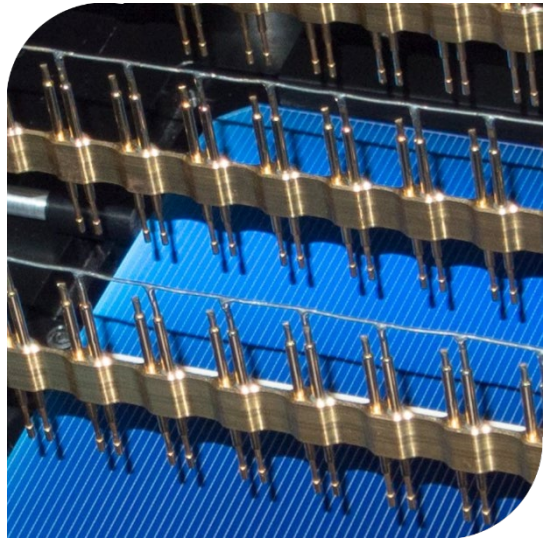
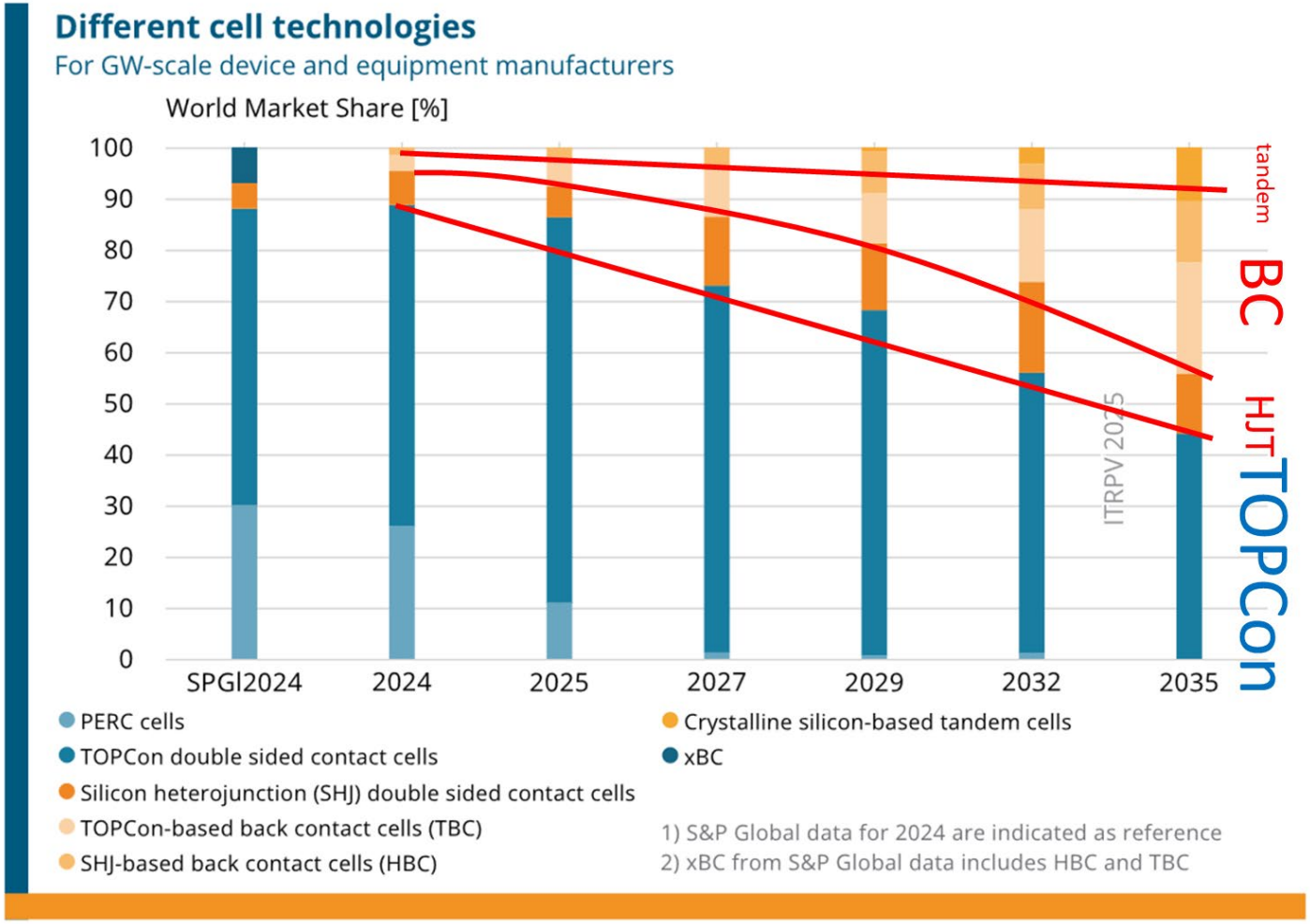



Status polyZEBRA TBC technology

Jonathan Linke, Jan Hoß, Saman Sharbaf Kalaghichi,
Christoph Peter, Valentin Mihailetchi,
Florian Buchholz, Lejo Joseph Koduvelikulathu

ISC research for a sunny future

Market situation and forecast



Status of BC production

CLEAN ENERGY REVIEWS

Most Efficient Residential Solar Panels 2025 * V5.2 July 2025

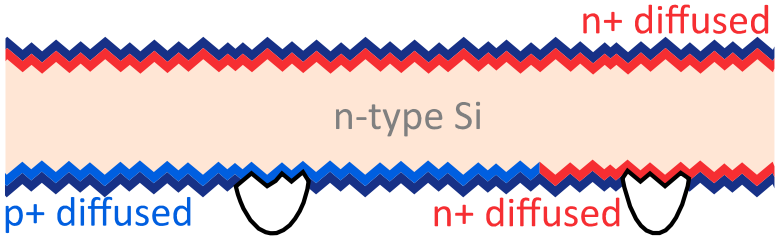
Manufacturer	Model	Power Rating	Cell Technology	Efficiency
AIKO	Neostar 3P54	495W	N-Type **ABC** (Back Contact)	**24.8 %**
maxeon	Maxeon 7	445W	N-Type **IBC** (Back-contact)	**24.1 %**
LONGi Solar	Hi-MO X10 Explorer	490W	N-Type **HPBC 2.0** Hybrid Back Contact	**24.0 %**
JinKO Solar	Tiger NEO 60HL4-V	515W	N-Type **TOPcon**	**23.8 %**
RECOM TECHNOLOGIES	Black Tiger Series	460W	N-Type **TOPcon** (Back Contact)	**23.6 %**
SPIC	Andromeda 3.0	460W	N-Type **TBC** (Back Contact)	**23.6 %**
ASTRONERGY	Astro N7s Series	515W	N-Type **TOPcon**	**23.2 %**
HUASUN	Himalaya G12R	450W	N-Type **HJT**	**23.0 %**
Trinasolar	Vertex S+	465W	N-Type **TOPCon**	**23.0 %**
CanadianSolar	TOPHiKu6	470W	N-Type **TOPcon**	**23.0 %**
WINAICO	WST-NGX-D3	450W	N-Type **TOPcon**	**23.0 %**

Based on ISC‘s ZEBRA technology

From ZEBRA to polyZEBRA

ZEBRA

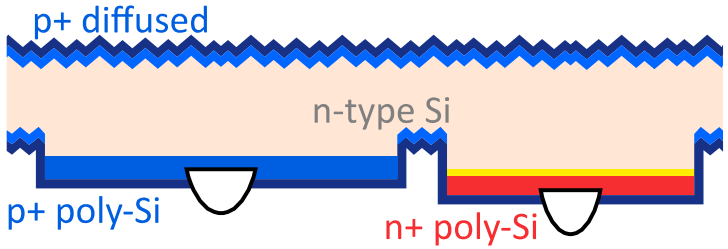
- p/n regions diffused
- Direct contact of p/n regions
- >24% efficiency in production

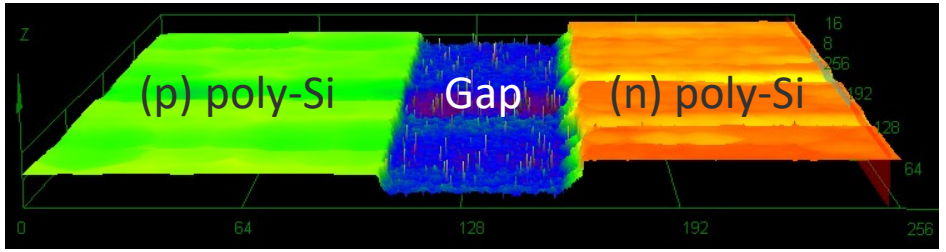


Upgrade

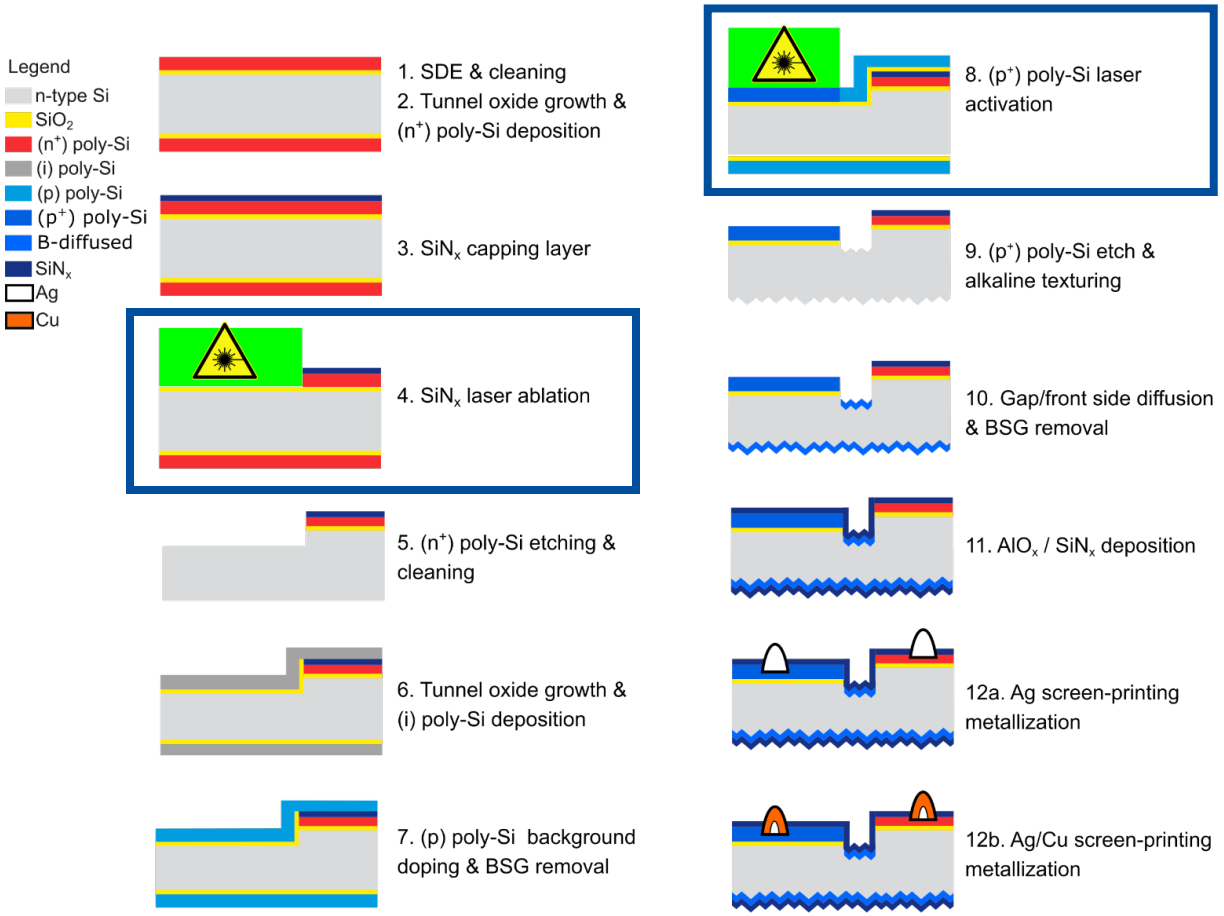
polyZEBRA

- p/n regions TOPCon technology
- Textured gap between p/n regions
- >25% efficiency potential



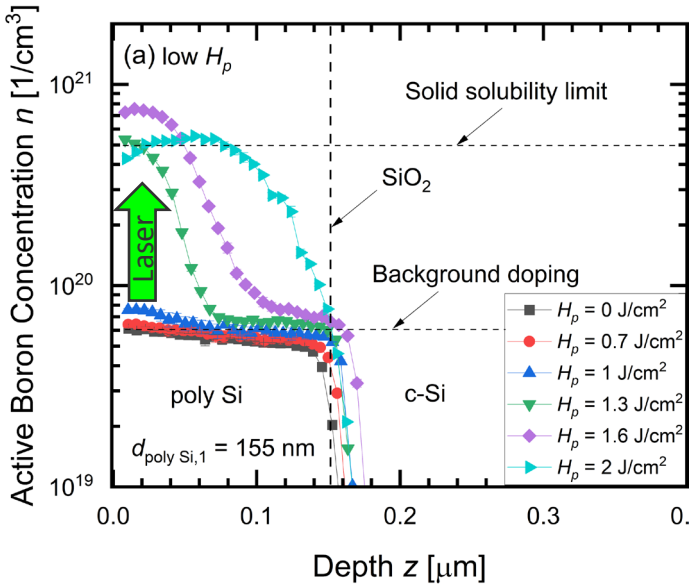


polyZEBRA process flow



Patent pending

- Compatible with PECVD a-Si depositions
- Electrode patterning by two laser steps
  - (n) poly-Si: Mask ablation
  - (p) poly-Si: Dopant activation (maskless)



S. Sharbaf Kalaghichi et al., Solar 2023, 3, 362-381

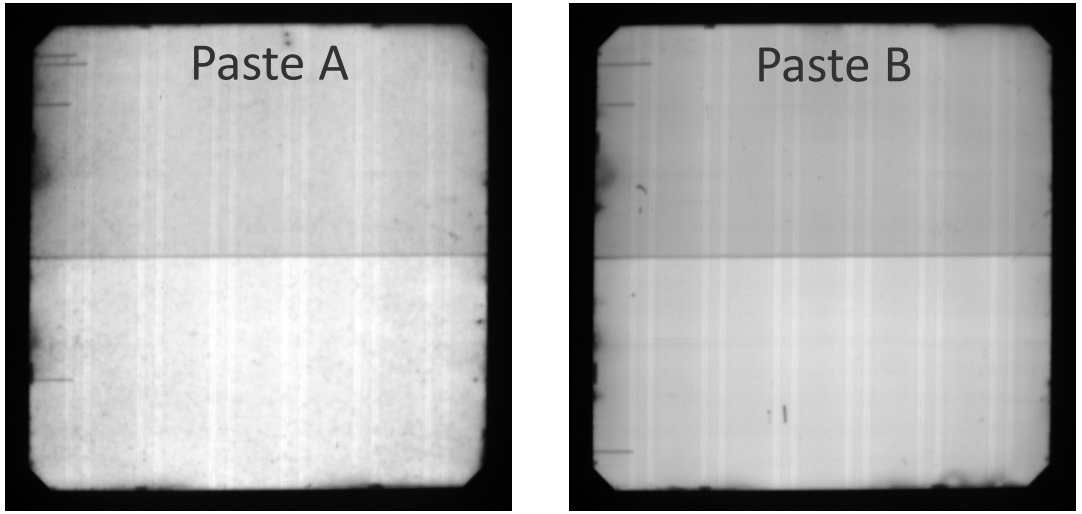
Requirements for successful TBC solar cells

1. Vanishing metal recombination
2. Excellent surface passivation
3. Low breakdown voltage
4. Low Ag consumption
5. Cost competitiveness

1. Vanishing metal recombination

- Vanishing $J_{0,met}$ with paste B:
  - Barely measurable iV_{oc}-to-V_{oc} loss
  - Higher Rshunt, pFF
    → less spiking through tunnel oxide
- Better contact of paste B:
  - Smaller pFF-to-FF loss
  - EL image smoother

		Paste A	Paste B
Passivation	$PL2V_{oc}$ cell precursor	716mV	**708mV**
	V_{oc} cell	709mV	706mV
	iV_{oc}-to-V_{oc} loss	7mV	**2mV**
Contact	pFF	82.7%	83.1%
	FF	80.3%	81.2%
	pFF-to-FF loss	2.4%	**1.9%**



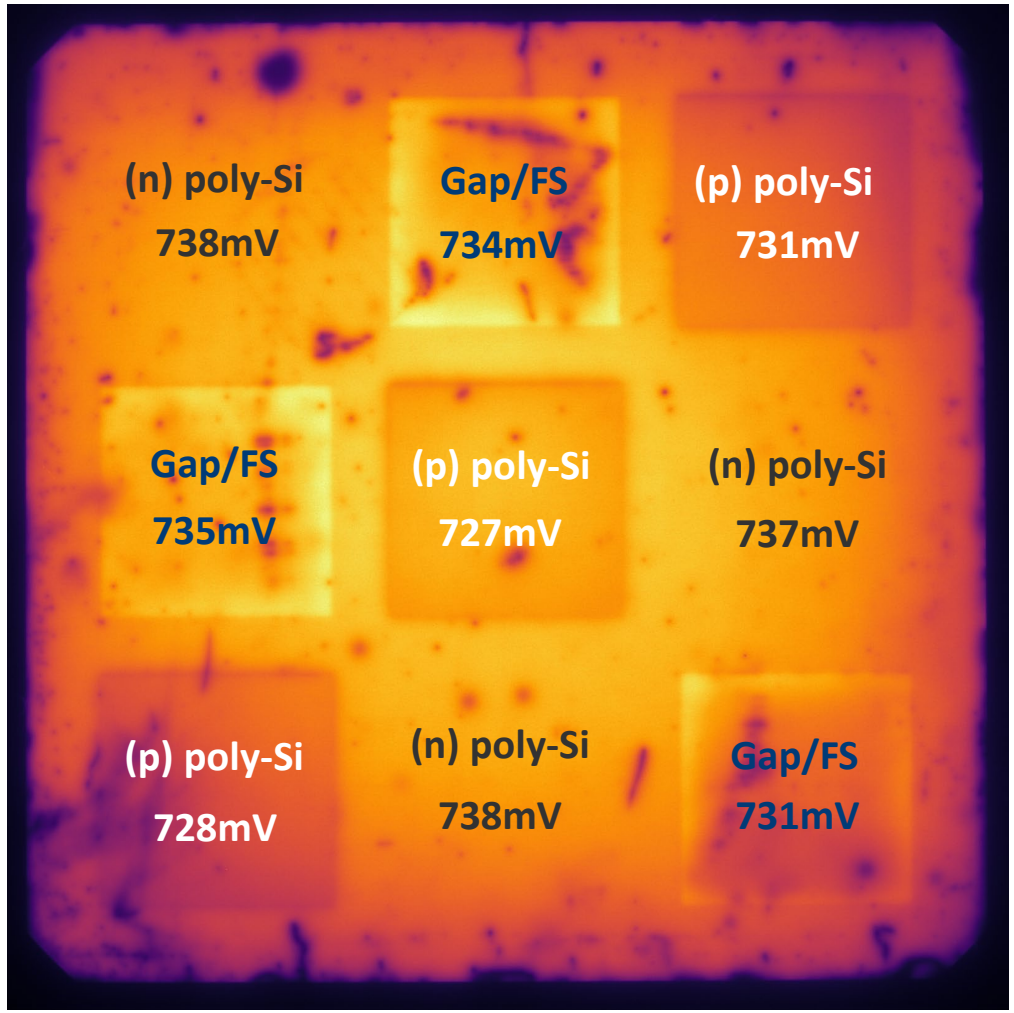
J. Linke et al., Proc. EU-PVSEC 2025, 020035

Requirements for successful TBC solar cells

1. Vanishing metal recombination ✓
2. **Excellent surface passivation**
3. Low breakdown voltage
4. Low Ag consumption
5. Cost competitiveness

2. Excellent surface passivation

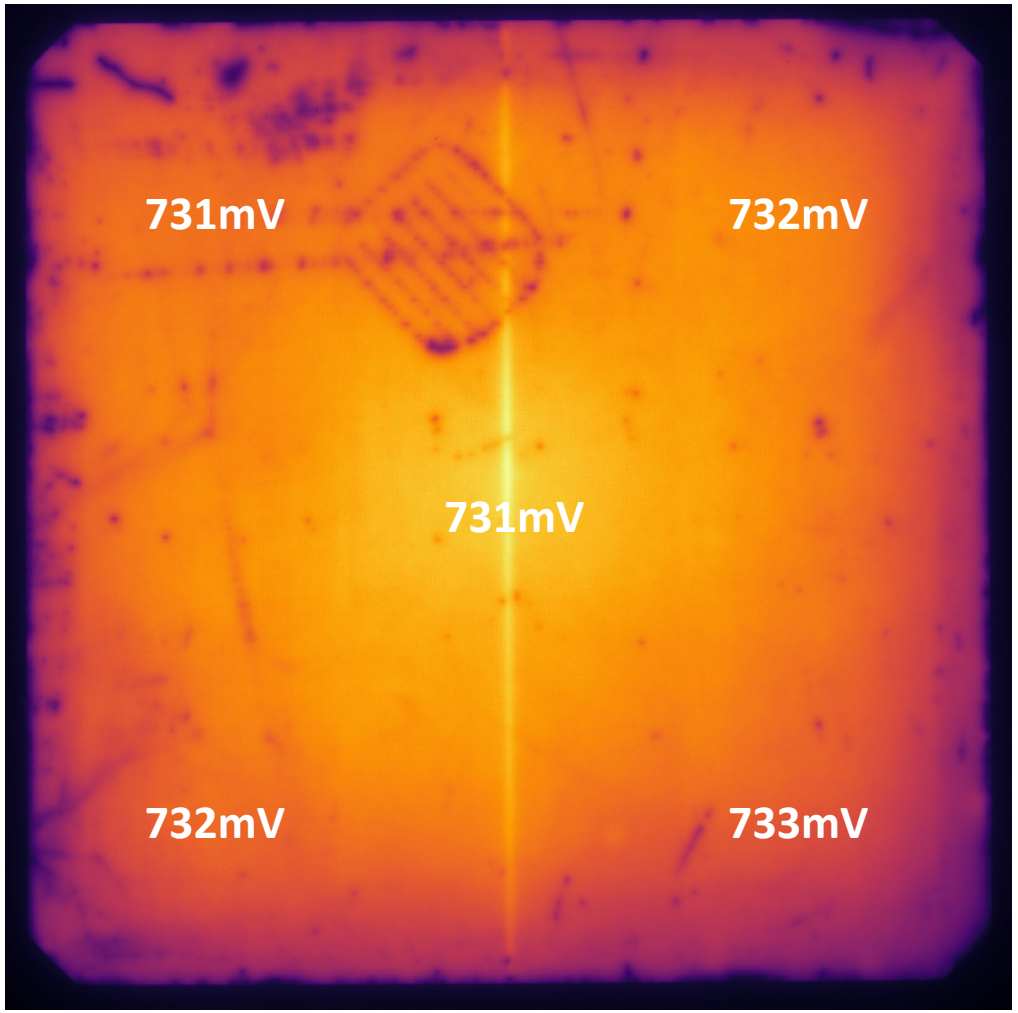
- Process traces from manual wafer handling
- Excellent surface passivation for all regions achieved with adjusted passivation stack



2. Excellent surface passivation

- Process traces from manual wafer handling
- Excellent surface passivation for all regions achieved with adjusted passivation stacks
- Confirmed on unmetallized cell precursors enabling >25% cell efficiency

From experience even higher voltages expected from lab to fab

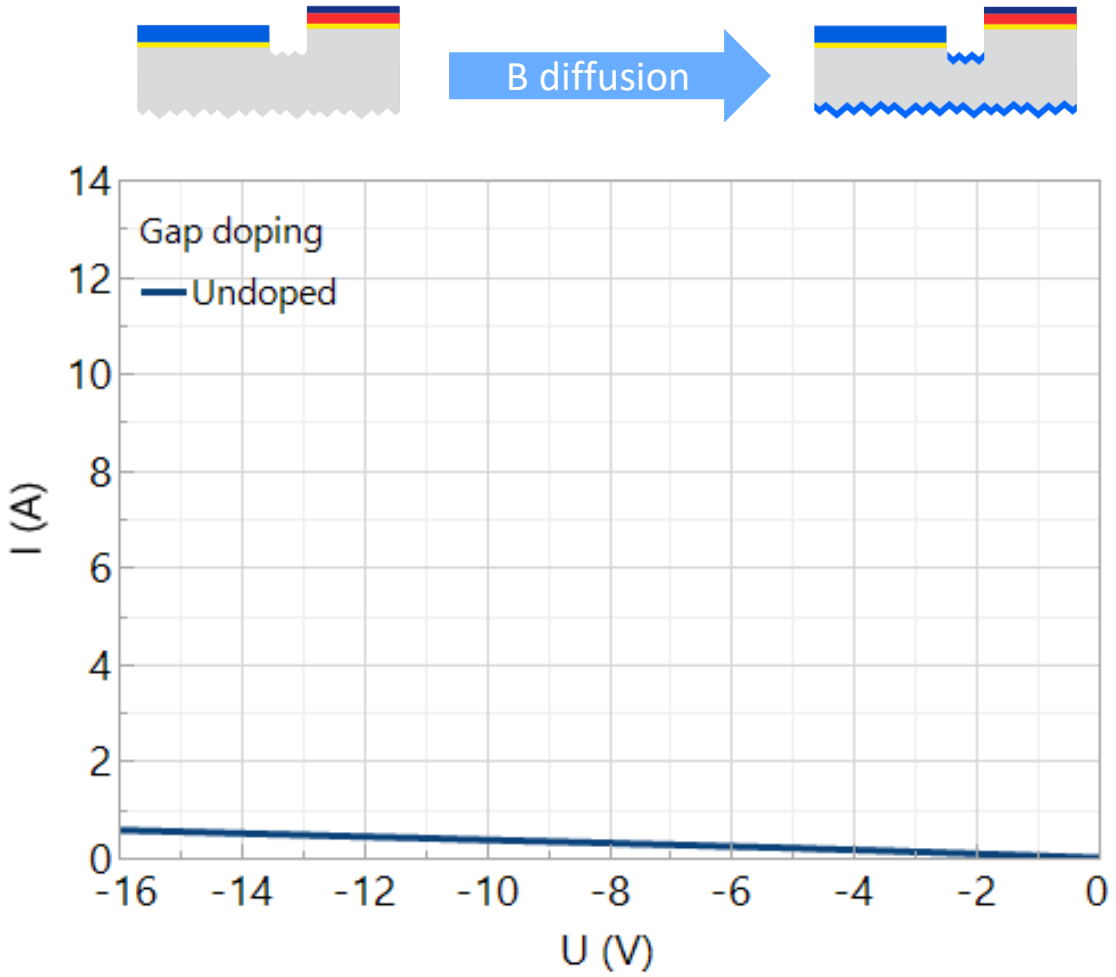


Requirements for successful TBC solar cells

1. Vanishing metal recombination ✓
2. Excellent surface passivation ✓
3. **Low breakdown voltage**
4. Low Ag consumption
5. Cost competitiveness

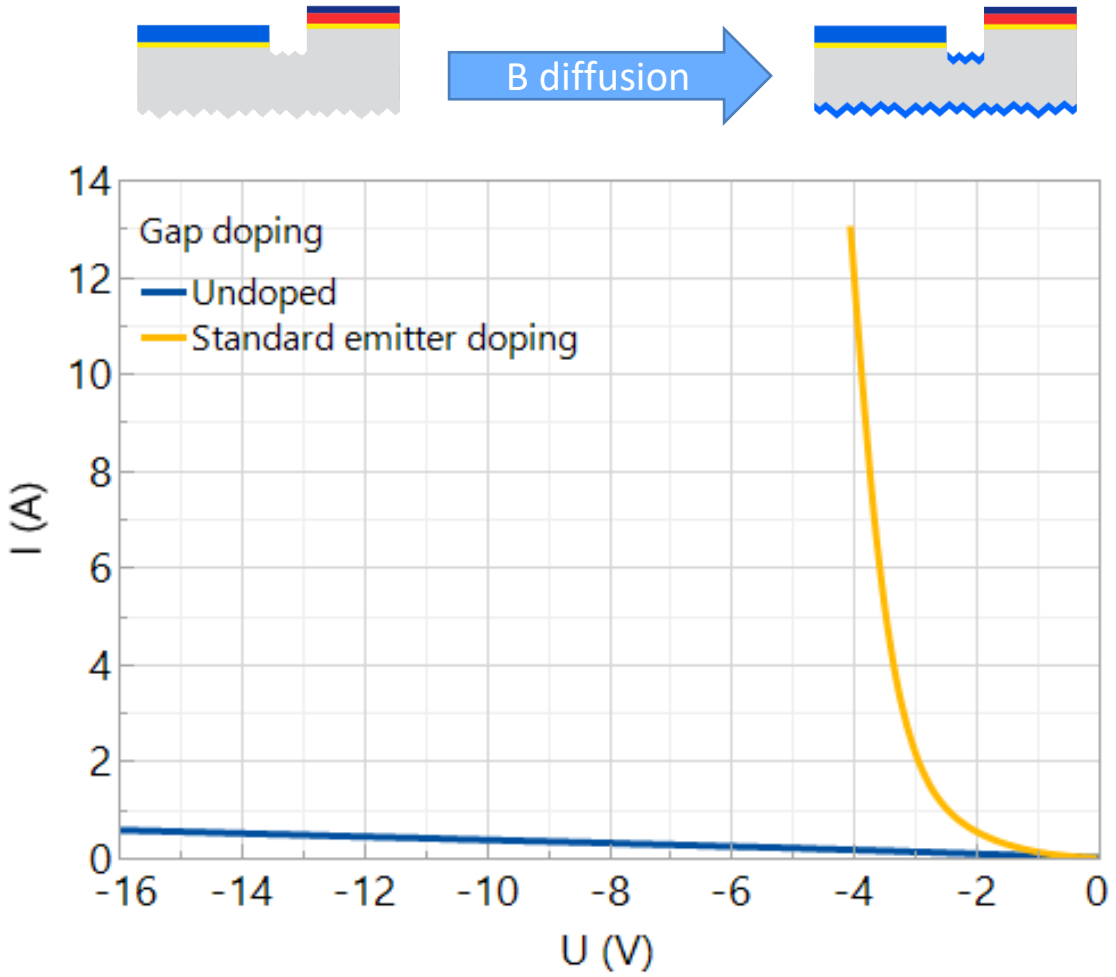
3. Low breakdown voltage

- Low breakdown voltage important for partial shading behavior
- Influence of gap doping
  - Undoped: No breakdown



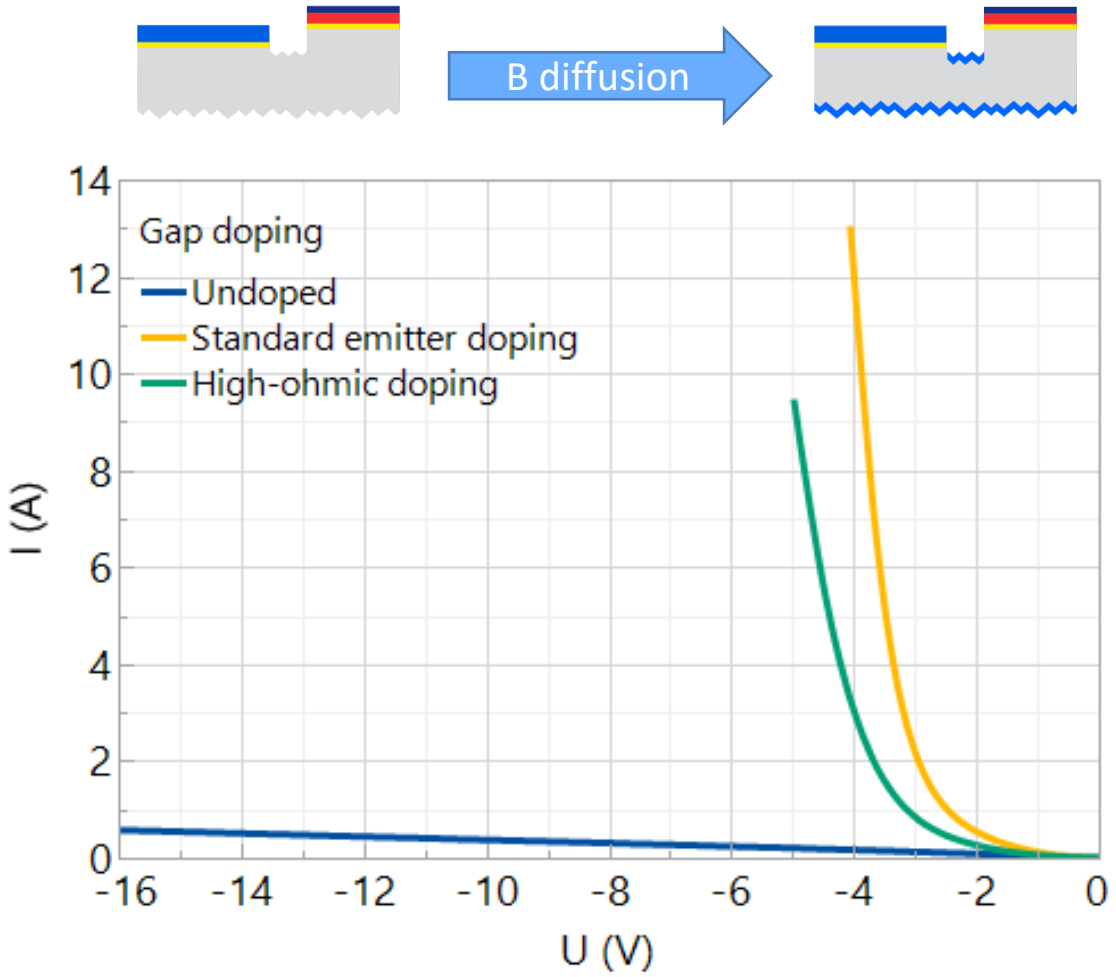
3. Low breakdown voltage

- Low breakdown voltage important for partial shading behavior
- Influence of gap doping
  - Undoped: No breakdown
  - Standard emitter doping: Breakdown at -3V



3. Low breakdown voltage

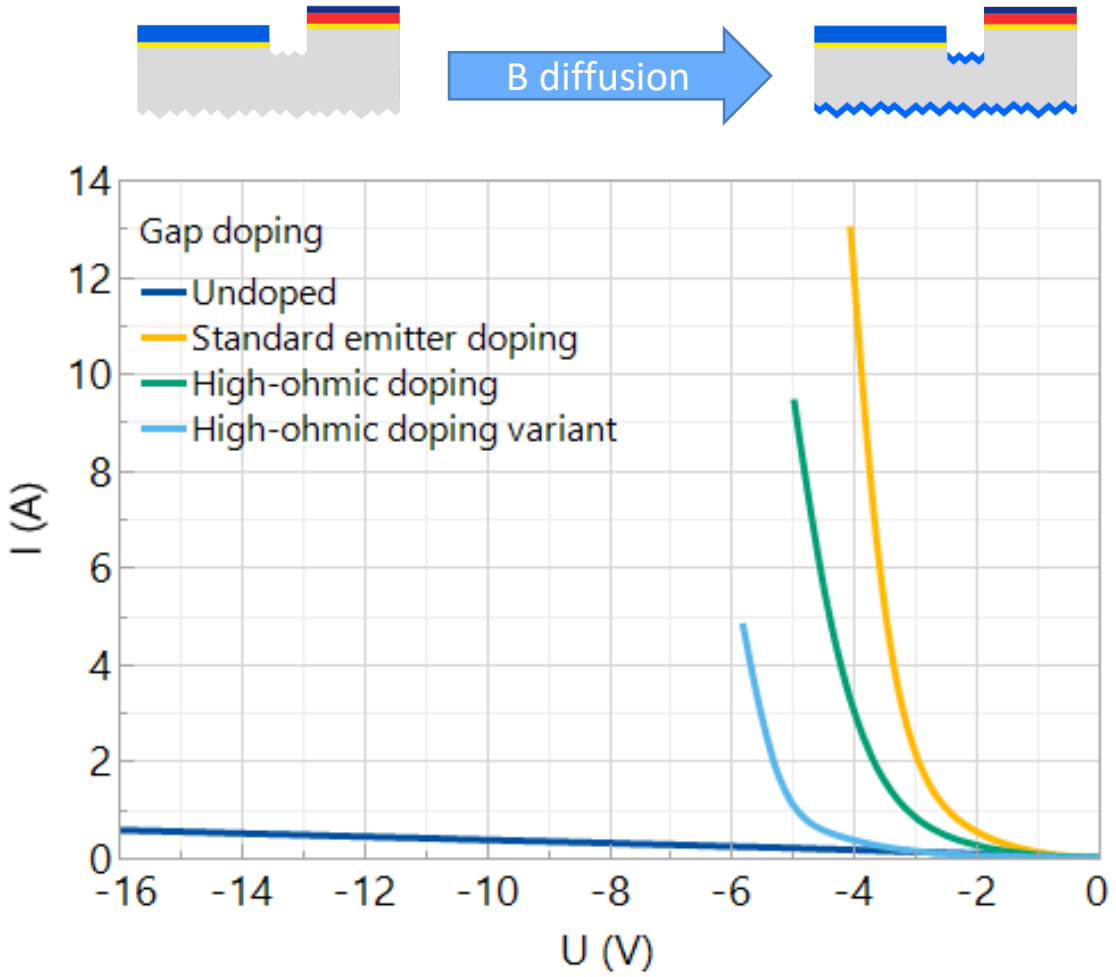
- Low breakdown voltage important for partial shading behavior
- Influence of gap doping
  - Undoped: No breakdown
  - Standard emitter doping: Breakdown at -3V
  - High-ohmic doping: Shift to -4V



3. Low breakdown voltage

- Low breakdown voltage important for partial shading behavior
- Influence of gap doping
  - Undoped: No breakdown
  - Standard emitter doping: Breakdown at -3V
  - High-ohmic doping: Shift to -4V
  - High-ohmic doping variant: Shift to -5V

Breakdown voltage can be tuned

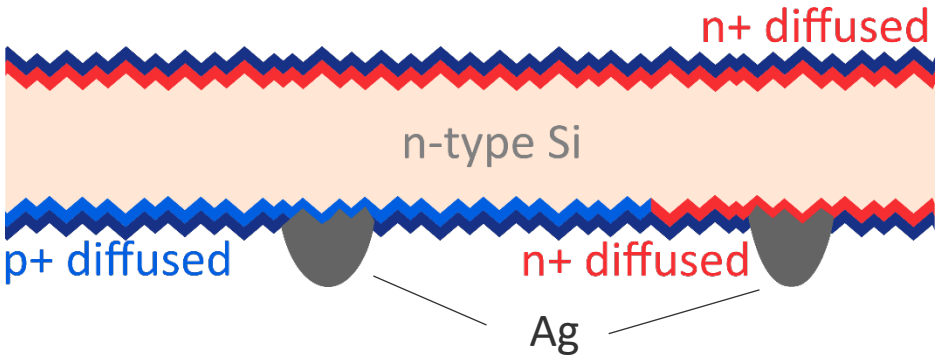


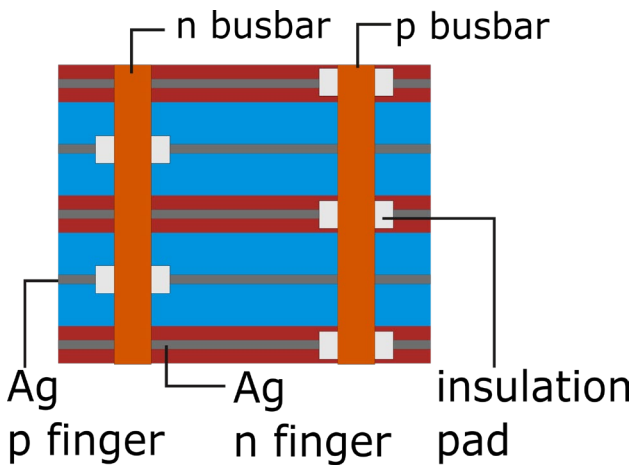
Requirements for successful TBC solar cells

1. Vanishing metal recombination ✓
2. Excellent surface passivation ✓
3. Low breakdown voltage ✓
4. **Low Ag consumption**
5. Cost competitiveness

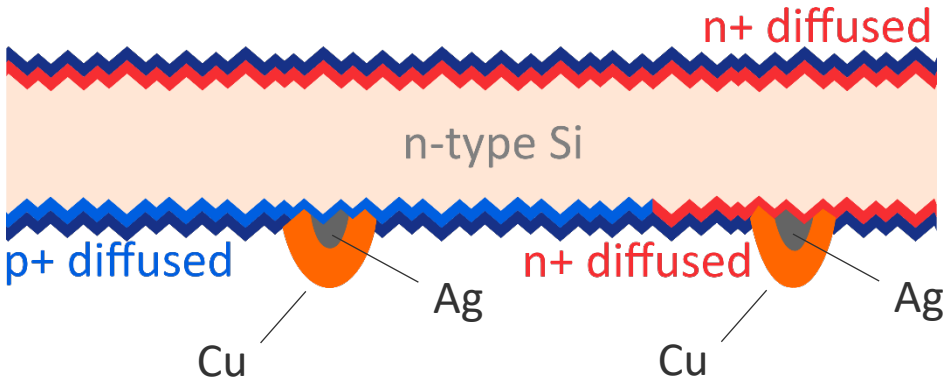
4. Low Ag consumption

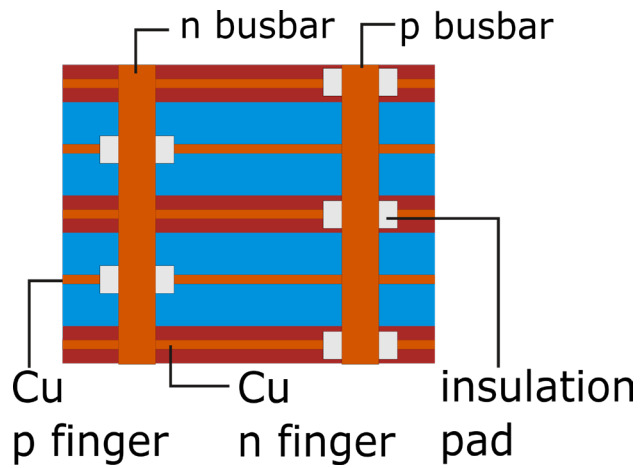
1. Replacement of **BBs**





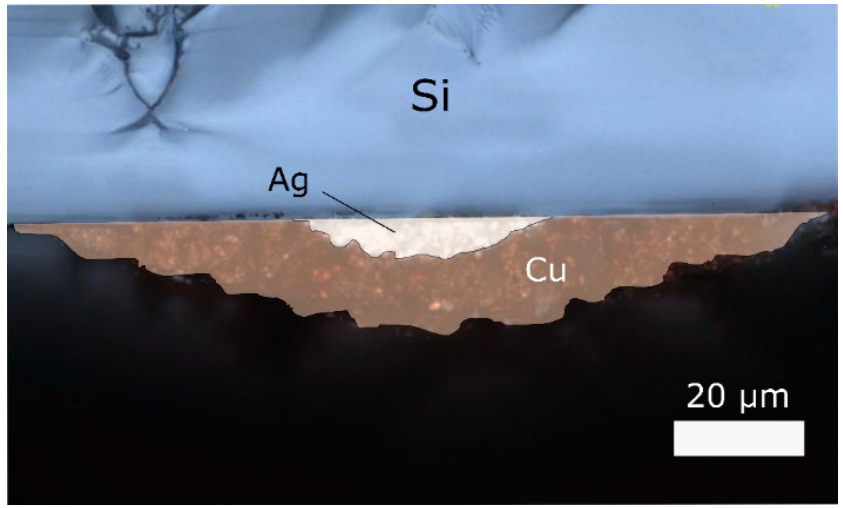
2. Replacement of **fingers**



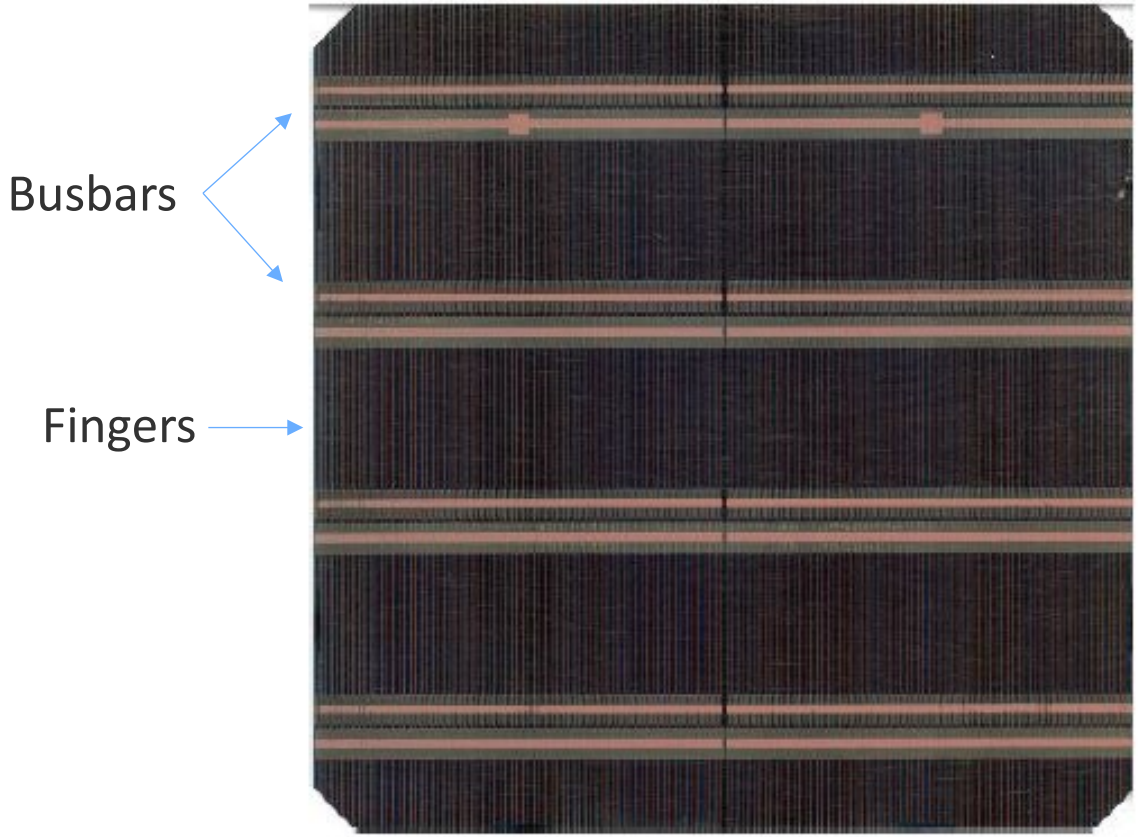


4. Low Ag consumption

Ag seed layer for contact formation,
Cu finger for lateral conductivity

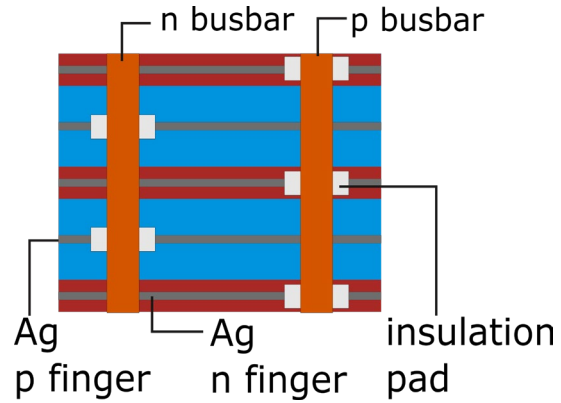


N. Chen et al, Proc. SiliconPV 2022



4. Low Ag consumption

	η	J_{sc} (mA/cm²)	V_{oc} (mV)	FF	pFF
Champion cell	**24.3%**	41.6	711	82.1%	83.7%
Mean ± stdev	24.0 ± 0.3%	41.5 ± 0.1	708 ± 3	81.6 ± 0.4%	83.1 ± 0.4%



- Screen-printed Ag fingers and Cu busbars with **24.3%** cell efficiency
- Cu paste cured on industrial double-belt laminator tool (throughput ~8.000wph)
- Champion cell efficiency +0.2% compared to previous reported data

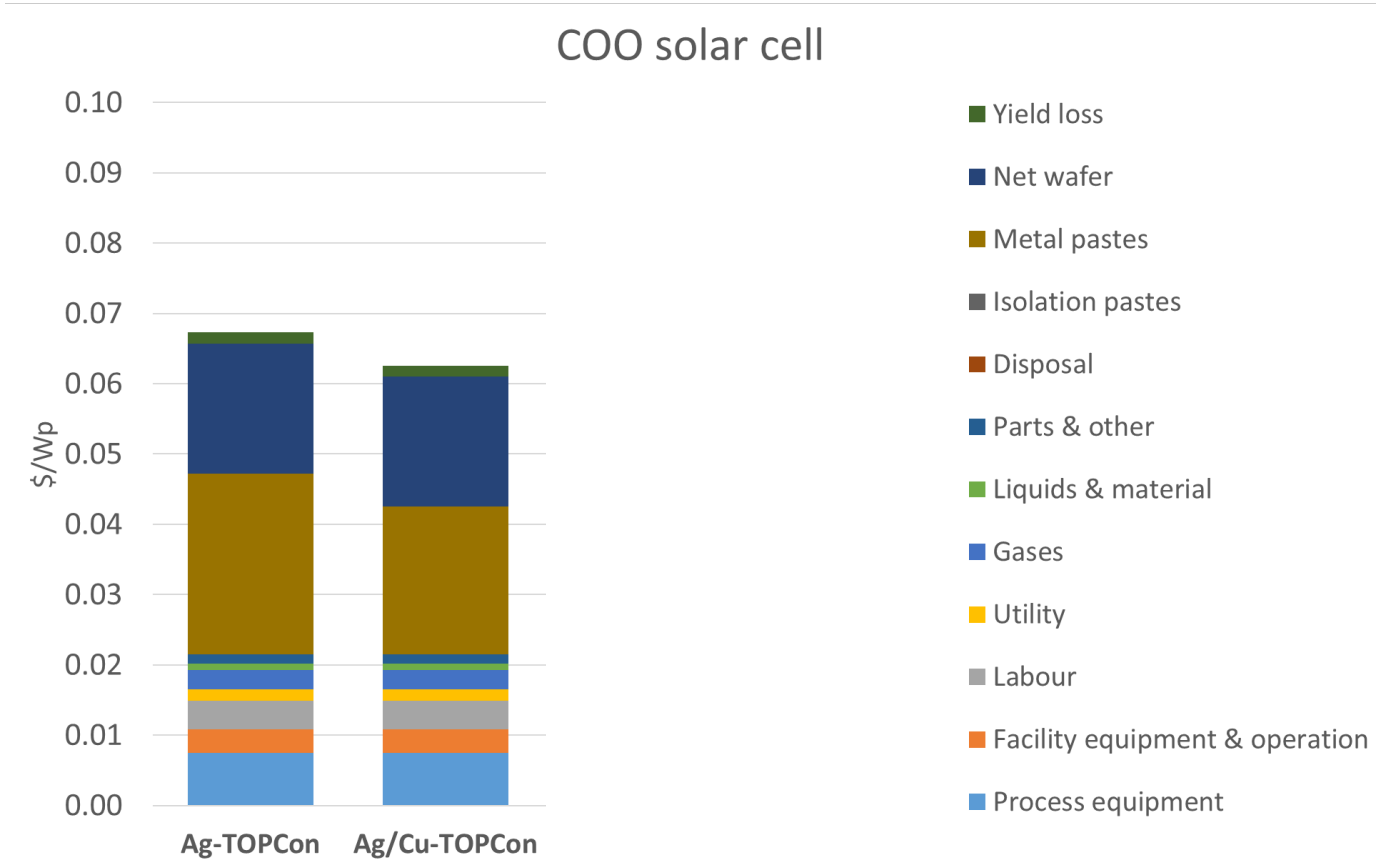
44% Ag saving (up to 83% with Cu fingers integrated)

Requirements for successful TBC solar cells

1. Vanishing metal recombination ✓
2. Excellent surface passivation ✓
3. Low breakdown voltage ✓
4. Low Ag consumption ✓
5. **Cost competitiveness**

5. Cost competitiveness

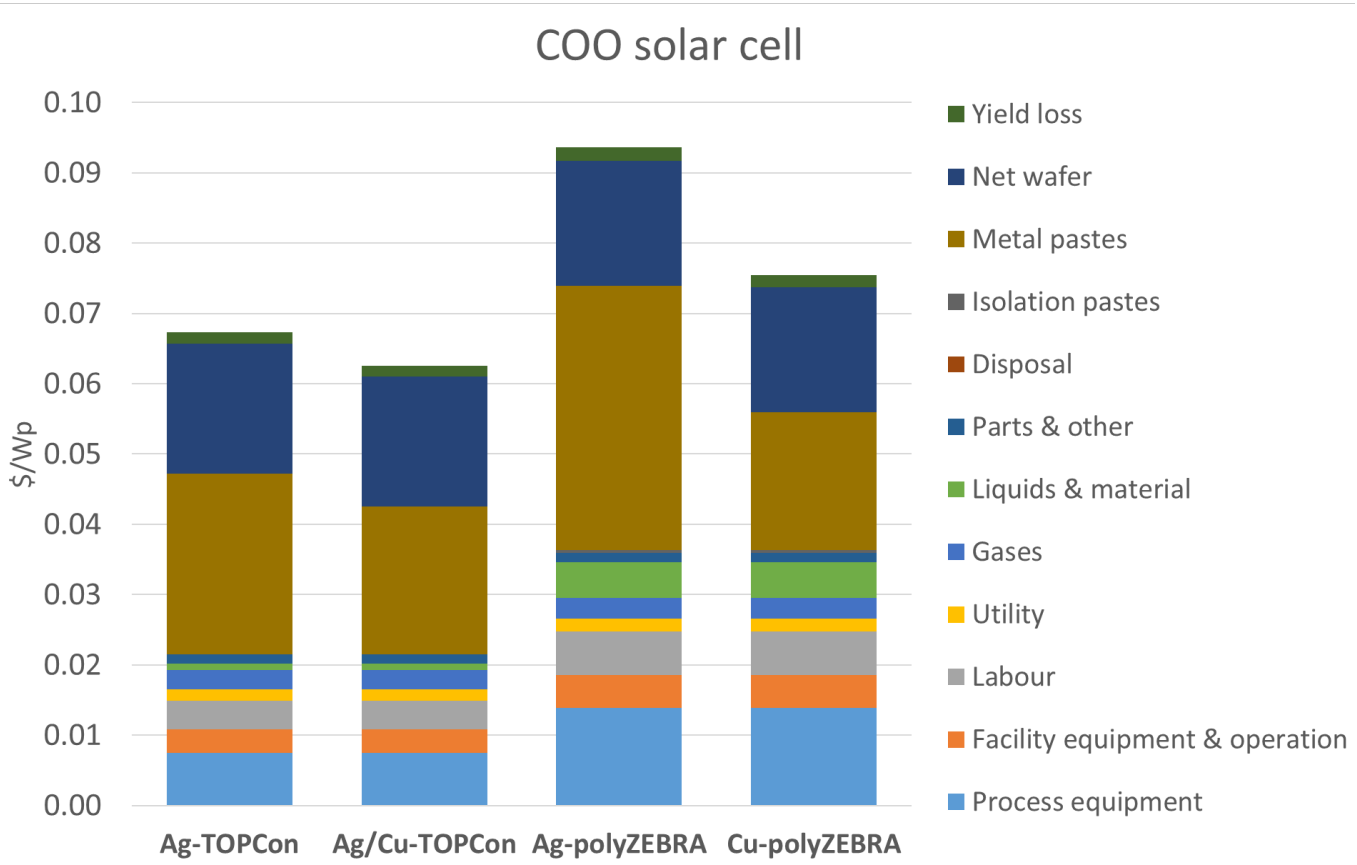
- Absolute values volatile, but differences stable



5. Cost competitiveness

- Absolute values volatile, but differences stable
- +0.8 $c/Wp for Cu-polyZEBRA compared to standard TOPCon
- Higher module efficiency of polyZEBRA reduces LCOE for utility systems

Cost competitive to TOPCon



5. Cost competitiveness

	η	J_{sc} (mA/cm²)	V_{oc} (mV)	FF	pFF
Champion cell	**24.2%**	41.9	705	81.8%	83.2%
Mean ± stdev	23.9 ± 0.2%	41.9 ± 0.1	701 ± 3	81.3 ± 0.3%	82.8 ± 0.3%

- First cell batch with PECVD a-Si depositions for both polarities
- 24.2% champion efficiency

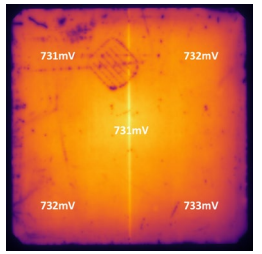
Requirements for successful TBC solar cells

1. Vanishing metal recombination ✓
2. Excellent surface passivation ✓
3. Low breakdown voltage ✓
4. Low Ag consumption ✓
5. Cost competitiveness ✓

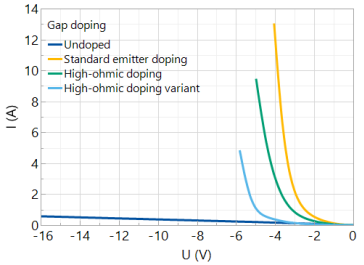
All requirements fulfilled

Conclusions

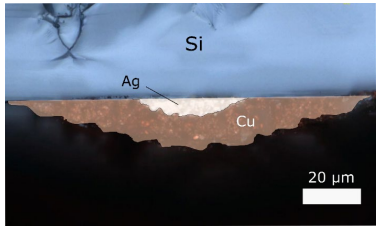
- Cell precursors >730mV and vanishing iV_{oc}-to-V_{oc} loss
  → >25% cell efficiency achievable



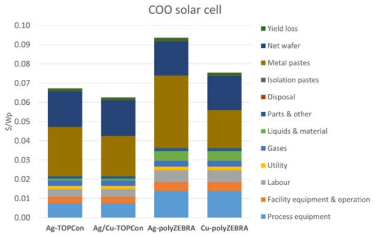
- Reverse breakdown voltage tunable by gap doping



- 44% Ag saving demonstrated, up to 83% possible



- Cost competitive to standard TOPCon



This work was partly funded by EU's Horizon Europe programme under the grant agreement No. 101084259

Thank you for your attention

Jonathan Linke

jonathan.linke@isc-Konstanz.de

+49 7531 36183 362

Building the Future Lab – Together

Full commitment. Better research.

Your support accelerates the energy transition.

We are building the place …

Donate now:

isc-konstanz.de/en/donations/#donate

Your donation will advance solar energy research in Europe and make an important contribution to a clean, independent, and sustainable energy supply – and thus to the livelihood of **future generations**.