Beyond 26% silicon solar cells in mass production:
poly-Si or a-Si contacts?

Daniel Macdonald, Sieu Pheng Phang, Tien Le, Rabin Basnet, Di Kang, Thien Truong, AnYao Liu and Andres Cuevas

School of Engineering, The Australian National University
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?
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 \(J_{\text{SC}}\) in SHJ** - parasitic absorption in TCOs and a-Si films
- **Lower \(V_{\text{OC}}\) 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.

<table>
<thead>
<tr>
<th>Cell type</th>
<th>(J_{\text{SC}}) (mA/cm(^2))</th>
<th>(V_{\text{OC}}) (mV)</th>
<th>FF (%)</th>
<th>(\eta) (%)</th>
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<tbody>
<tr>
<td>TOPCon – industry state-of-the-art range (^1)</td>
<td>40.6 – 41.6</td>
<td>717 - 722</td>
<td>83.9 – 84.5</td>
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<td>TOPCon – champion – Jinko (^2)</td>
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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.

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!

$J_0 \sim 500 \text{ fA/cm}^2$

$J_0 \sim 5 \text{ fA/cm}^2$

$J_0 \sim 1 \text{ fA/cm}^2$

$J_0 \sim 0.5 \text{ fA/cm}^2$

$J_0 < 50 \text{ fA/cm}^2$

$J_0 \sim 2 \text{ fA/cm}^2$

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.
- Is this easily achieved in practice?

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.
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$^{-3}$.

$n$-type FZ 2.0 Ohm.cm, Fe implanted sample

$n$-type Cz 1.75÷2.0 Ohm.cm wafers
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.

\[ R_{\text{sheet}} \approx 200 \, \Omega/\text{sq} \]

\[ R_{\text{sheet}} \approx 50 \, \Omega/\text{sq} * \]

\[ R_{\text{sheet}} \approx 90 \, \Omega/\text{sq} \]

\[ R_{\text{sheet}} \approx 40 \, \Omega/\text{sq} * \]
Transport losses – lateral resistance

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

\[ R_{\text{sheet}} \sim 200 \ \Omega/\text{sq} \]

\[ R_{\text{sheet}} \sim 50 \ \Omega/\text{sq} \]
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?

\[ Jinko Solar Champion TOPCon cells \]

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<th>Date</th>
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<td>July 2020</td>
<td>24.8%</td>
</tr>
<tr>
<td>October 2021</td>
<td>25.4%</td>
</tr>
<tr>
<td>April 2022</td>
<td>25.7%</td>
</tr>
<tr>
<td>October 2022</td>
<td>26.1%</td>
</tr>
<tr>
<td>December 2022</td>
<td>26.4%</td>
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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

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Alternative architectures for poly-Si cells >26%

**Standard n-TOPCon**

- ALOₓ/SiNx
- p+ diffusion
- oxide
- n+ poly-Si
- SiNx

**p+ poly-Si under the fingers**

- ALOₓ/SiNx
- p+ diffusion
- oxide
- n+ poly-Si
- SiNx

- p+ poly-Si
- and oxide
- n-type c-Si

**poly-Si IBC**

- SiNx
- oxide
- n+ poly-Si
- p+ poly-Si

- n-type c-Si

**Benefits**

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

- 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?

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Difficulties with p+ poly-Si contacts...

- Poorer surface passivation than n+ poly-Si... \( \sim 20 \text{mV lower } V_{\text{OC}} \)

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!

This work has been supported by the Australian Renewable Energy Agency (ARENA)