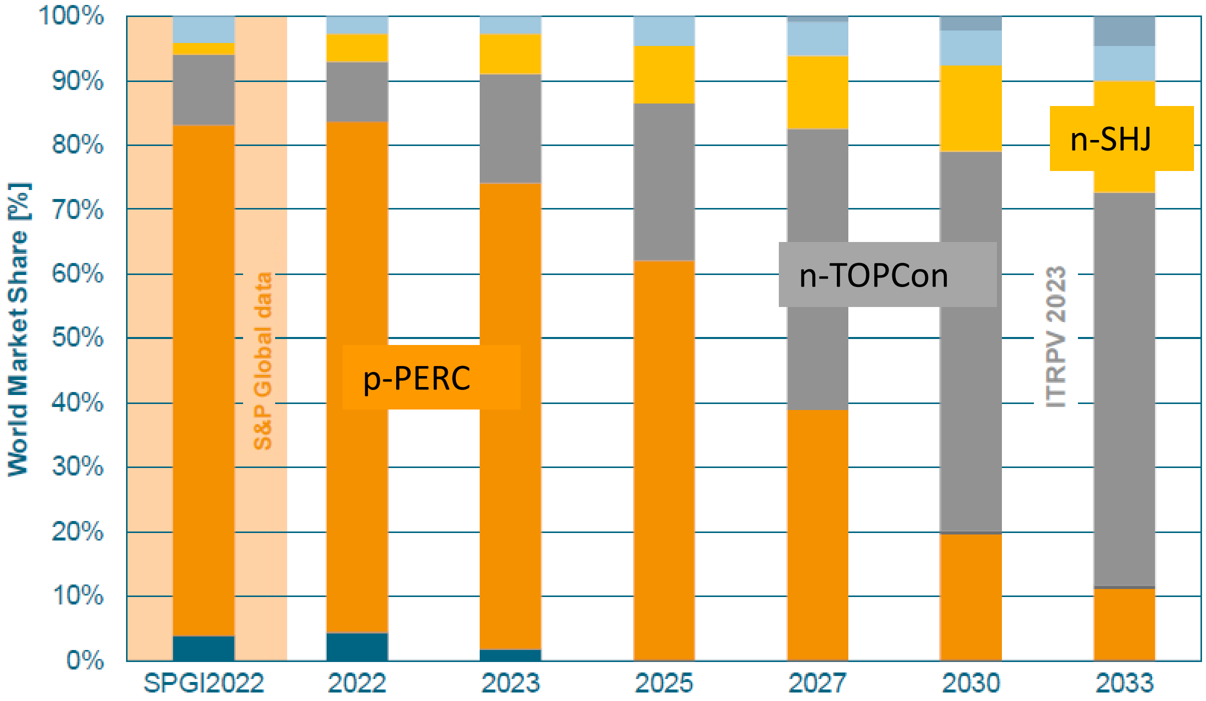
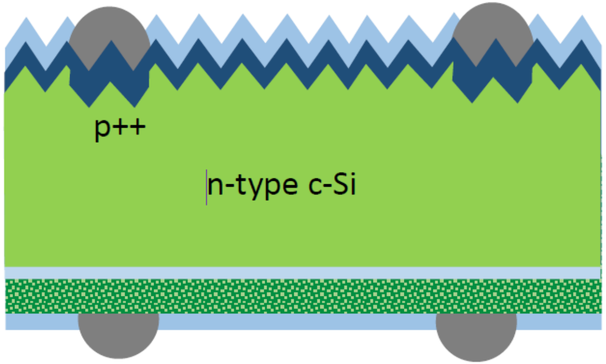
Emergence of passivating contact devices

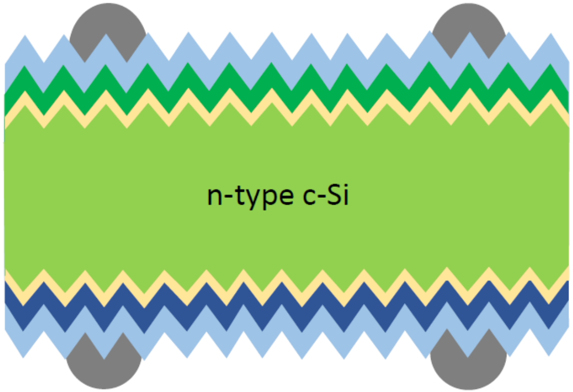
- p-PERC efficiency limited to 23-24%.
- Being replaced by passivating contact technologies:
  - n-TOPCon – poly-Si
  - n-SHJ – a-Si(H)
- Both can achieve > 25%
- n-TOPCon early leader - compatibility with PERC equipment, lower capital costs.
- Which will win in the long run?



ITRPV Roadmap 2023

Features of TOPCon and SHJ devices





n-TOPCon:

- **Oxide interlayer** with doped poly-Si.
- **High processing temps** (> 800°C).
- Passivating contact on rear only…
- Diffused front side contacts – high recombination but very transparent.
- Front junction.
- Rear side planar.

n-SHJ:

- **i-a-Si(H) interlayers** with doped a-Si (or μc-Si/SiO_x).
- **Low processing temps** (< 250°C).
- Outstanding surface passivation both sides, even under contacts.
- Parasitic absorption in TCO and doped a-Si.
- Rear junction.
- Textured both sides.

Comparison of typical device parameters

Typical and champion large-area TOPCon and SHJ cells [1,2,3].

- **Lower J_{SC} in SHJ** - parasitic absorption in TCOs and a-Si films
- **Lower V_{OC} in TOPCon** - front side recombination
- **Lower FF in TOPCon** – front side sheet resistance

Aims of this work:

- Understand these **optical, recombination and transport** losses in detail.
- Evaluate **prospects for achieving >26%** in mass production at low cost.

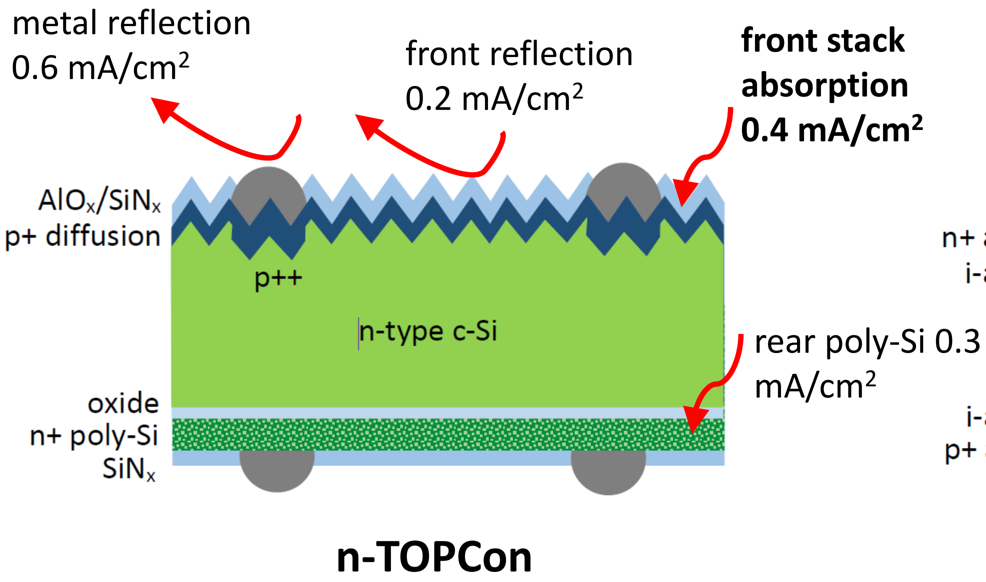
Cell type	J_{SC} (mA/cm²)	V_{OC} (mV)	FF (%)	η (%)
TOPCon – industry state-of-the-art range [1]	**40.6 – 41.6**	**717 - 722**	**83.9 – 84.5**	**24.6 – 25.2**
TOPCon – champion – Jinko [2]	42.2	719	83.7	25.4
SHJ - industry state-of-the-art range [1]	**39.6 – 40.5**	**746 - 750**	**84.6 – 86.6**	**25.1 – 26.3**
SHJ – champion – LONGi [3]	41.5	751	86.1	26.8

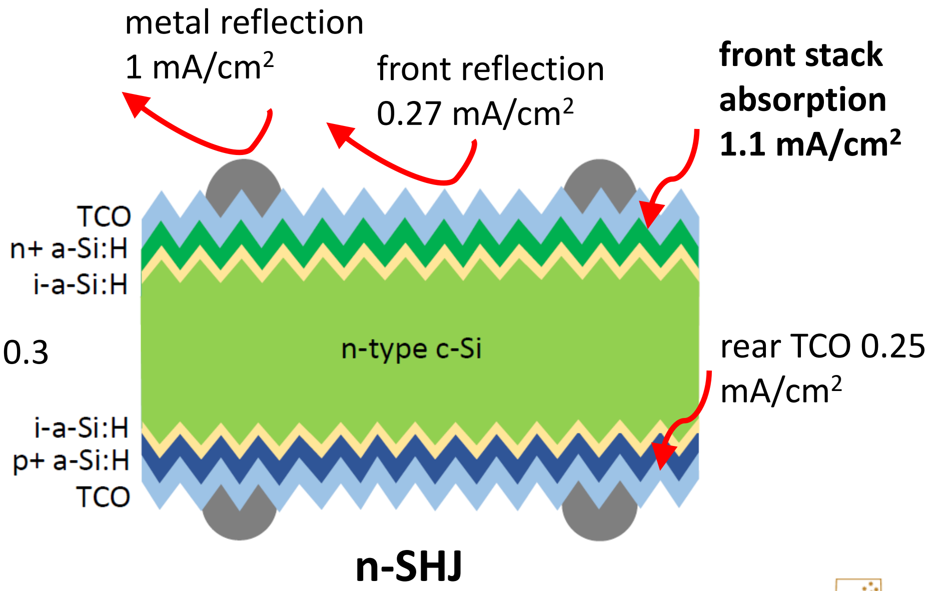
[1] Di Yan *et al.* PIPV **31(4),** 310-326 (2022). [2] P. Zheng *et al.* submitted to IEEE JPV (2023). [3] Hao Lin *et al.* Nature Energy, published online May 2023.

Optical losses

Comparison of 25.4% TOPCon (Jinko) and 26.8% SHJ (LONGi) champion cells.

- Primary avoidable optical losses shown.
- **Parasitic absorption in front stack** larger for SHJ.
- Parasitic absorption at rear side similar for both.

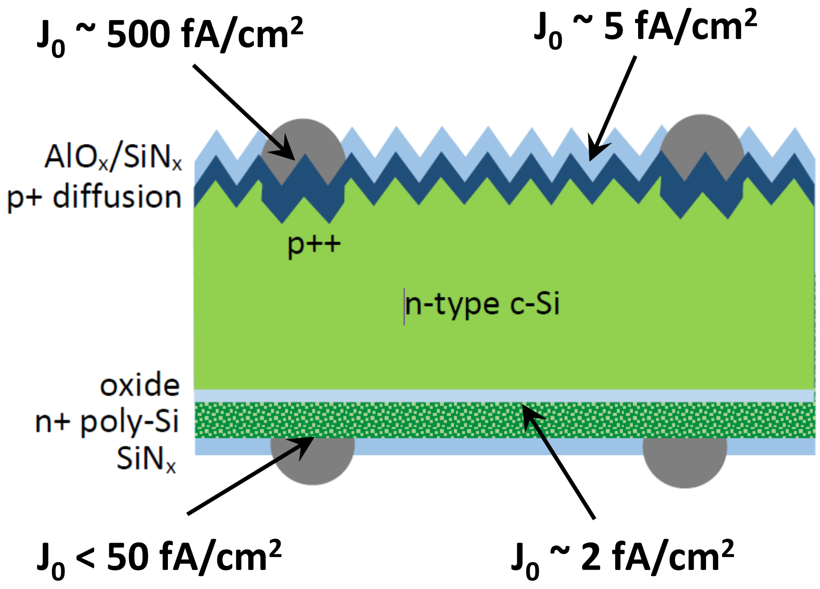


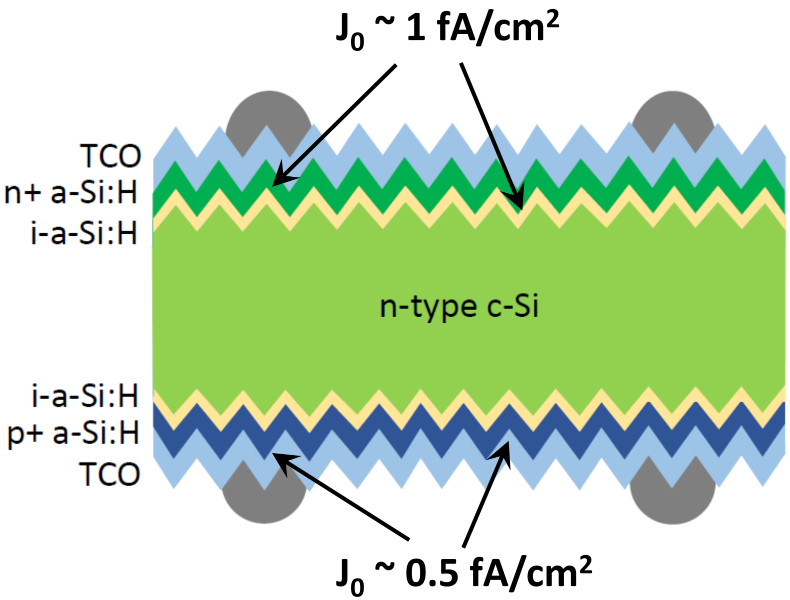


P. Zheng *et al.* submitted to IEEE JPV (2023). Hao Lin *et al.* Nature Energy, published online May 2023.

Recombination losses – surface passivation

- Higher J_0 values on TOPCon front side cause V_{OC} loss ~20-30 mV.
- SHJ passivation on textured surfaces is truly remarkable!





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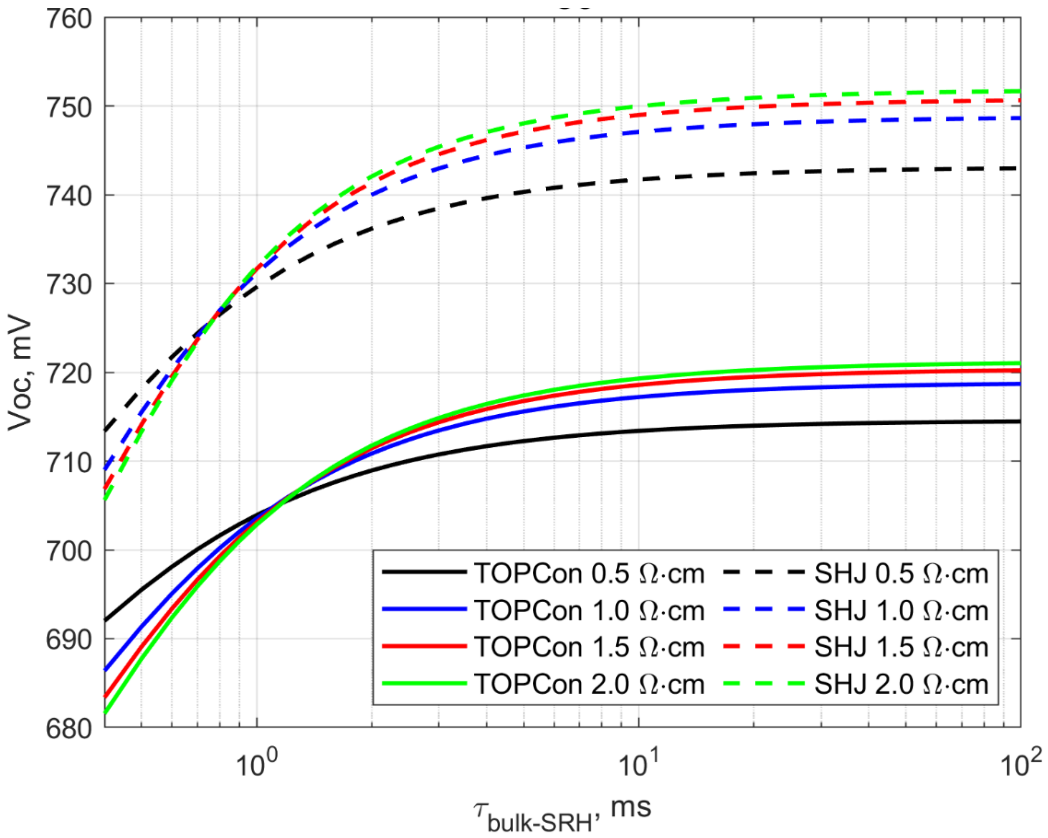
Recombination losses - bulk

Quokka modelling for champion TOPCon and SHJ devices.

- Bulk SRH lifetimes > **5-10 ms** required to achieve best V_{OC}.
- 15 ms and 25 ms used in models for 25.4% (TOPCon) and 26.8% (SHJ) cells.[1,2]
- Is this easily achieved in practice?



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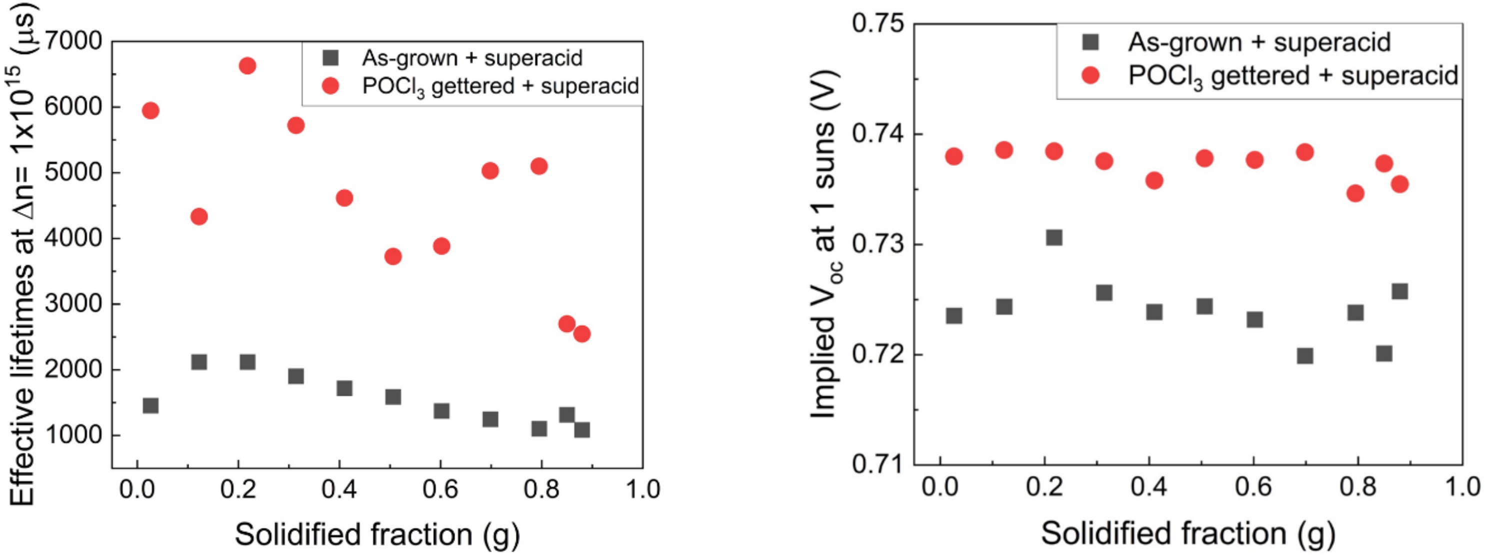
Recombination losses - bulk

Bulk lifetimes for a standard n-type Cz ingot grown for the PV industry.

- Implied V_{OC} increased from ~725 to ~738 mV after phosphorus gettering.
- Gettering embedded in TOPCon process.
- Pre-gettering required for SHJ cells.

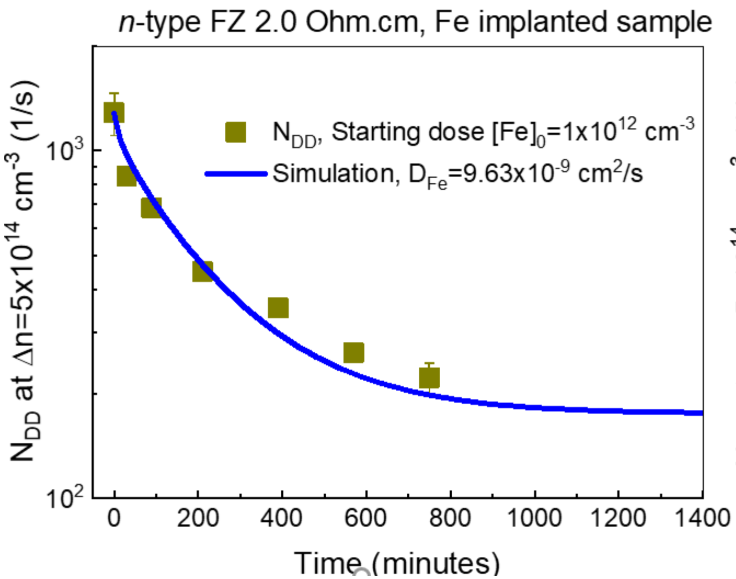


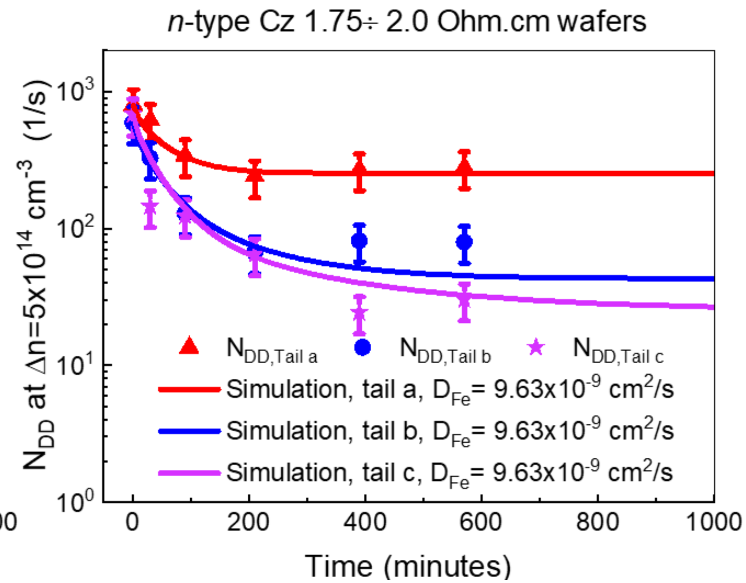
Tien Le *et al.*, in preparation (2023).

Recombination losses - bulk

What impurities are removed by the gettering?

- Cannot use the FeB or FeGa pairing method to identify Fe…
- However - can use kinetics of lifetime increase during gettering process…
- Fe_i is still an important recombination source in n-type Cz, $[Fe_i] \sim 10^{11-12}$ cm^{-3}.

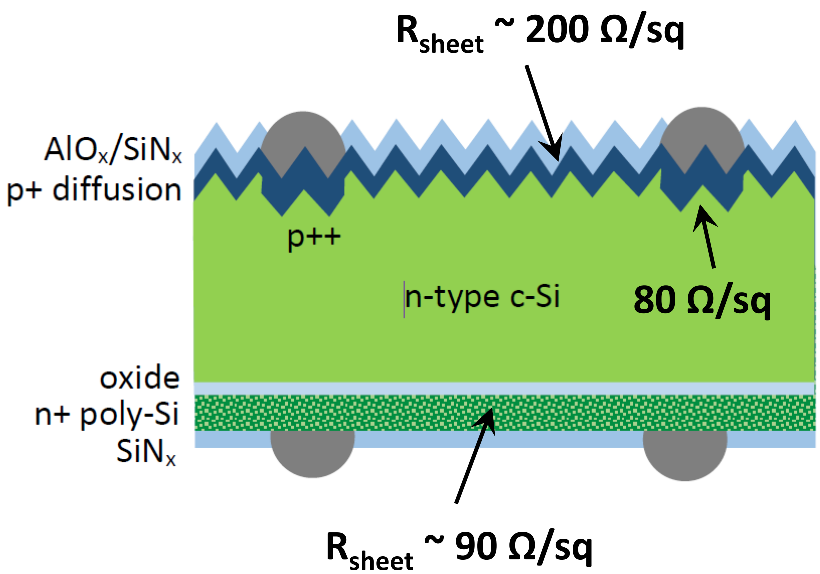


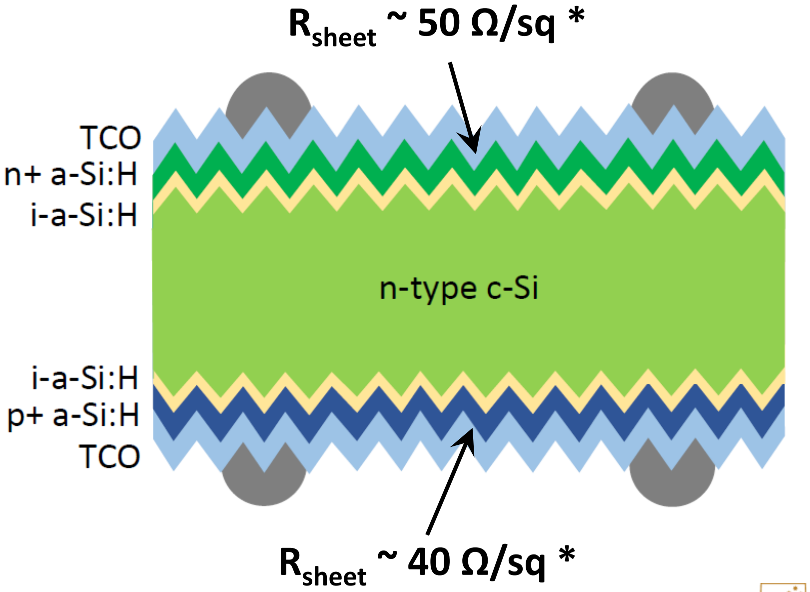


Tien Le *et al.*, in preparation (2023).

Transport losses – lateral resistance

- Very low sheet resistances in SHJ device – due to TCOs with higher mobilities (*more typically 80 – 150 Ω/sq).
- TOPCon front side sheet resistance must be kept high to reduce recombination and remain optically transparent.





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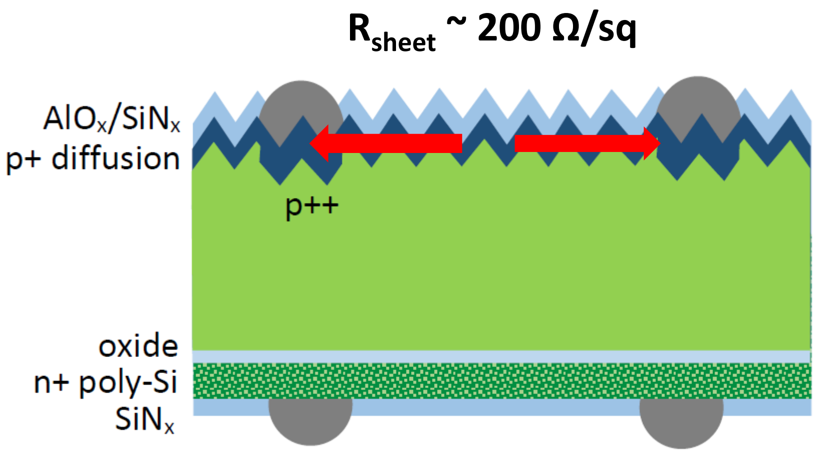
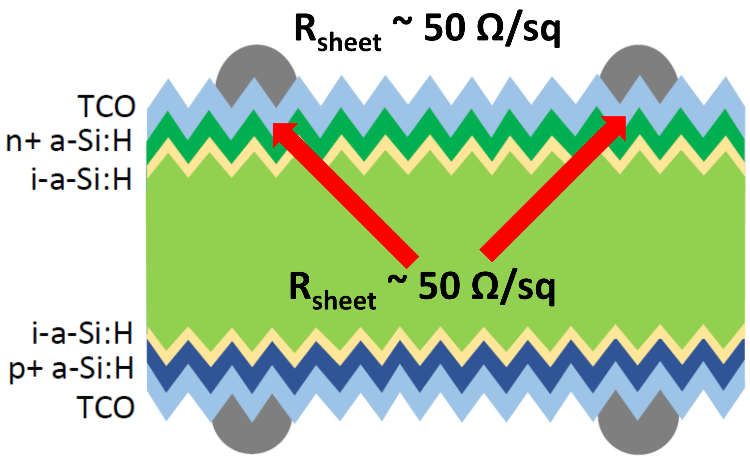
Transport losses – lateral resistance

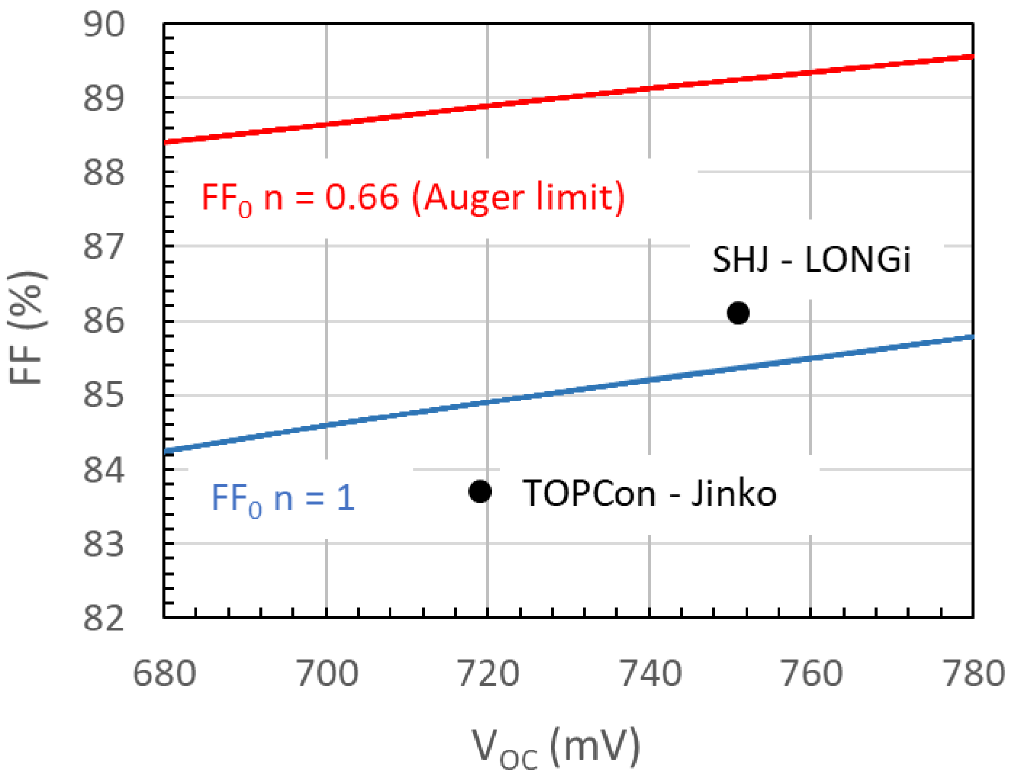
- SHJ rear junction allows wafer bulk to contribute to front side collection.
- Provides parallel conduction path with sheet resistance ~ 50 Ω/sq to assist front TCO.
- By contrast, **all** front side collection in TOPCon cell has to pass through the light p+ region.





Impact of V_{OC} on FF

- In principle, higher V_{OC} allows higher ideal fill factor, FF_0.
- This effect is small compared to the difference in FF.
- Higher FF for SHJ is caused largely by improved lateral transport.
- Note ideality factor is below 1 for SHJ cell – approaching Auger limit!



MA Green, Solid-State Electronics, 1981.

Achieving >26% in mass production – SHJ cells

SHJ cells have already shown potential for > 26% on large-area wafers.

Key challenges for low cost in mass production:

- Equipment capital costs - can these come down quickly enough with scale?
- Low-cost TCOs with high transparency and mobility.
- Wafer pre-gettering required.

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Achieving >26% in mass production – TOPCon cells

- TOPCon cells have also shown potential for > 26% on large area.
- What is required to achieve this in practice?

Jinko Solar Champion TOPCon cells

Date	Efficiency
July 2020	**24.8%**
October 2021	**25.4%**
April 2022	25.7%
October 2022	26.1%
December 2022	26.4%

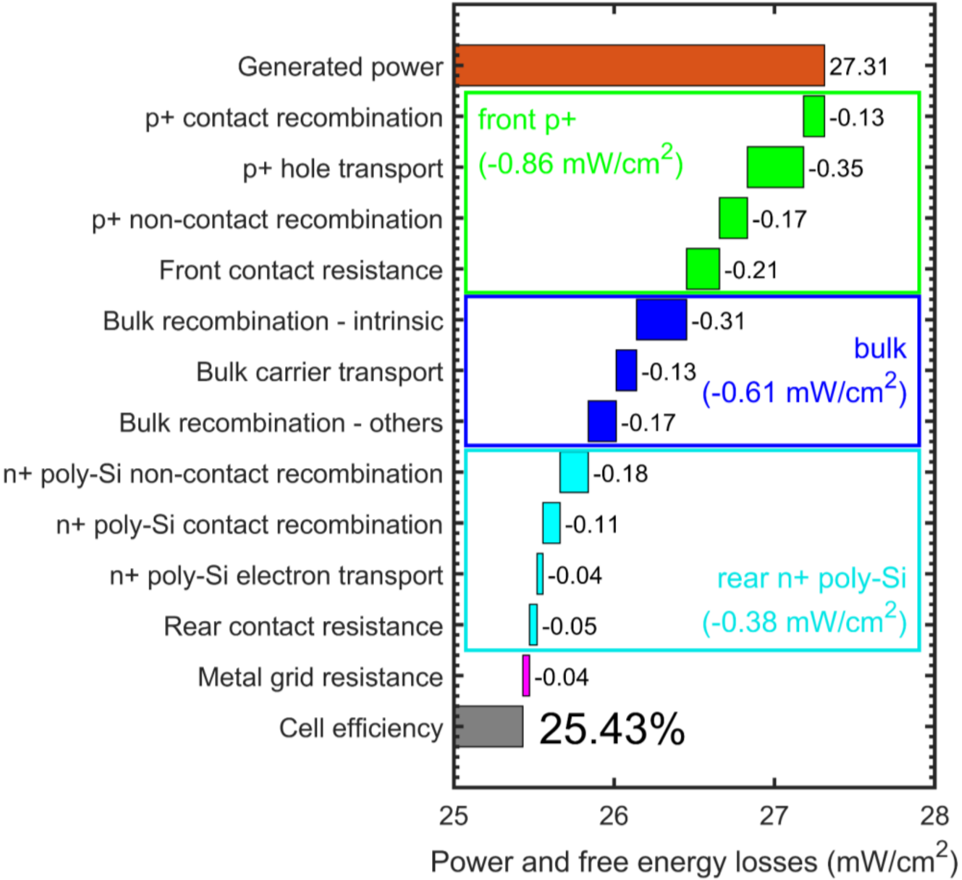
Various Press Releases, Jinko Solar

Loss analysis of 25.4% TOPCon cell

- Quokka 3 simulations.
- Most electrical losses are on the front side:
  - Resistive losses in p+ layer
  - Recombination below and between front contacts.
  - Contact resistance.
  - Very restrictive trade-offs between these…

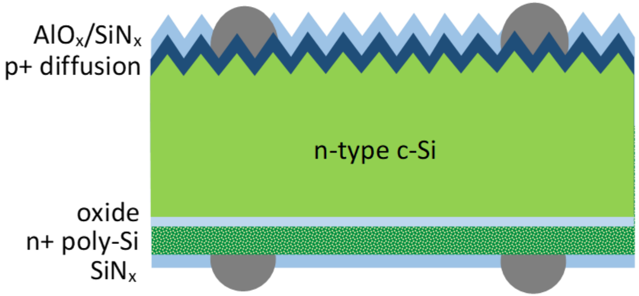
Bulk defects still important

V_{OC} (mV)	J_{SC} (mA/cm²)	FF	efficiency
719	42.2	83.7	25.4%

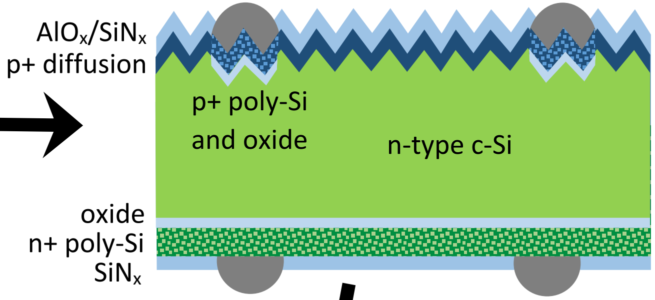


Alternative architectures for poly-Si cells >26%

Standard n-TOPCon

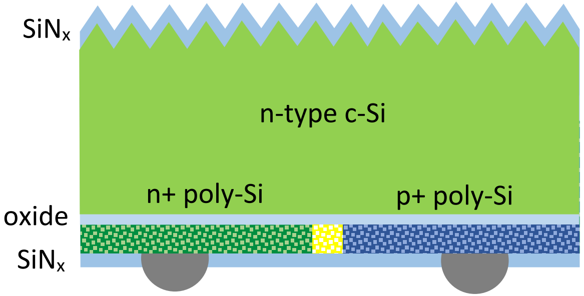


p+ poly-Si under the fingers



- Relaxes front side trade offs.
- Higher V_{OC}
- Requires p+ poly-Si on texture…

poly-Si IBC



- Contact fractions fully optimised.
- No poly-Si on texture.
- Complex processing…

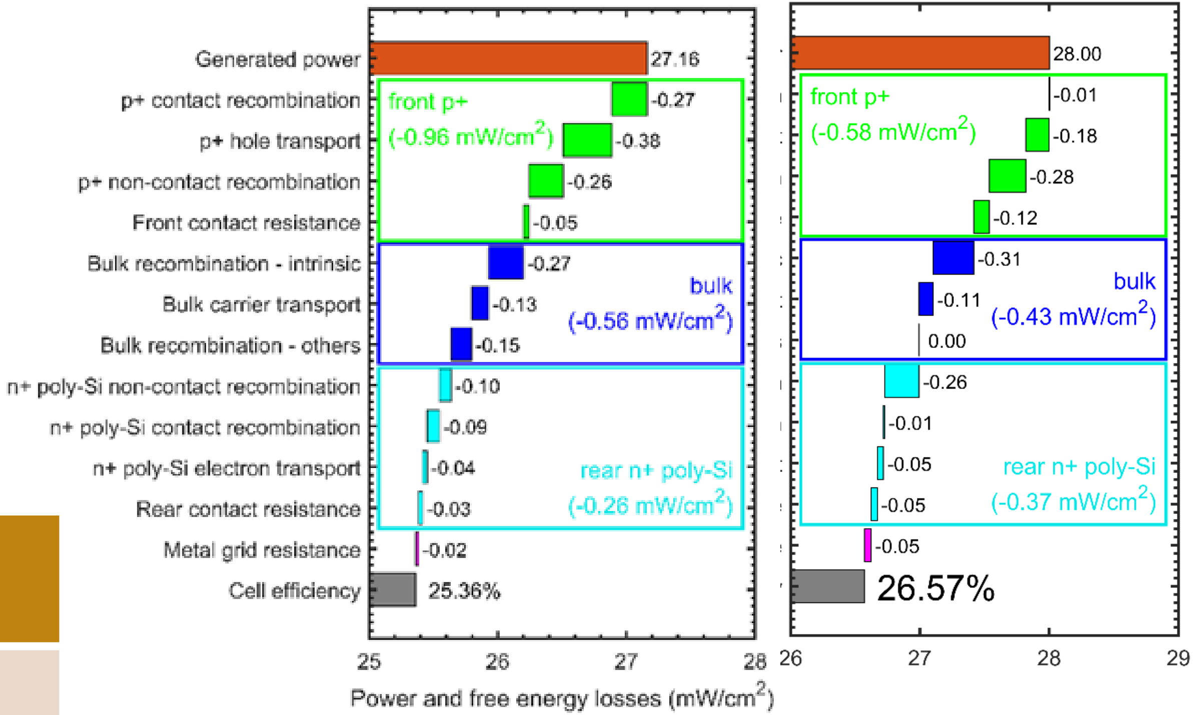
Modelled example - p+ poly-Si under the fingers

Efficiency improves from 25.4% to 26.6%:

- p+ poly-Si under the fingers.
- Intrinsic bulk lifetime (no defects).
- 20 micron fingers (print or plate).

Significantly improved V_{OC} and FF.

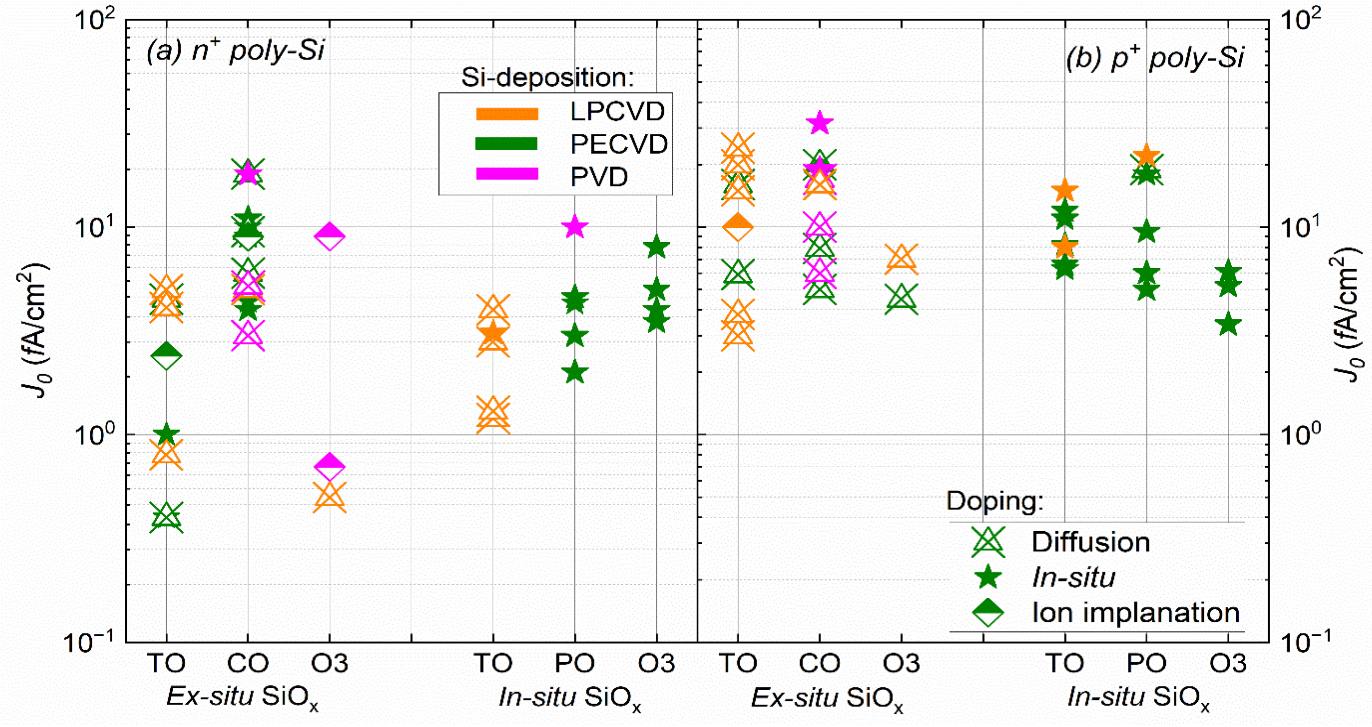
Can compete with SHJ for tandems?



V_{OC} (mV)	J_{SC} (mA/cm²)	FF	efficiency
719	42.2	83.7	25.4%
738	42.4	85.0	26.6%

Difficulties with p+ poly-Si contacts…

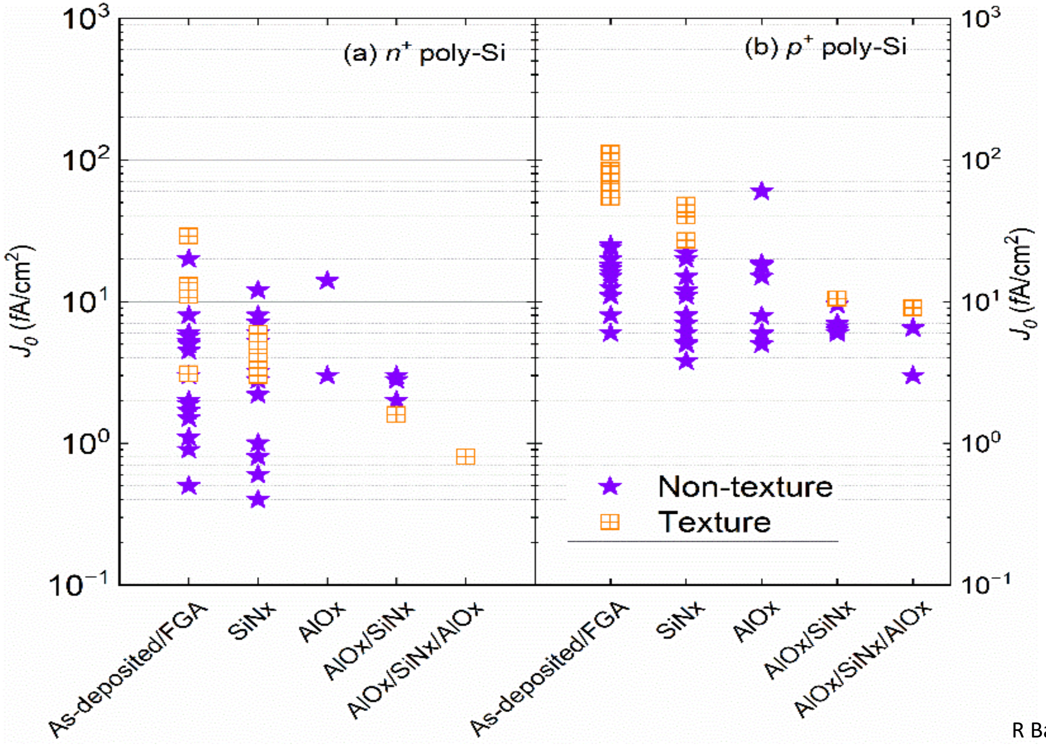
- Poorer surface passivation than n+ poly-Si… ~20mV lower V_{OC}



R Basnet *et al.*, upcoming publication

Difficulties with p+ poly-Si contacts…

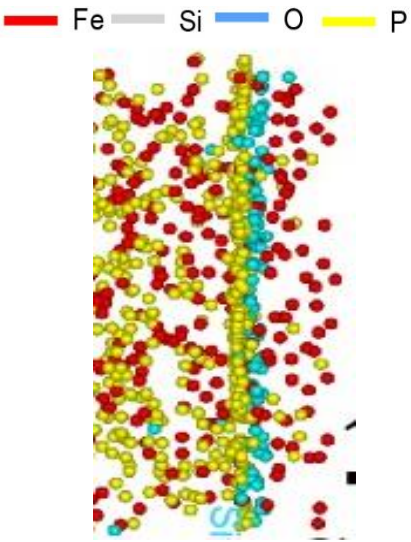
- Even more so on textured surfaces…

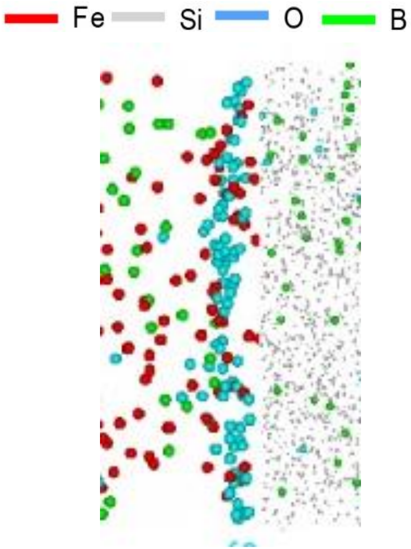


R Basnet *et al.*, upcoming publication

P and B behaviour at oxide interface

- P is more soluble in c-Si than SiO_x – piles-up at interface.
- B is more soluble in SiO_x – accumulates in the oxide, causing damage.
- Effect amplified on textured surface where oxide is locally thin/stressed.
- Alternatives – oxy-nitride interlayers, Ga-doping, pinhole oxides…





A Yadav *et al.* upcoming publication

Conclusions

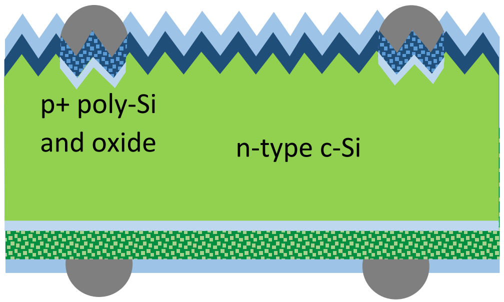
Both TOPCon and SHJ technologies can achieve >26% in production

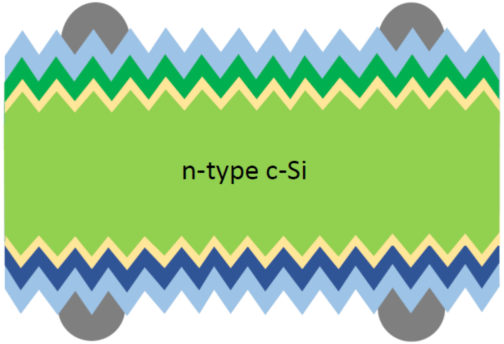
Key challenges for TOPCon

- ~ 26% possible with current architecture.
- > 26.5% will require p+ poly-Si contacts to increase V_{OC}
- Poly under the fingers, or IBC…

Key challenges for SHJ

- Potential for > 26.5% with current architecture.
- Capital costs have to be reduced further (about 2.5 – 3 times higher than TOPCon).
- Development of cost-effective TCOs that are sufficiently transparent and conductive.





Thank you!

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