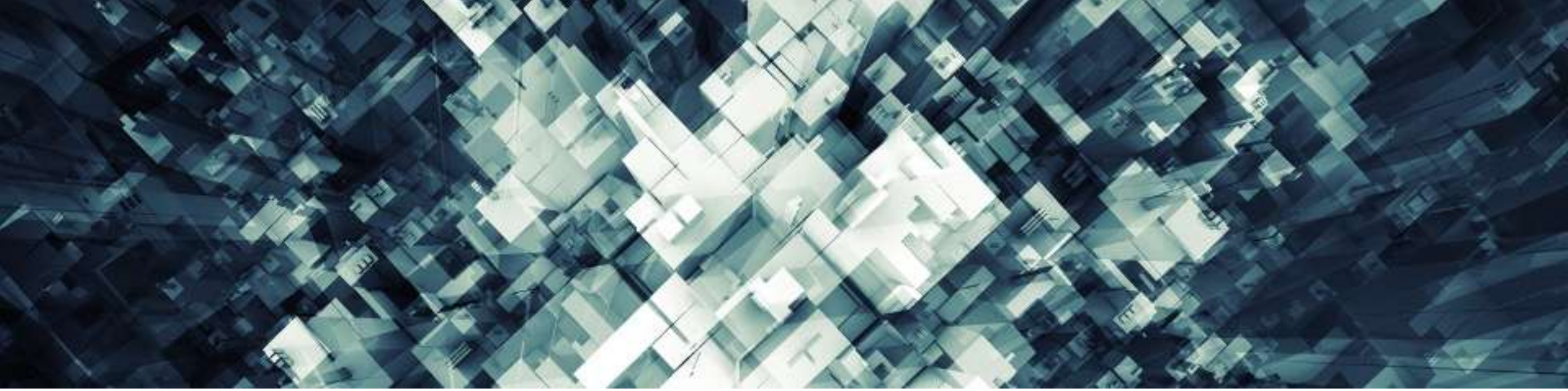

Sustainable SHJ Module Fabrication: Multiwire TWILL Interconnection for Cu/Ag-based Metallization and Indium-Free TCO

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Metallization & Interconnection Workshop

20 October 2025—Berlin

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Background and Motivation

Can SHJ deliver both efficiency and sustainability?

Better Performance

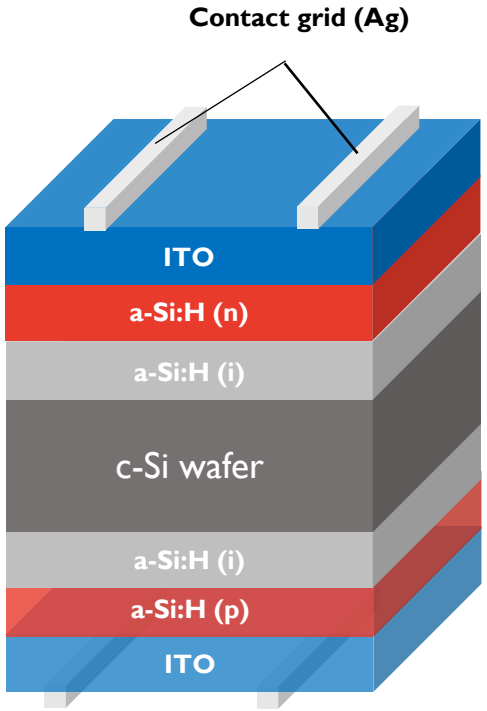
- World-record c-Si efficiency uses SHJ architecture
- Excellent bifacial performance
- Thinner wafers → less bulk recombination
- Future tandem integration

Limitations & Material Criticality

- High Ag consumption → cost & supply risk
- Pb toxicity → low-temp soldering (interconnection)
- In & Bi criticality → used in TCO & low-temp (interconnection)
- Processing temp < 200°C → limits metallization & interconnection

Manufacturing cost & CO_2 footprint

- Thinner wafers (≤100 µm) → less Si use, less energy
- Alternative TCOs & metallization → ZnO/ITO-free + Cu replacing Ag
- Leaner multi-wire approach → interconnection & encapsulation in a single step



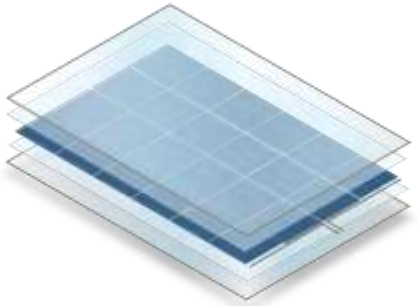
Si HJT solar cell architecture

SiLEAN project

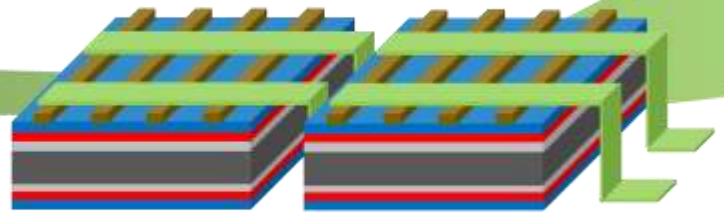
- Epitaxially-grown wafers
- Low Si consumption

EpiWafers → Modulated nanopyramids → Novel HJ stacks (• In-free TCO) → Ag-free contacts (• Cu plating • Cu screen-printing) → Metal-free contacts (• C screen-printing • Graphene pastes)

SiLEAN process approach



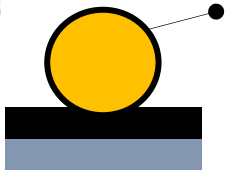
23.5% modules for TW-scale production



- Low-stress MW interconnection of Ag-free cells
- Solder-free Bi-free MW interconnection with carbon

Multiwire interconnection of 25.5% cells

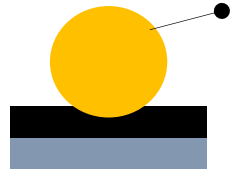
Standard MW



SnBi coating
Cu wire
Ag fingers
ITO TCO

Go for zero!

Bi-free MW with In-free TCO & Ag-free fingers

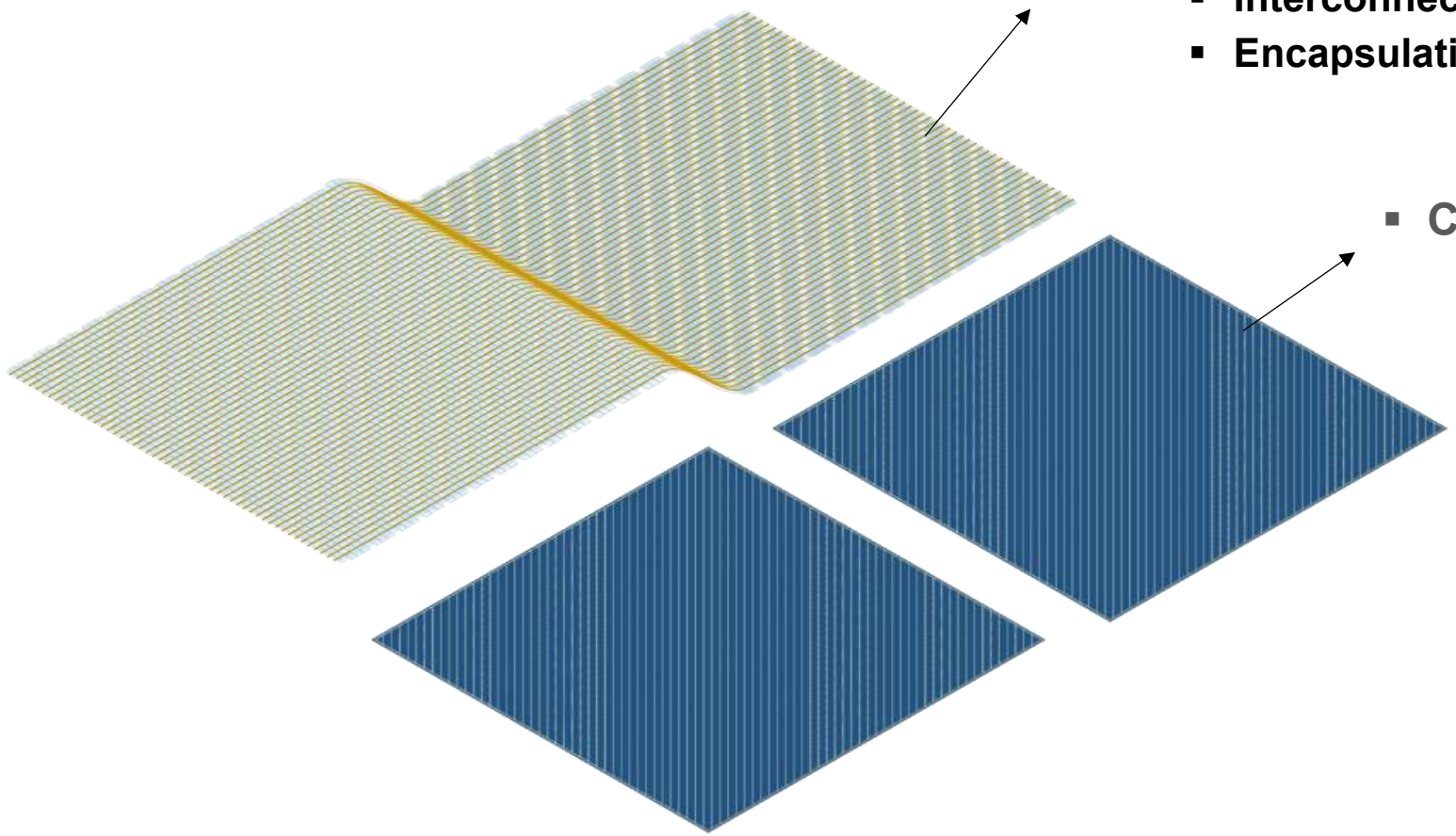


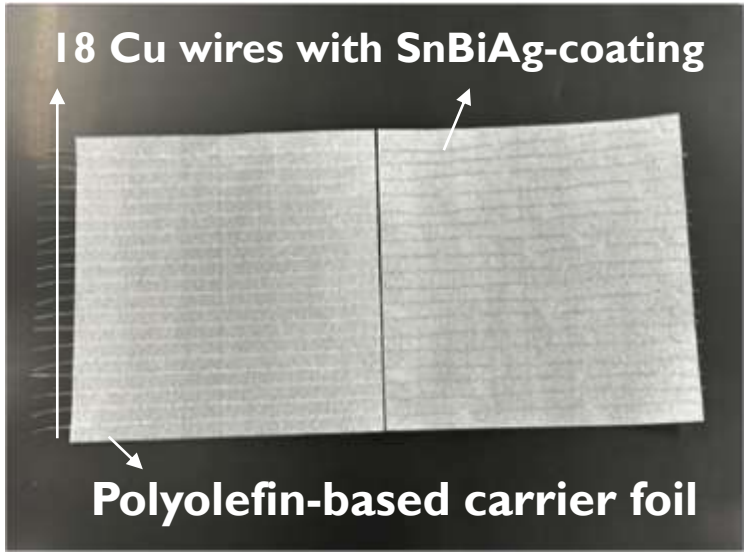
Bi free
Cu wire
Cu fingers
Zno TCO

IMO-IMOMEC UHASSELT imec Energy Ville

Twill interconnection concept*

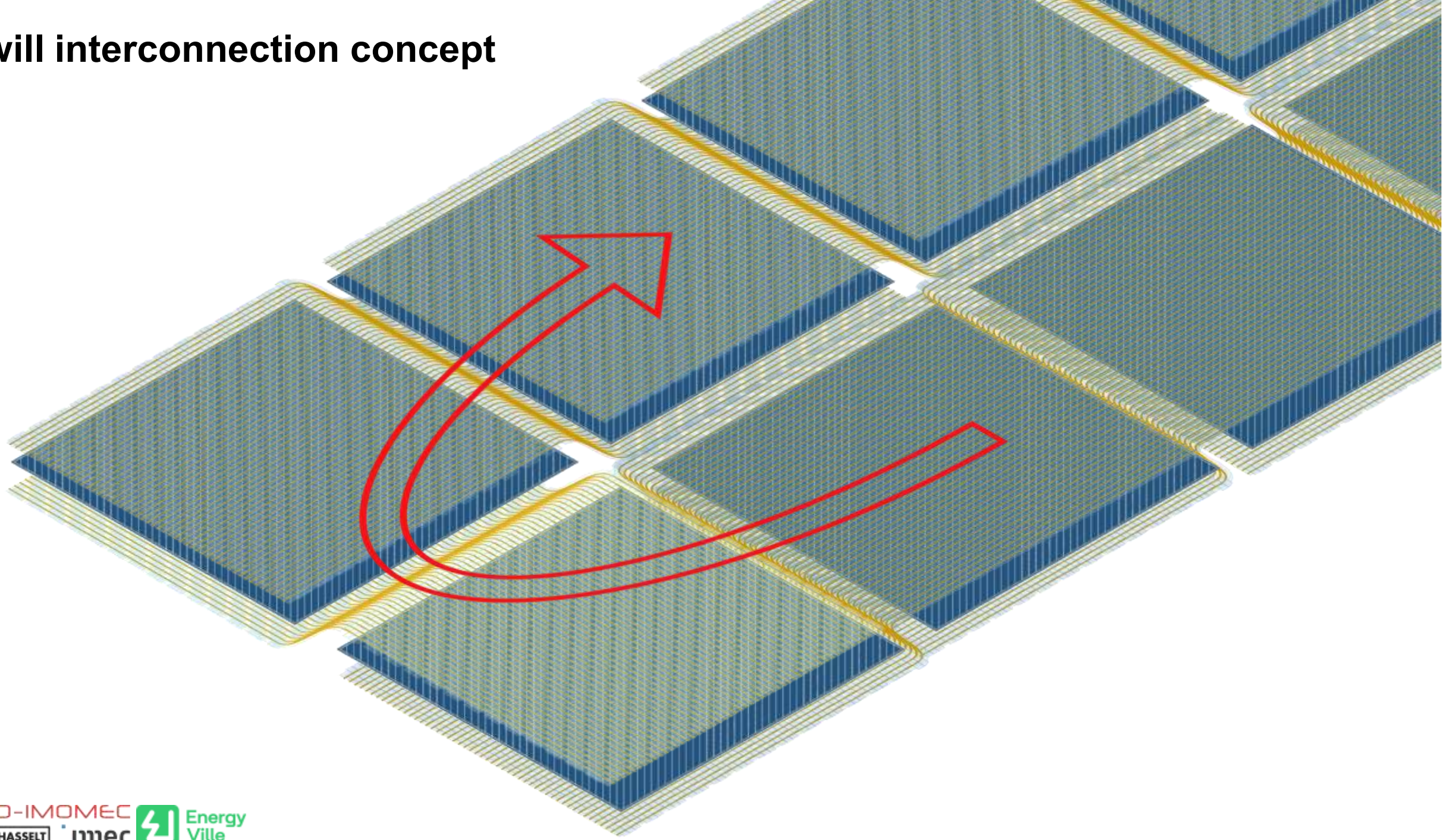
- Contact foils
  - Interconnection
  - Encapsulation
- Cells





* Patented: EP3790059A1

Twill interconnection concept



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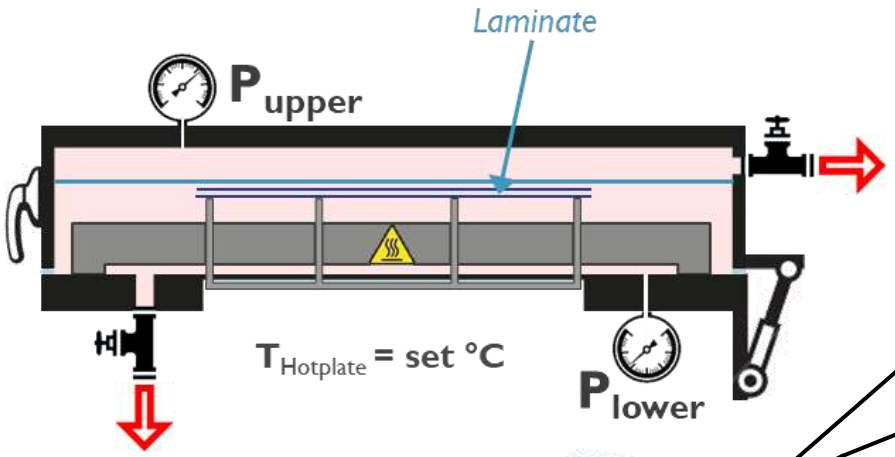
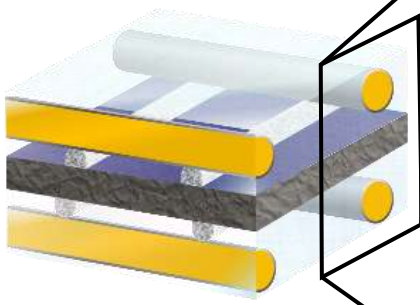
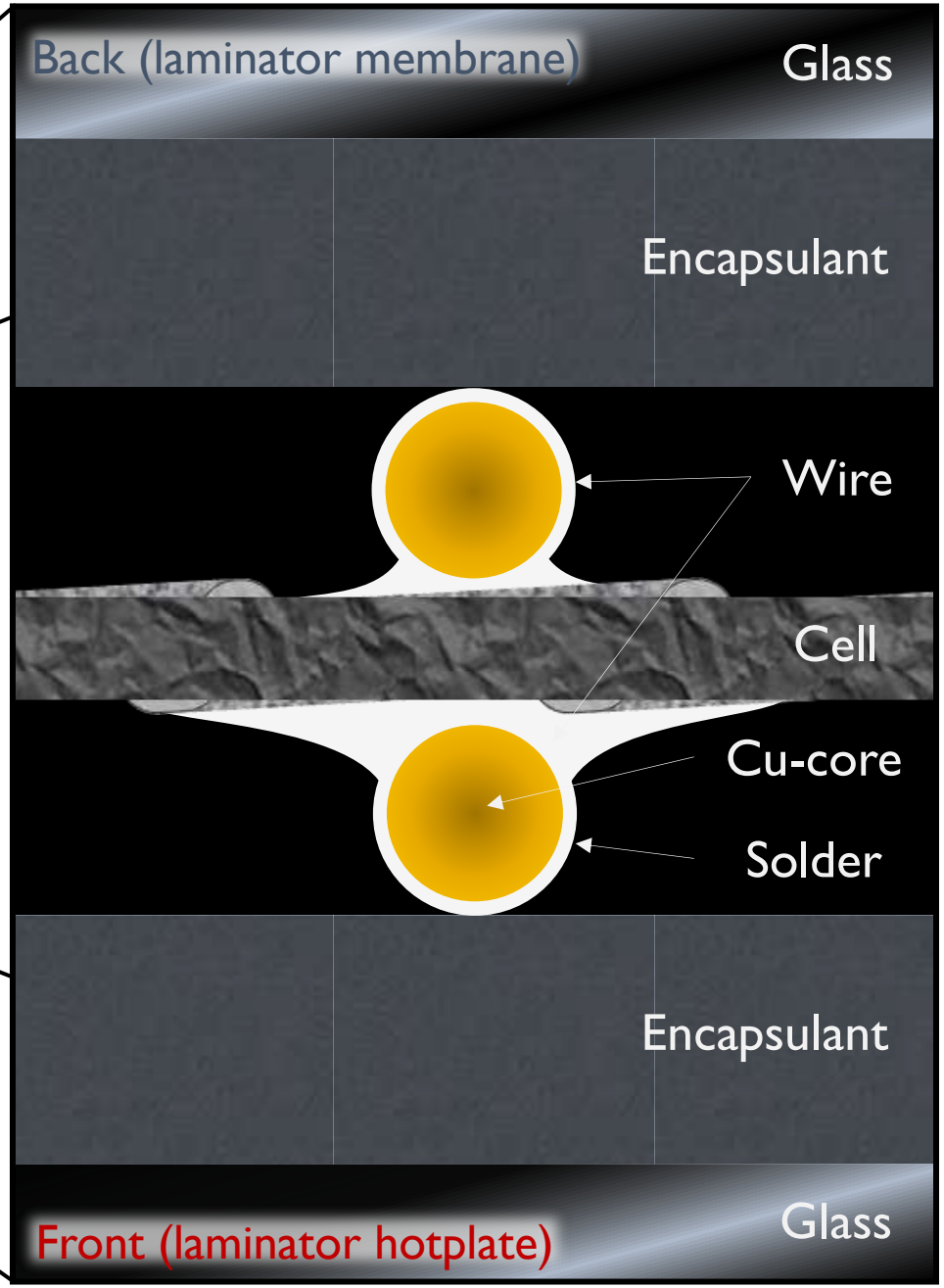
Reflow during lamination

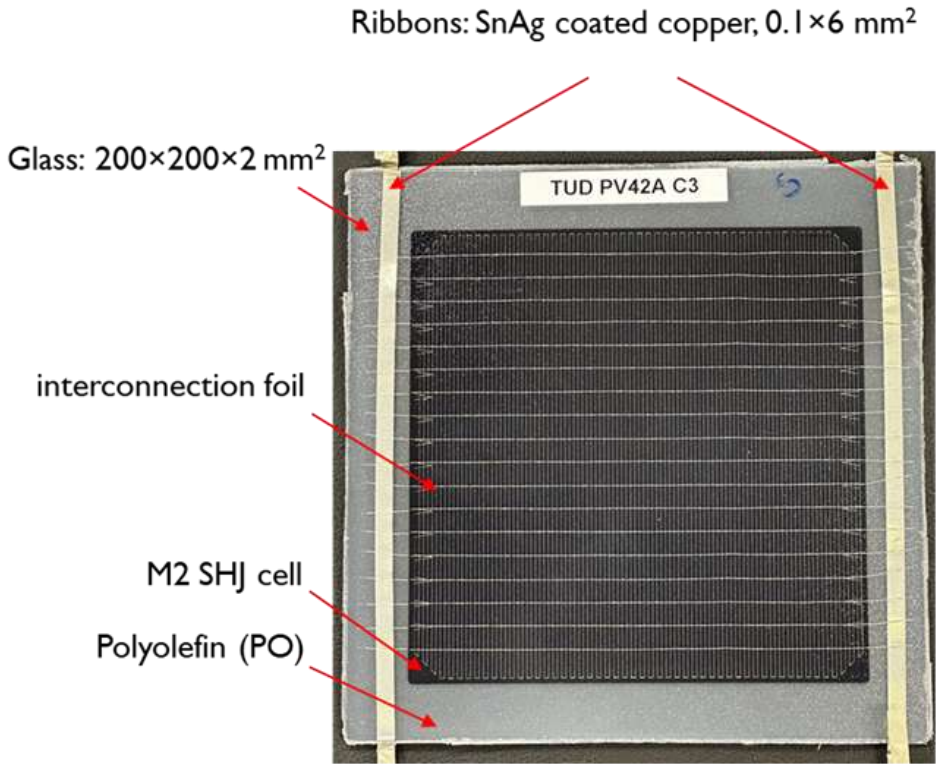






Sample fabrication and Experimental matrix

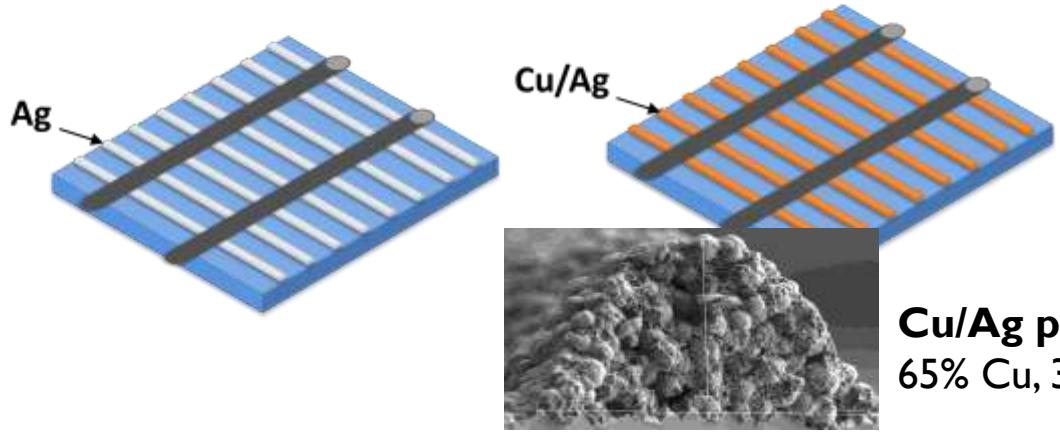
Materials



No edge sealant is used!

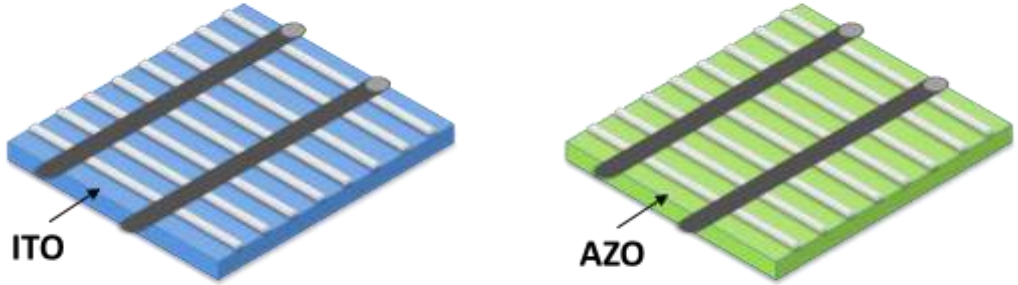
One-cell glass-glass module

- **Part 1:** Twill on different metallizations



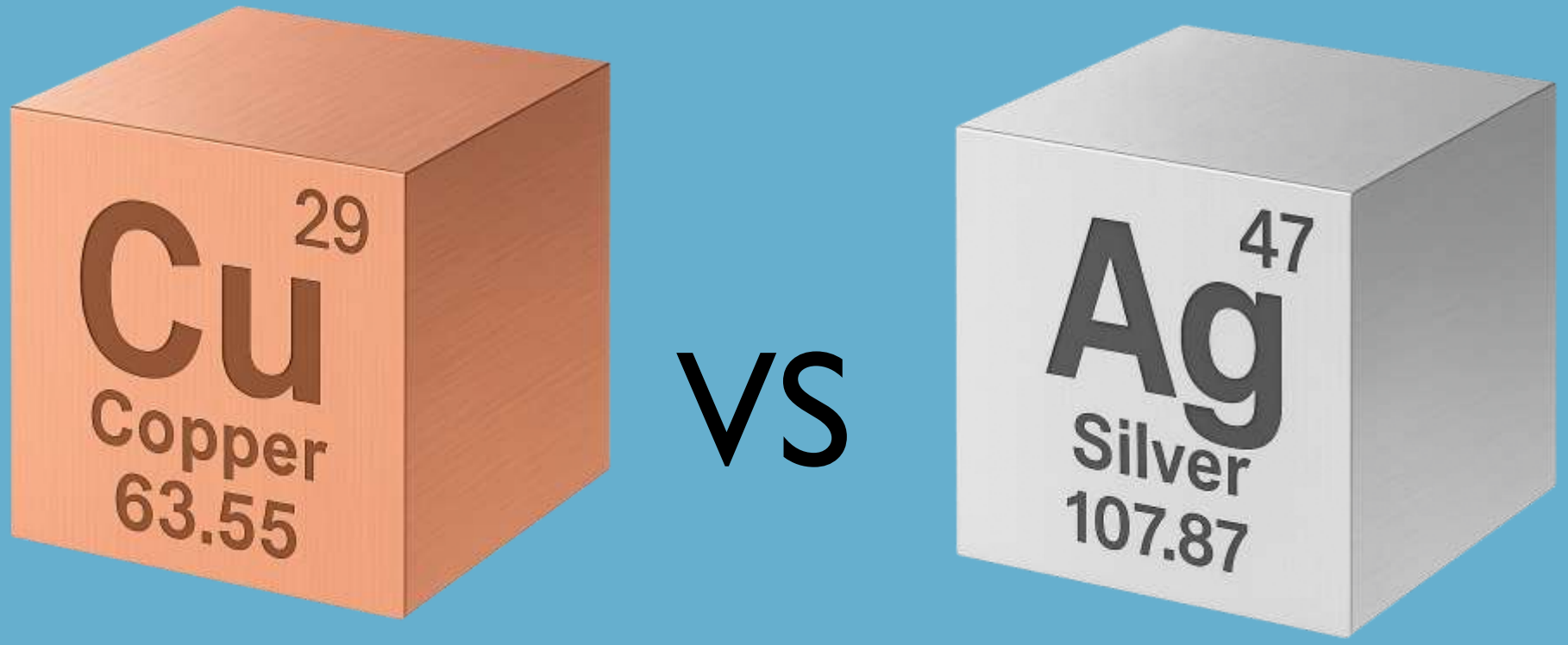
Cu/Ag paste
65% Cu, 35% A

- **Part 2:** Twill on different TCOs



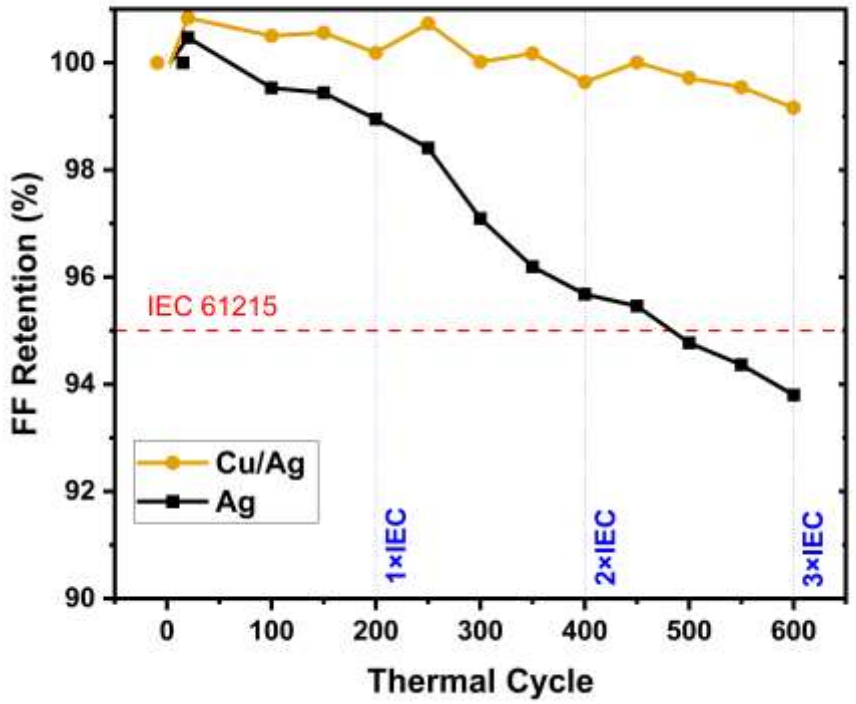
Results

Twill on metallized cells

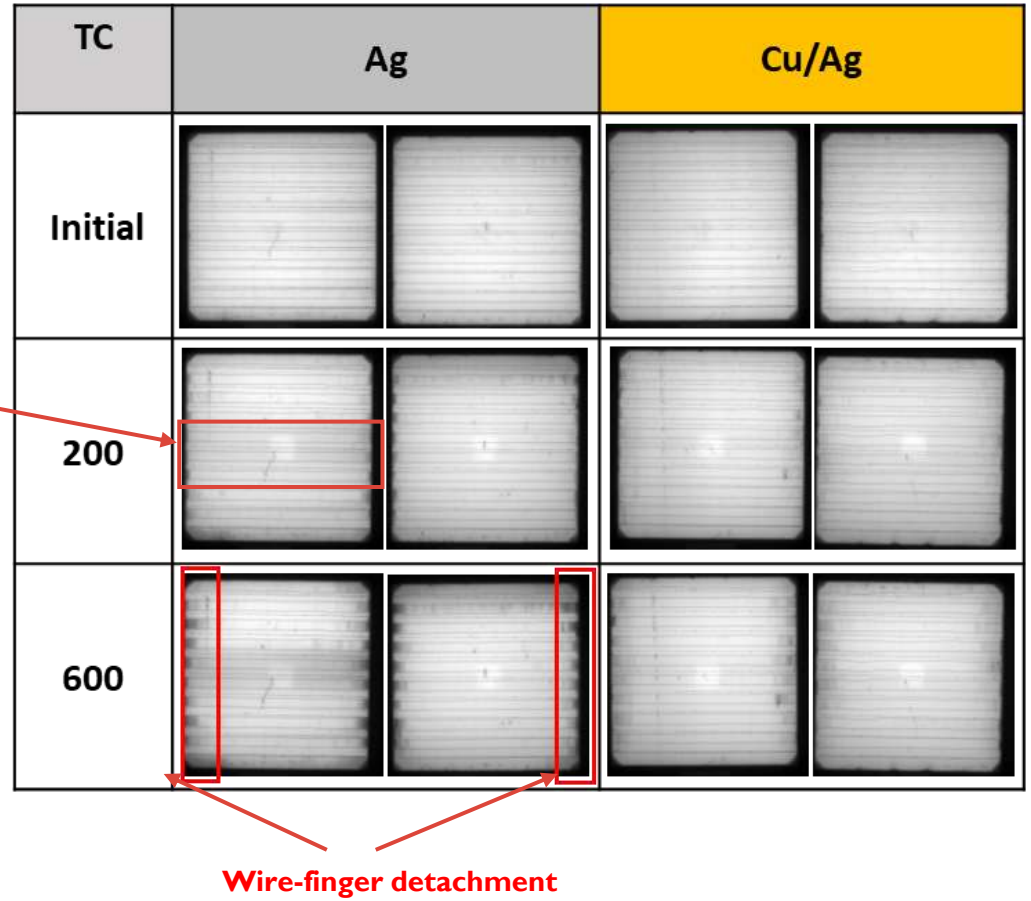


Reliability Assessment

Thermal cycling (-40 to 85 °C, IEC 61215)



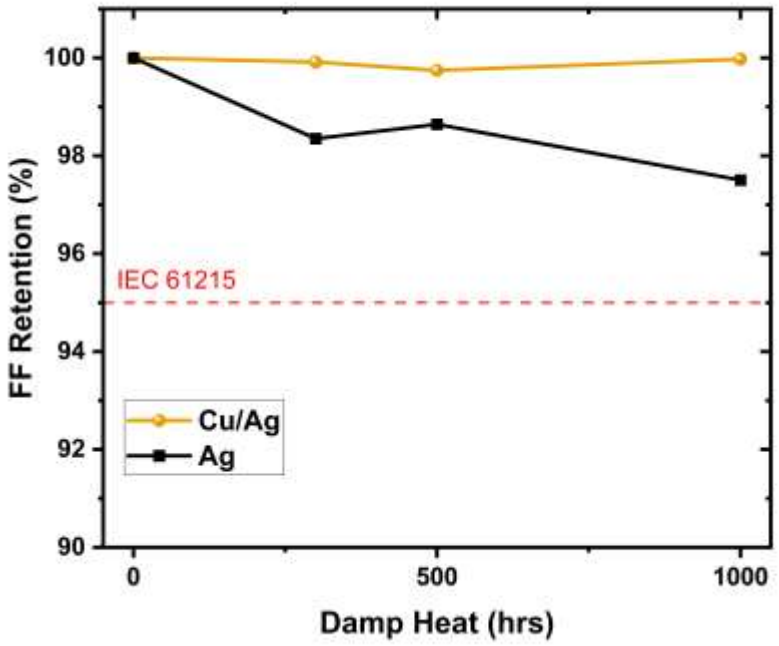
EL images



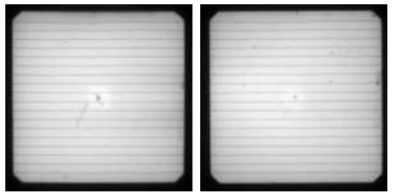
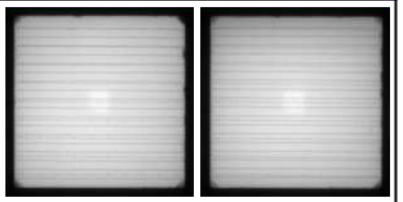
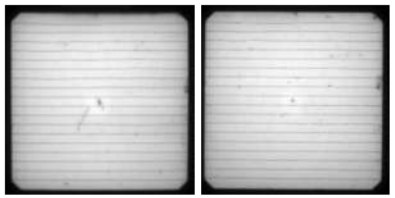
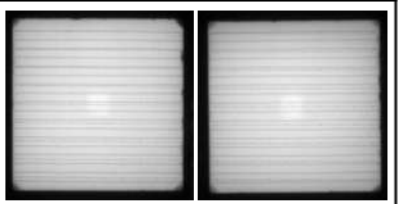
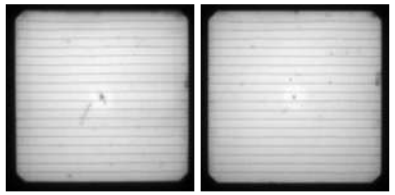
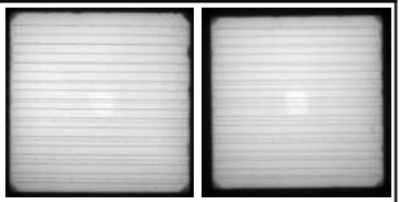
- Modules with **Cu/Ag** metallization: **< 2% FF** loss over 600 TC
- Modules with Ag metallization: ≈ 6% FF loss over 600 TC →
  - Partially due to fabrication faults (wire-ribbon detachment)
  - Wire-finger detachment at the edges, due to thermo-mechanical stress

Reliability Assessment

Damp Heat (85 °C & 85% RH, IEC 61215)

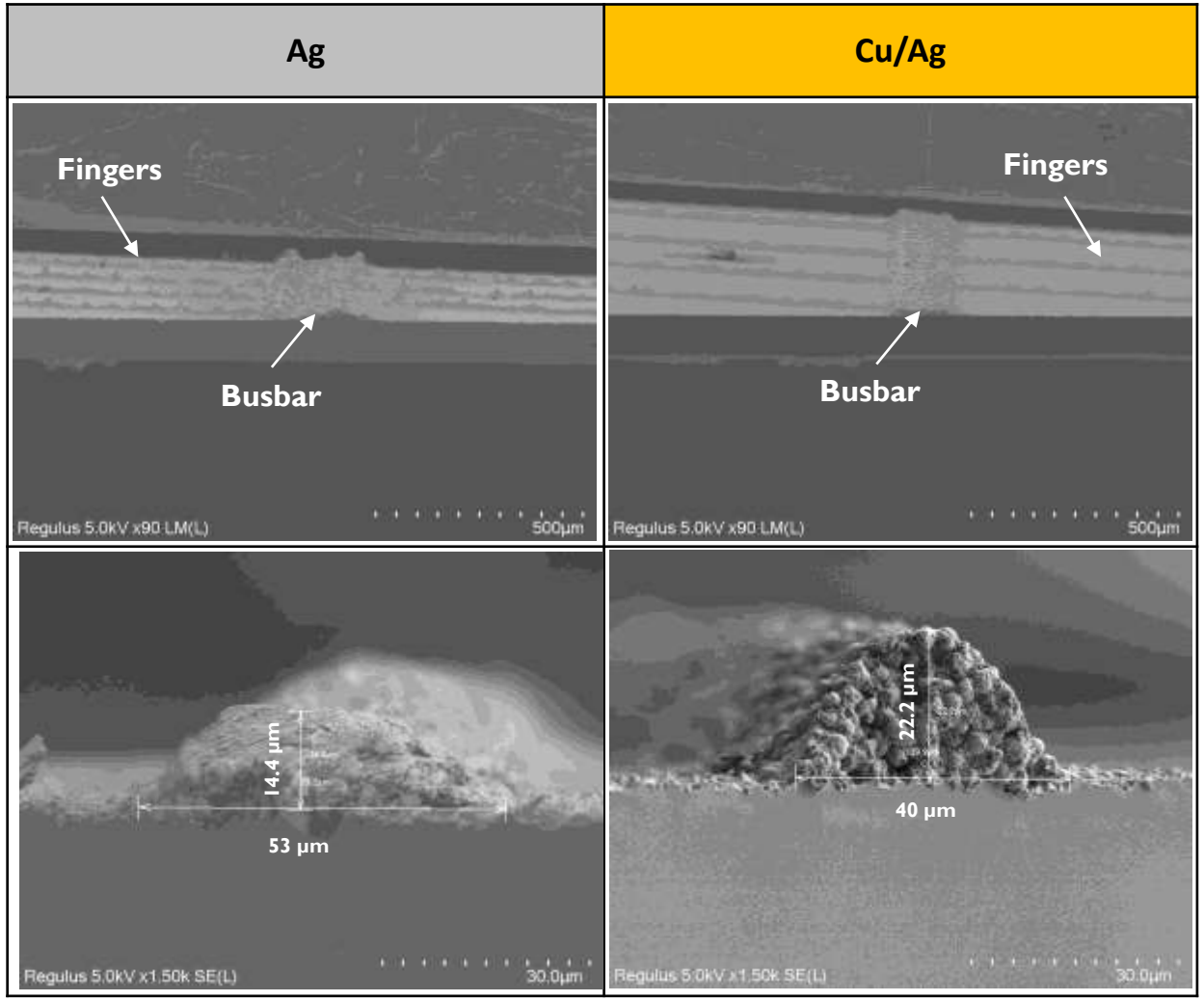


EL images

DH (hrs)	Ag	Cu/Ag
Initial		
500		
1000		

- **Cu/Ag** modules in damp heat (1000 hrs): **≈ 100% FF retention**, no degradation.
- EL images show some minor degradation in Ag modules.

SEM observations of printed fingers



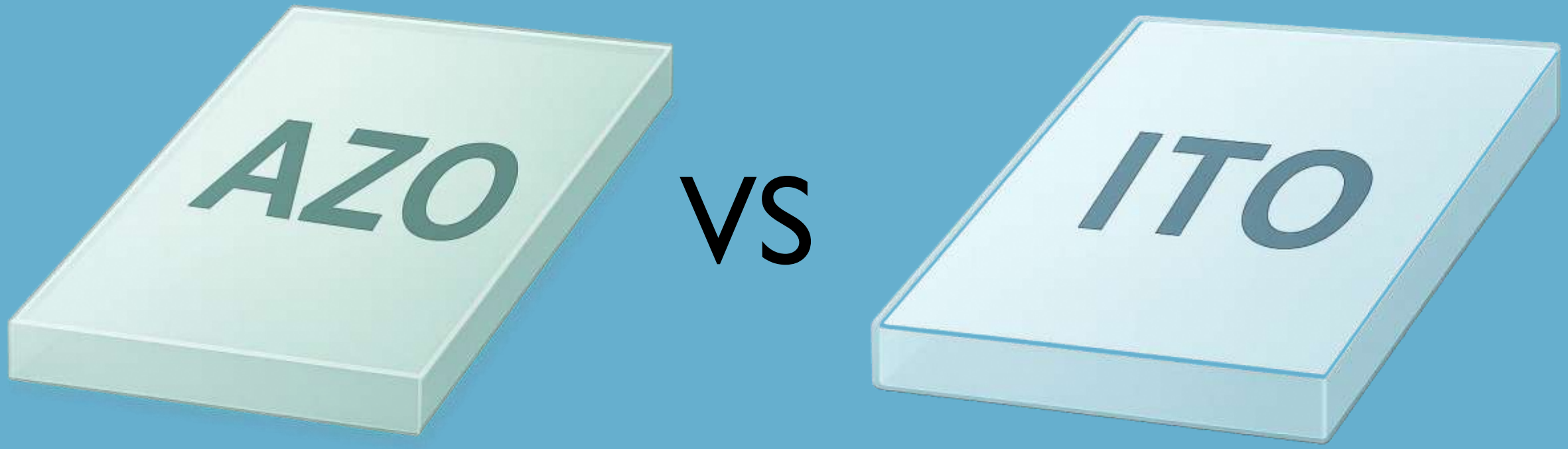
- Cu/Ag paste fingers show more uniform morphology.
- Cu/Ag fingers are narrower and have a higher aspect ratio compared to Ag.

- Cu/Ag fingers may allow **better wire contact → higher reliability**.

SEM investigation of wire–finger cross-sections is ongoing.

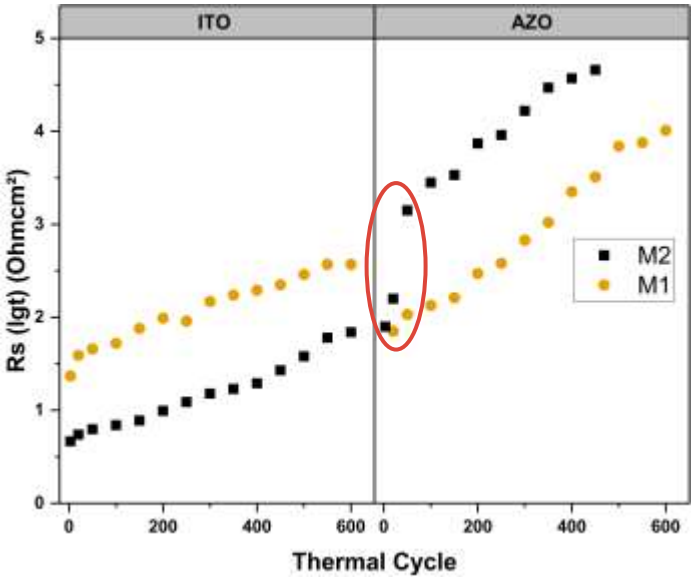
Results

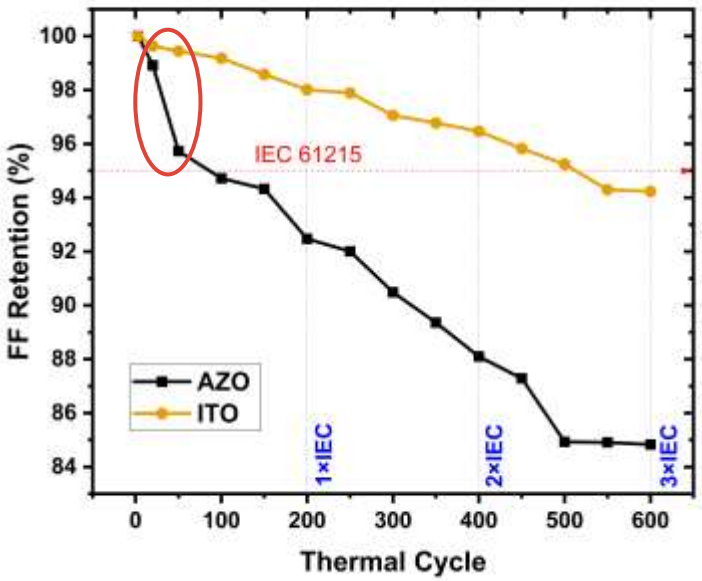
Twill on TCOs

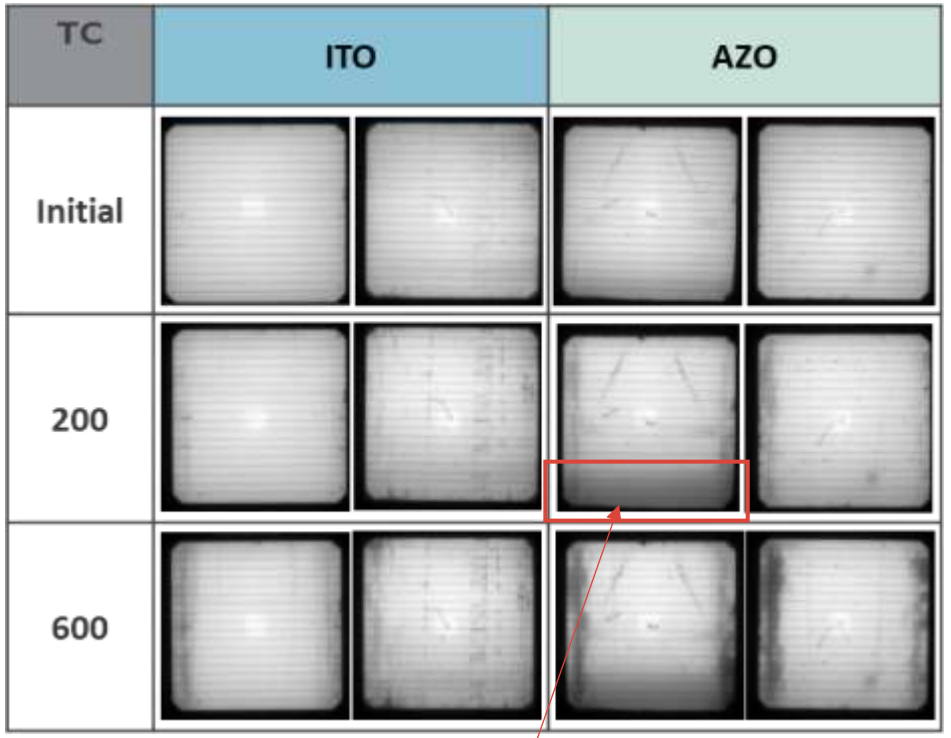


Reliability Assessment

Thermal cycling (-40 to 85 °C, IEC 61215)





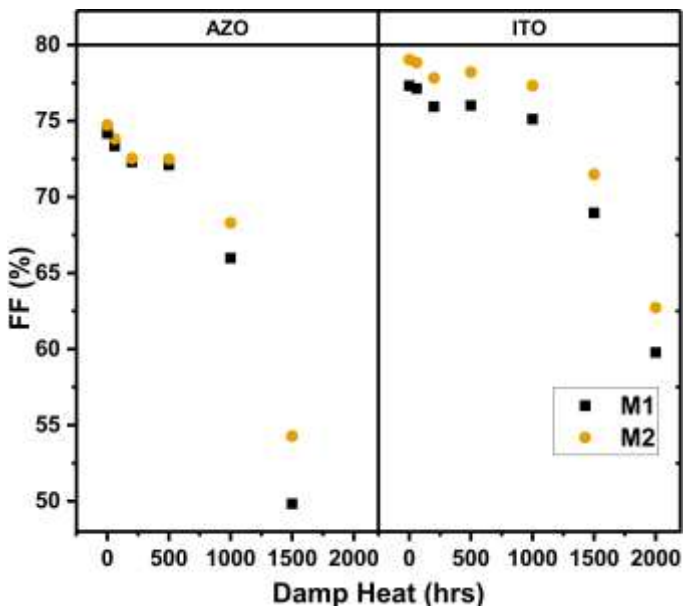


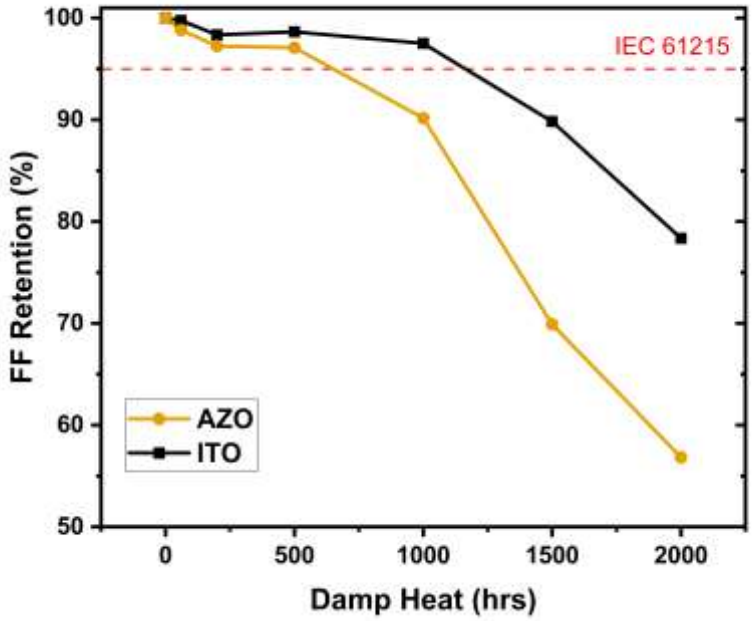
- ITO-based cells: passed 2×IEC standard in TC testing.
- AZO-based cells: did not pass, though they were close to passing 1×IEC.

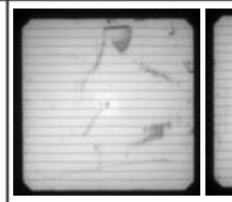
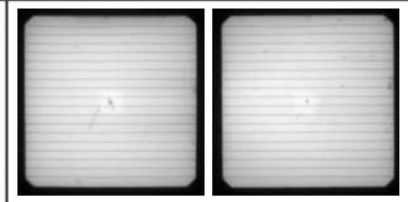
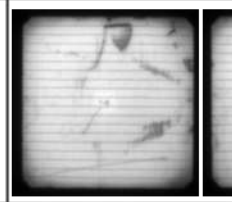
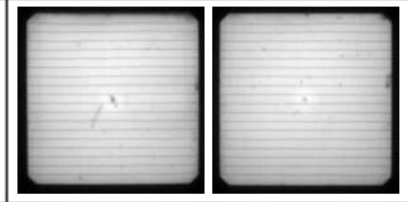
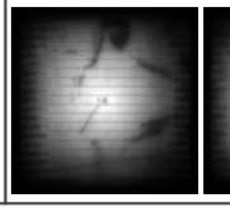
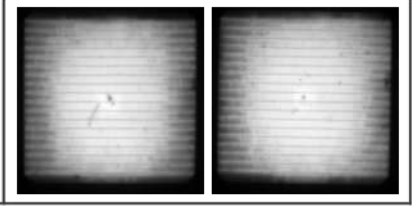
Increased series resistance
(wire loosening/detachment)

Reliability Assessment

Damp Heat (85 °C & 85% RH, IEC 61215)





DH (hrs)	AZO	ITO
Initial		
1000		
2000		

- AZO-based modules: did not pass the DH test.
- AZO-based modules: showed a lower initial FF compared to ITO-based modules.
- Degradation in perimeter likely caused by moisture ingression (**No edge sealant** is used).
- Work on **optimizing AZO** is currently in progress.

Conclusions

1. **Twill on Cu/Ag metallization:**
   - High reliability: **<2% FF loss** over 3×IEC
   - **100% FF retention** after 1000 hrs DH.

2. **Twill on AZO-based modules:**

- Showed lower reliability, but performance was close to pass IEC and can improve with optimization.
- No **edge sealant** was used; with sealant, the modules could likely pass IEC, though **further optimization** is still needed to match **ITO performance**.

Outlook:

- Reliability of Ag based modules could improve with better metallization quality and fewer fabrication faults.
- Twill will be applied on **Cu-based cells (Ag-free metallization).**
- **Edge sealant** will be applied to future modules to improve **moisture resistance** and overall durability.
- Reliability of **mini-modules** with **cells in series** will be investigated.

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Thank you for your attention!

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