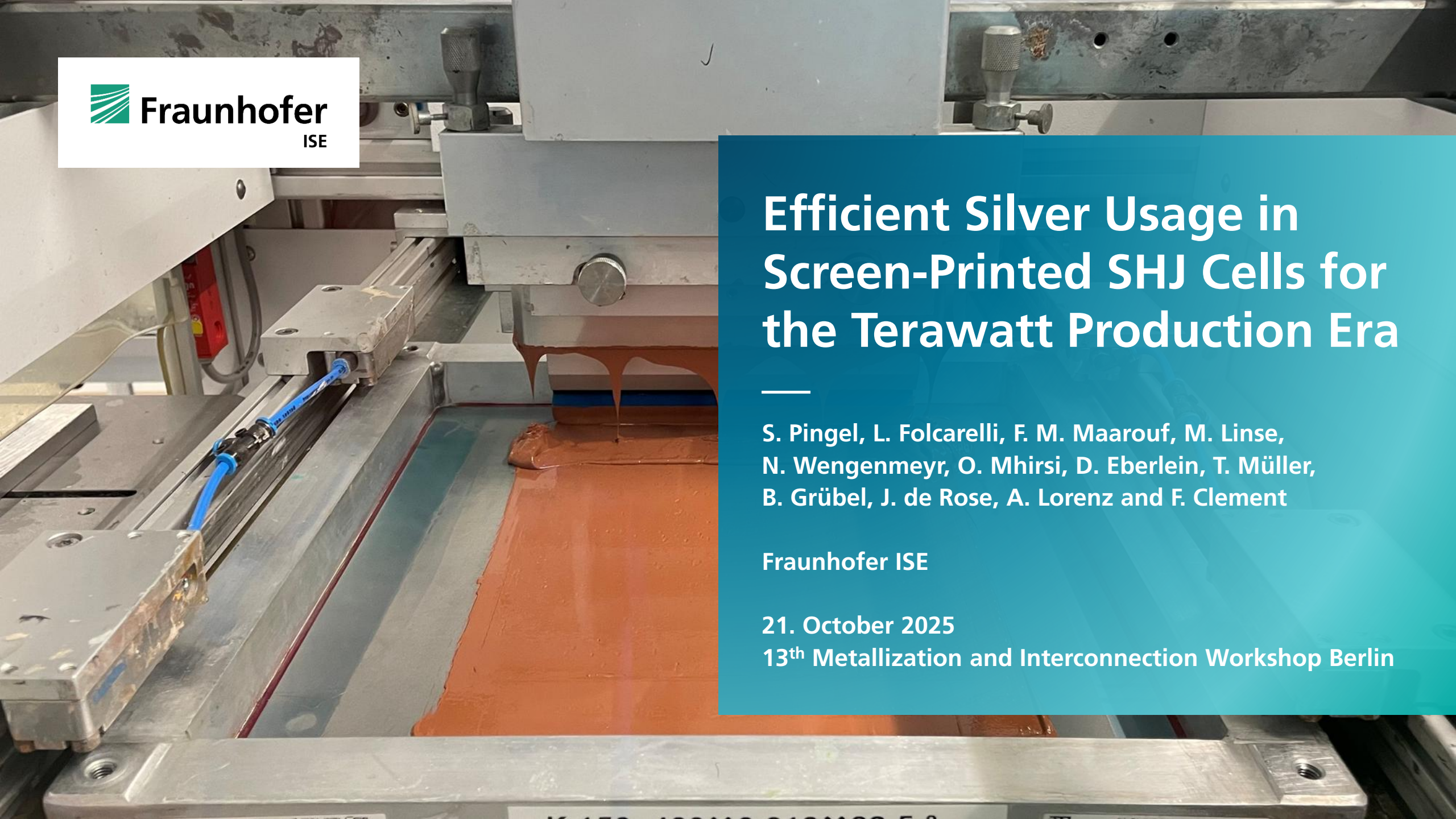

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Efficient Silver Usage in Screen-Printed SHJ Cells for the Terawatt Production Era

S. Pingel, L. Folcarelli, F. M. Maarouf, M. Linse, N. Wengenmeyr, O. Mhirsi, D. Eberlein, T. Müller, B. Grübel, J. de Rose, A. Lorenz and F. Clement

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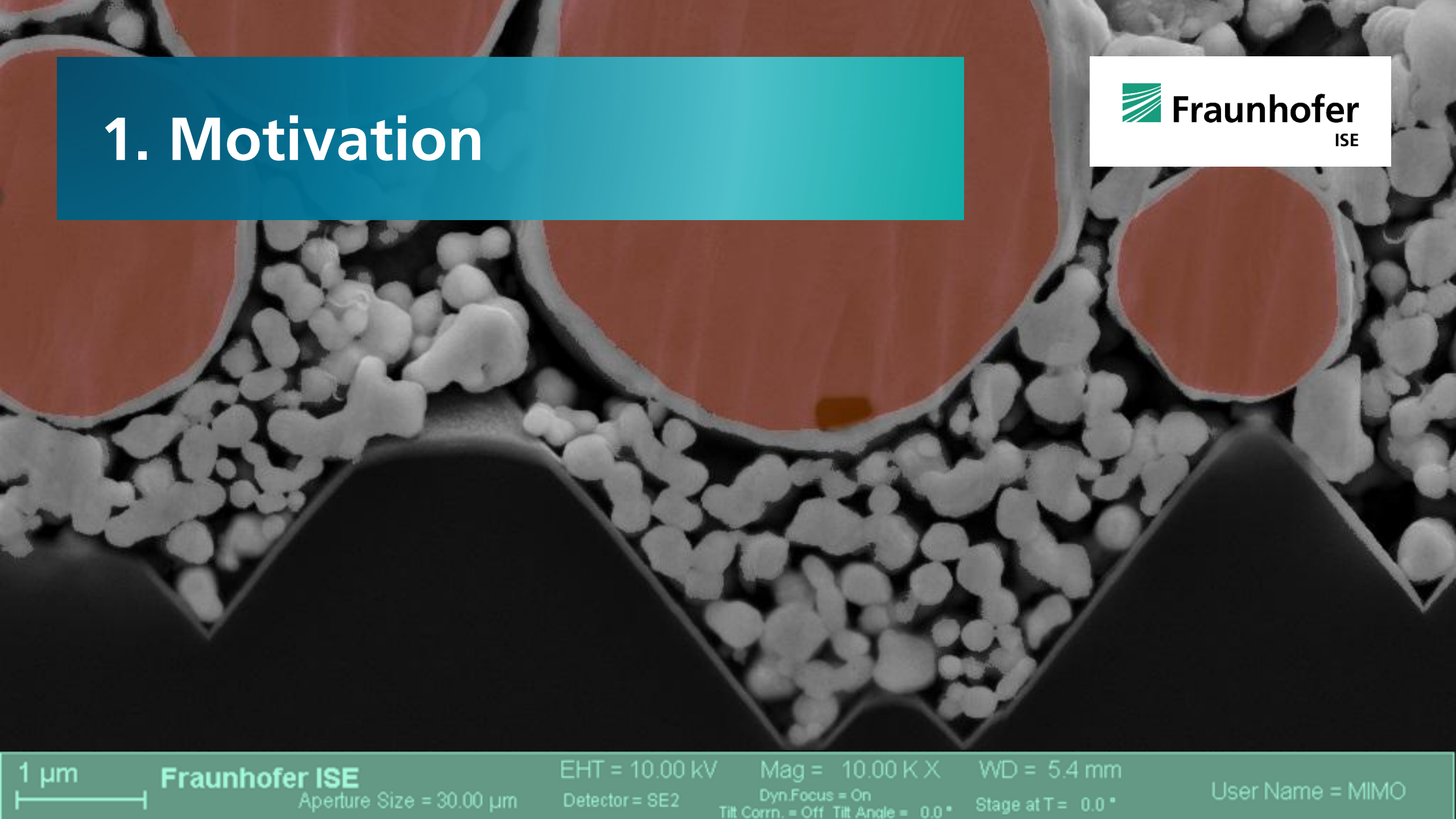
21. October 2025
13th Metallization and Interconnection Workshop Berlin

1. Motivation



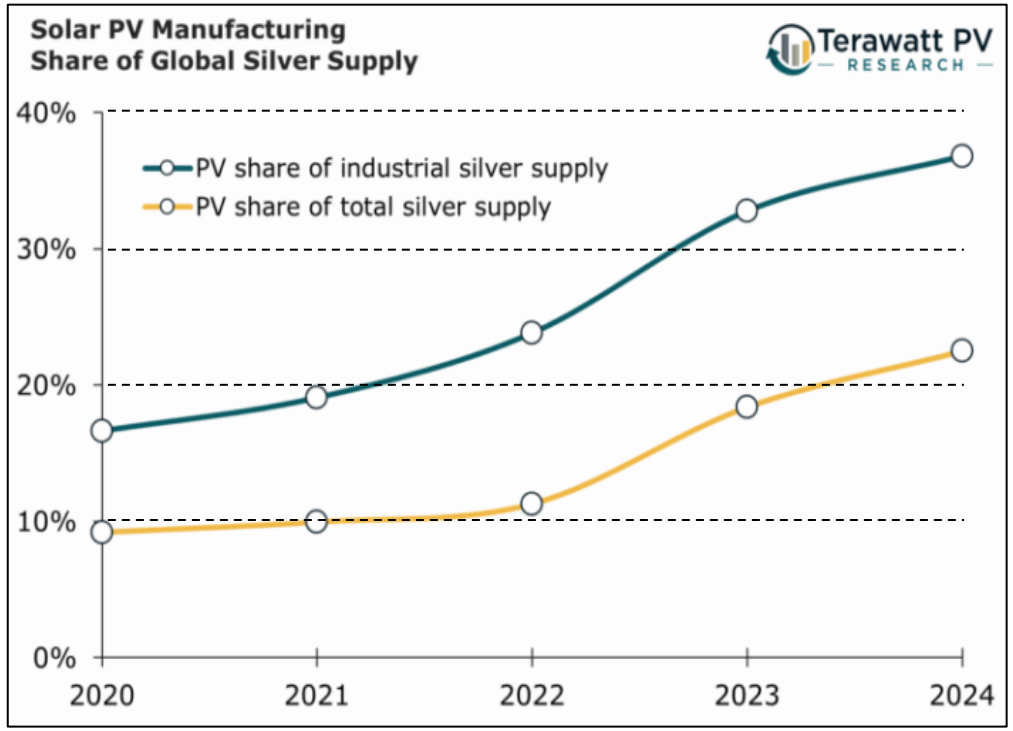
Motivation

Silver: a Scarce Material

PV Silver Consumption of global supply:

- 2024: ~ 23%[1]

1



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[1] F. Colville 2025: https://terawatt-pv.com
[2] V. Carraneo 2025, https://doi.org/10.1016/j.resconrec.2025.108562
[3] P. Newman 2025, PV Magazine
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[5] Y. Chang et al., 2024, https://doi.org/10.1002/pip.3799
[6] S. Pingel et al., 2025,https://doi.org/10.1016/j.solmat.2025.113593

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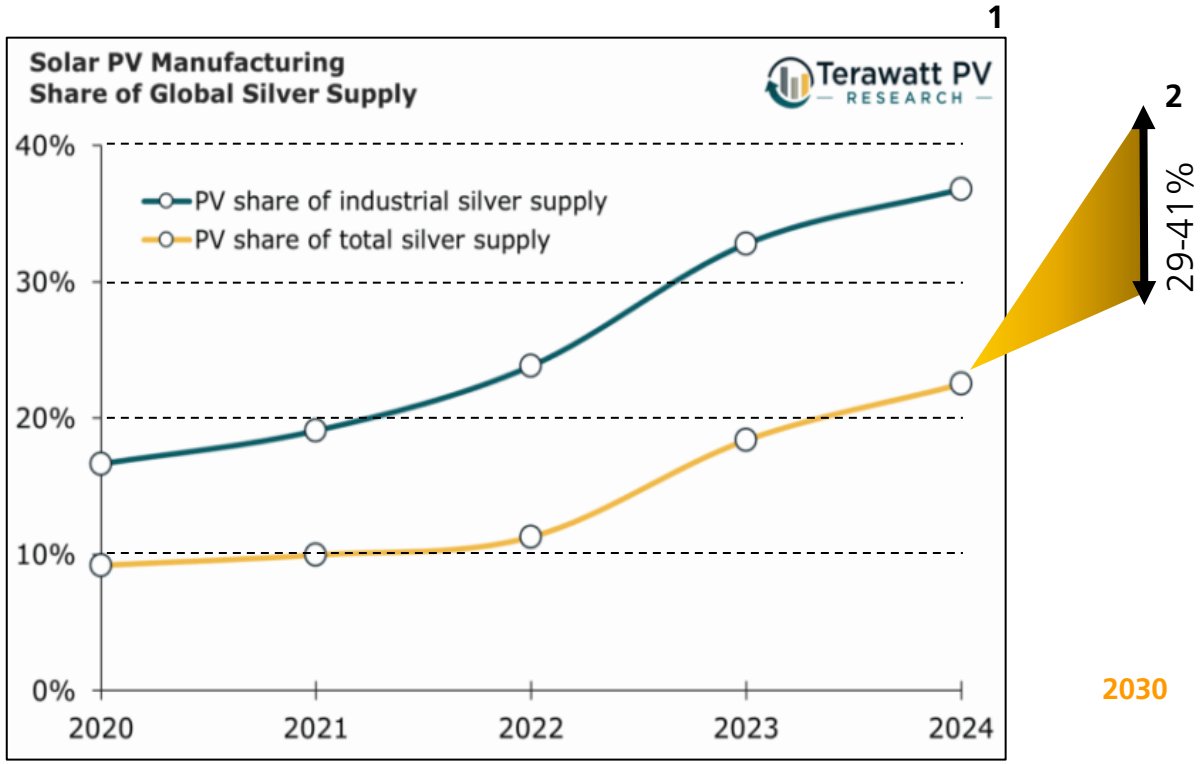
PV Silver Consumption of global supply:

- 2024: ~ 23%[1]
- 2030: ~ 35% (forecast 29-41%)[2]

Silver price:

- 2025: > $44/oz., +30% in 6 months
- 2026: maybe > $50/oz.[3] (last week ~ 1700$/kg)



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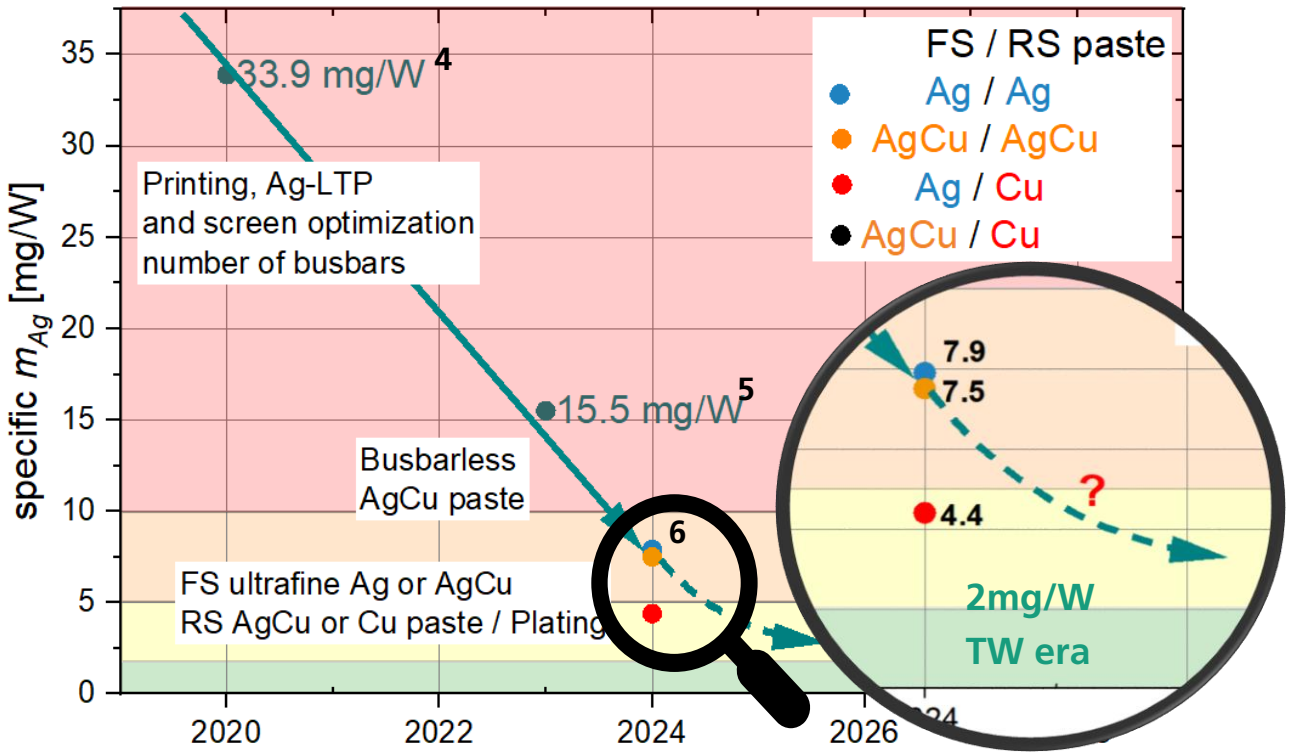
- SHJ: transition from **Ag** to **AgCu**, next step **Cu** (**?**)



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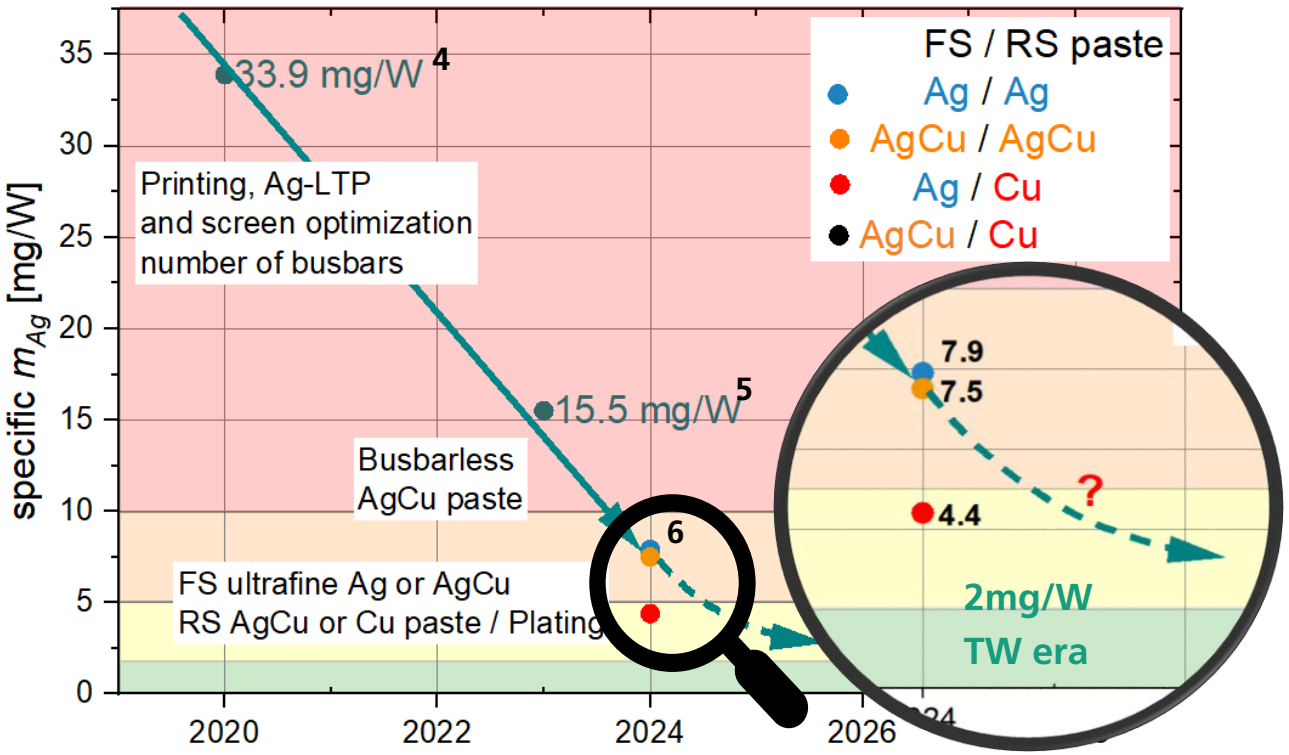
Ag

Cu



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Photos from: Ag: www.tradestation.com, Cu: www.degussa-goldhandel.de

[4] Y. Zhang et al., EES 2021 https://doi.org/10.1039/D1EE01814K
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PV:

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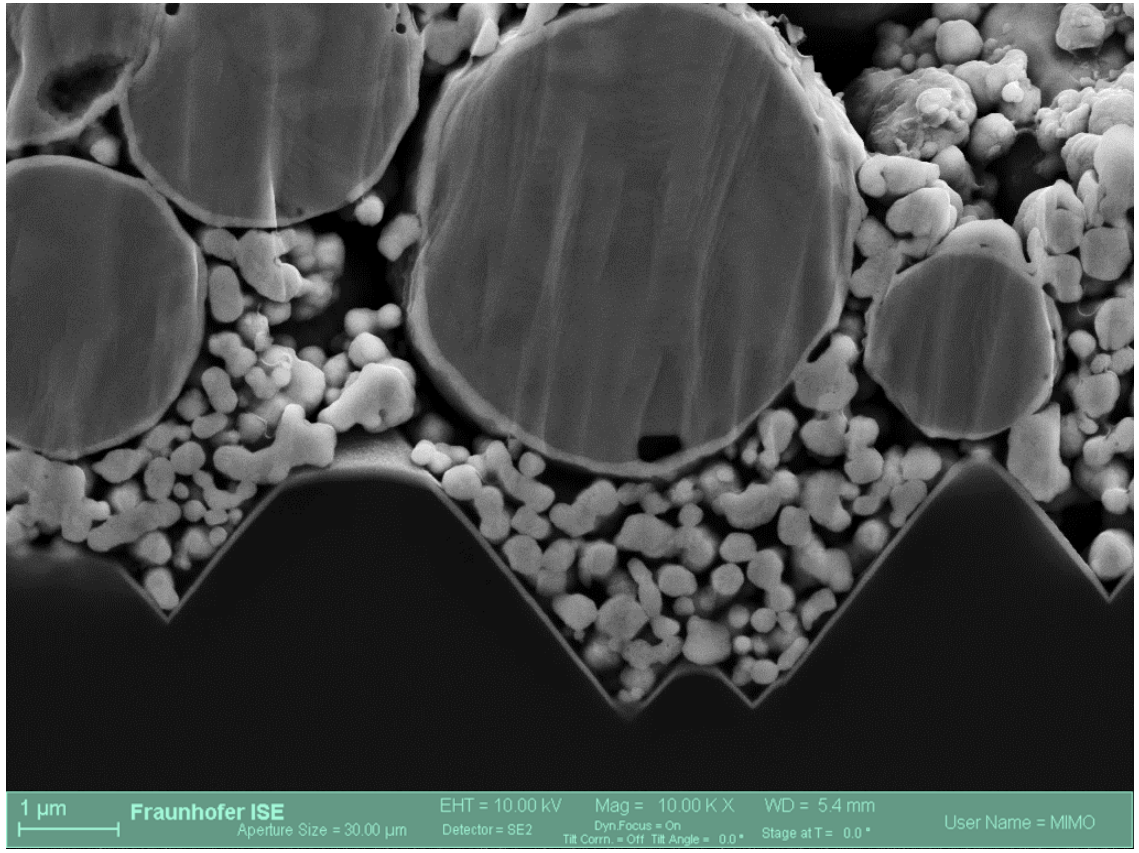
- SHJ: transition from **Ag** to **AgCu**, next step **Cu** (**?**)

AgCu 70 /Ag 30 mass ratio AgCu paste made at ISE[7]



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[7] O. Mhirsi et al.: to be published EUPVSEC 2025 and this workshop

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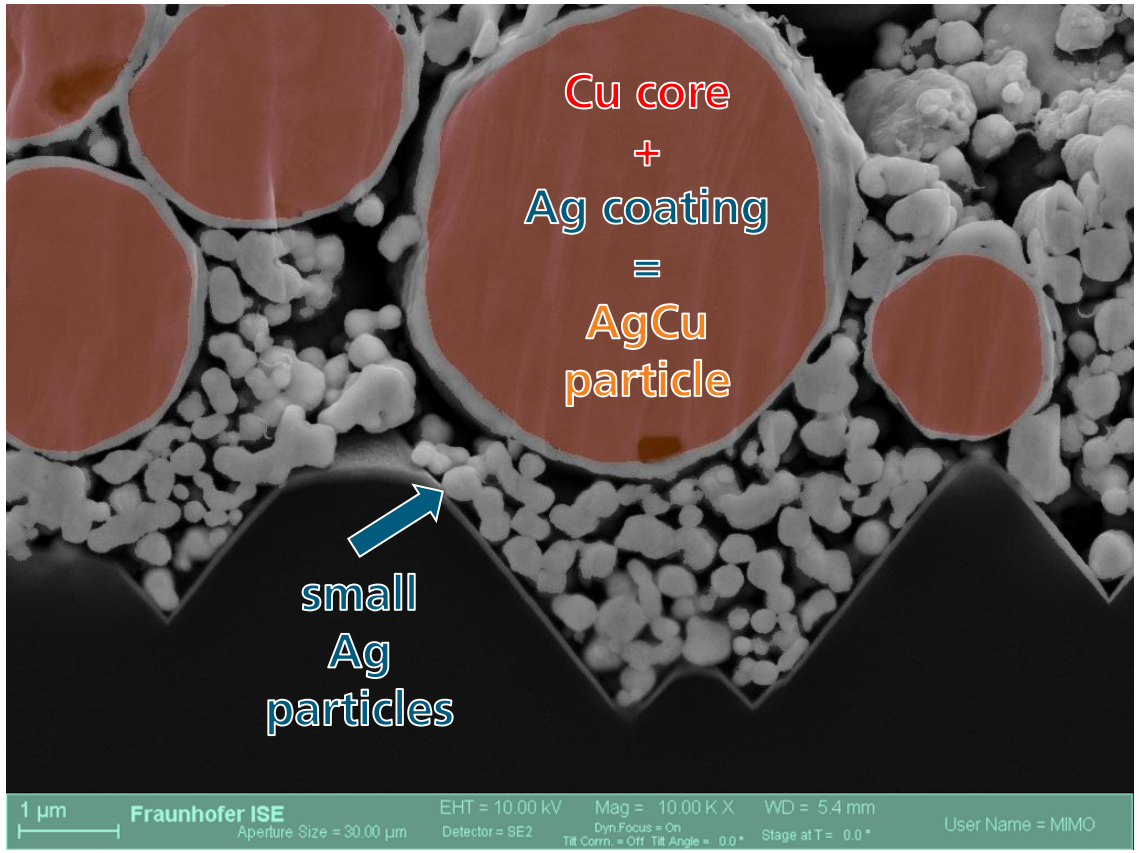
PV:

- Reduction of specific silver consumption m_{Ag}
- SHJ: transition from **Ag** to **AgCu**, next step **Cu** (**?**)

How much can we reduce the Ag consumption without compromising the η of SHJ?

AgCu 70 /Ag 30 mass ratio AgCu paste made at ISE[7]



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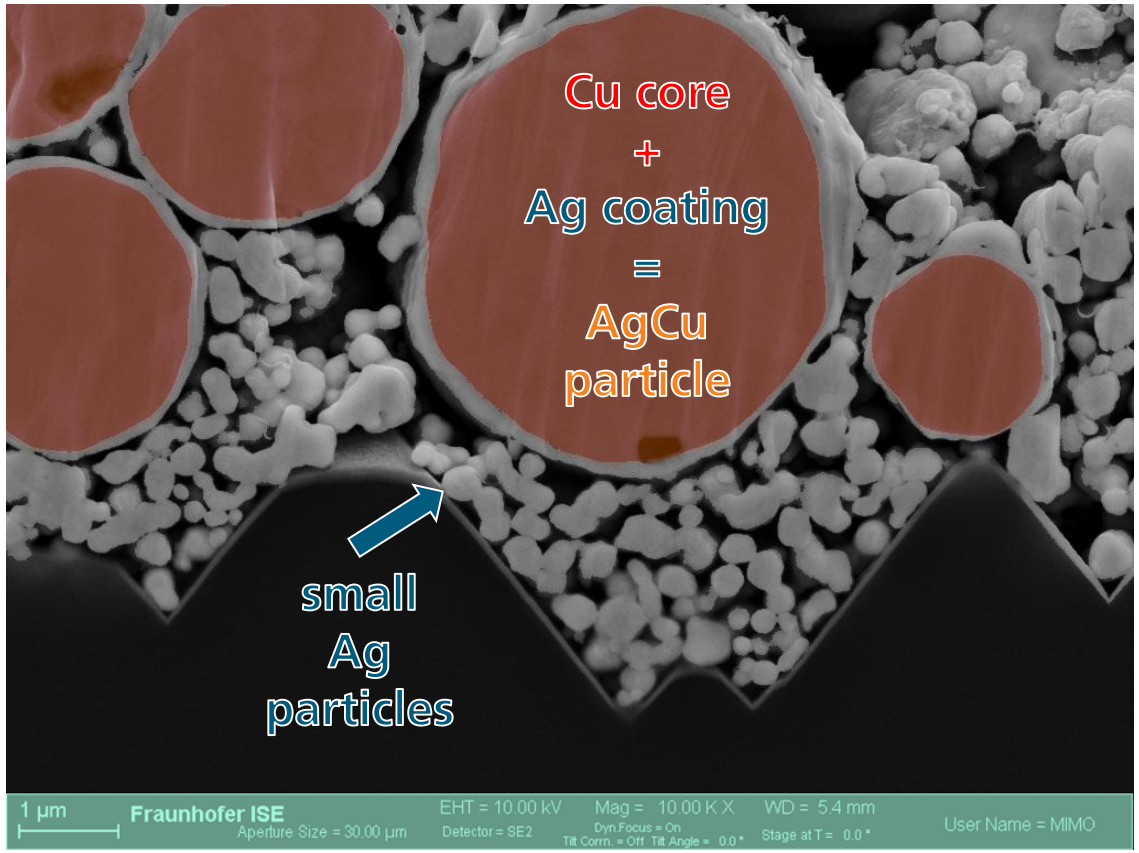
PV:

- Reduction of specific silver consumption m_{Ag}
- SHJ: transition from **Ag** to **AgCu**, next step **Cu** (**?**)

High η SHJ cells with low Ag consumption:

- Metallization losses dominated by shading J_{SC} (w_F)
  → fine line printing of low Ag content pastes

AgCu 70 /Ag 30 mass ratio AgCu paste made at ISE[7]



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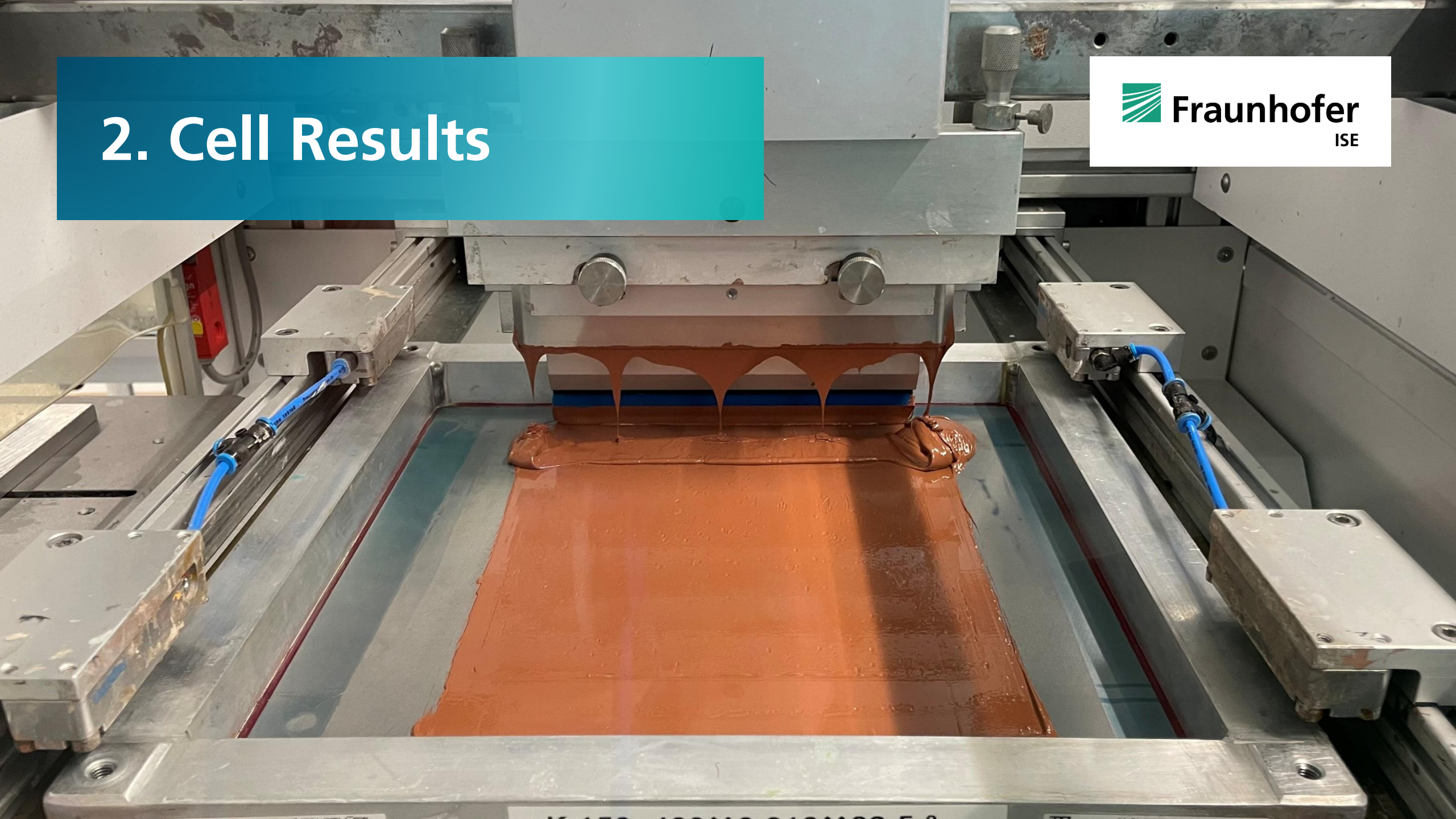
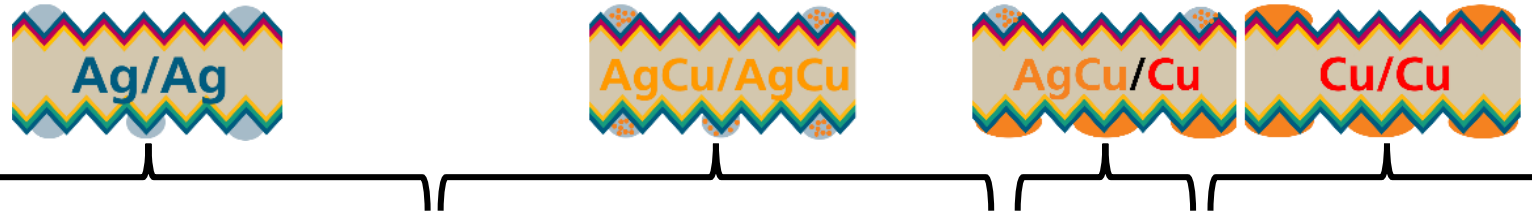
2. Cell Results



Process Plan
Cell production



Grp	0	1	2	3	4	5	6*	7	8
#	10x	10x	10x	10x	10x	10x	10x	10x	10x
Type	Ind. cell	SHJ M10 industrial precursor							
RS LTP Print & Dry	Ag?	Ag (91%)		AgCu (28%)			Cu (0%)		
	?	20 µm	17 µm	20 µm	17 µm		80 µm		
	?	#180F							
FS LTP Print & Dry	Ag?	Ag (91%)		AgCu (37%)				Cu (0%)	
	?	20 µm	17 µm	20 µm	17 µm			80 µm	27 µm
	?	#120F				#90F	#120F	#90F	
Curing	?	220°C 1 Min						Snap Cure	
Char. & Analysis	**IV**	**IV** 0BB cells with 16 contact bars FS+RS + Grid Res → R_{LINE}							
		Finger geometry 3D-CLSM (Olympus Lext)							
		Laydown *M, Ag content* + R_{LINE} → Calculation λ_{ESU} **Laydown *M, Ag content* + η** → Calculation m_{Ag}							

*FS first then RS

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Process Plan
Cell production

	Grp	0	1	2	3	4	5	6*	7	8
	#	10x	10x	10x	10x	10x	10x	10x	10x	10x
	Type	Ind. cell	SHJ M10 industrial precursor							
Nominal shading rates	RS LTP Print & Dry	Ag?	Ag (91%)		AgCu (28%)			Cu (0%)		
		?	20 µm	17 µm	20 µm	17 µm		80 µm		
		?	2.0%	1.7%	2.0%	1.7%		7.9 %		
	FS LTP Print & Dry	Ag?	Ag (91%)		AgCu (37%)				Cu (0%)	
		?	20 µm	17 µm	20 µm	17 µm			80 µm	27 µm
		?	1.3%	1.1%	1.3%	1.1%	0.8%	1.1%	4.0%	1.3%
	Curing	?	220°C 1 Min						Snap Cure	
	Char. & Analysis	IV	**IV** 0BB cells with 16 contact bars FS+RS + Grid Res → R_{LINE}							
			Finger geometry 3D-CLSM (Olympus Lext)							
			Laydown *M, Ag content* + R_{LINE} → Calculation λ_{ESU}							
			Laydown *M, Ag content* + η → Calculation m_{Ag}							

*FS first then RS

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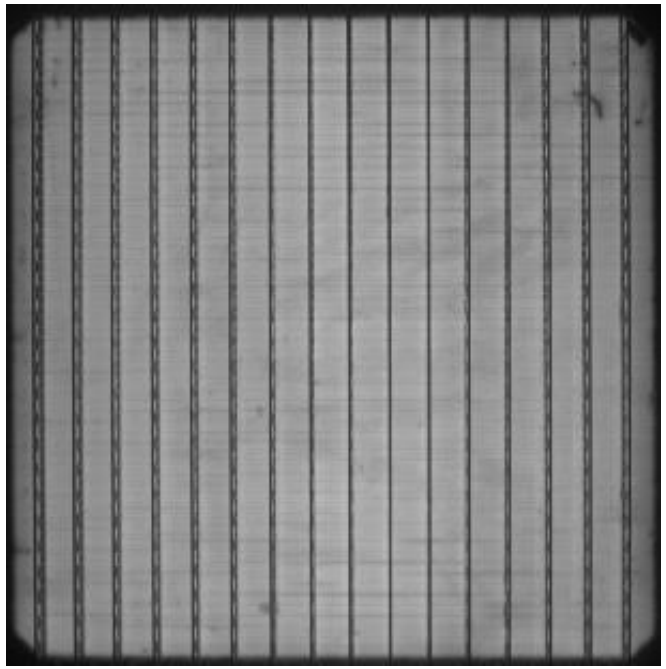
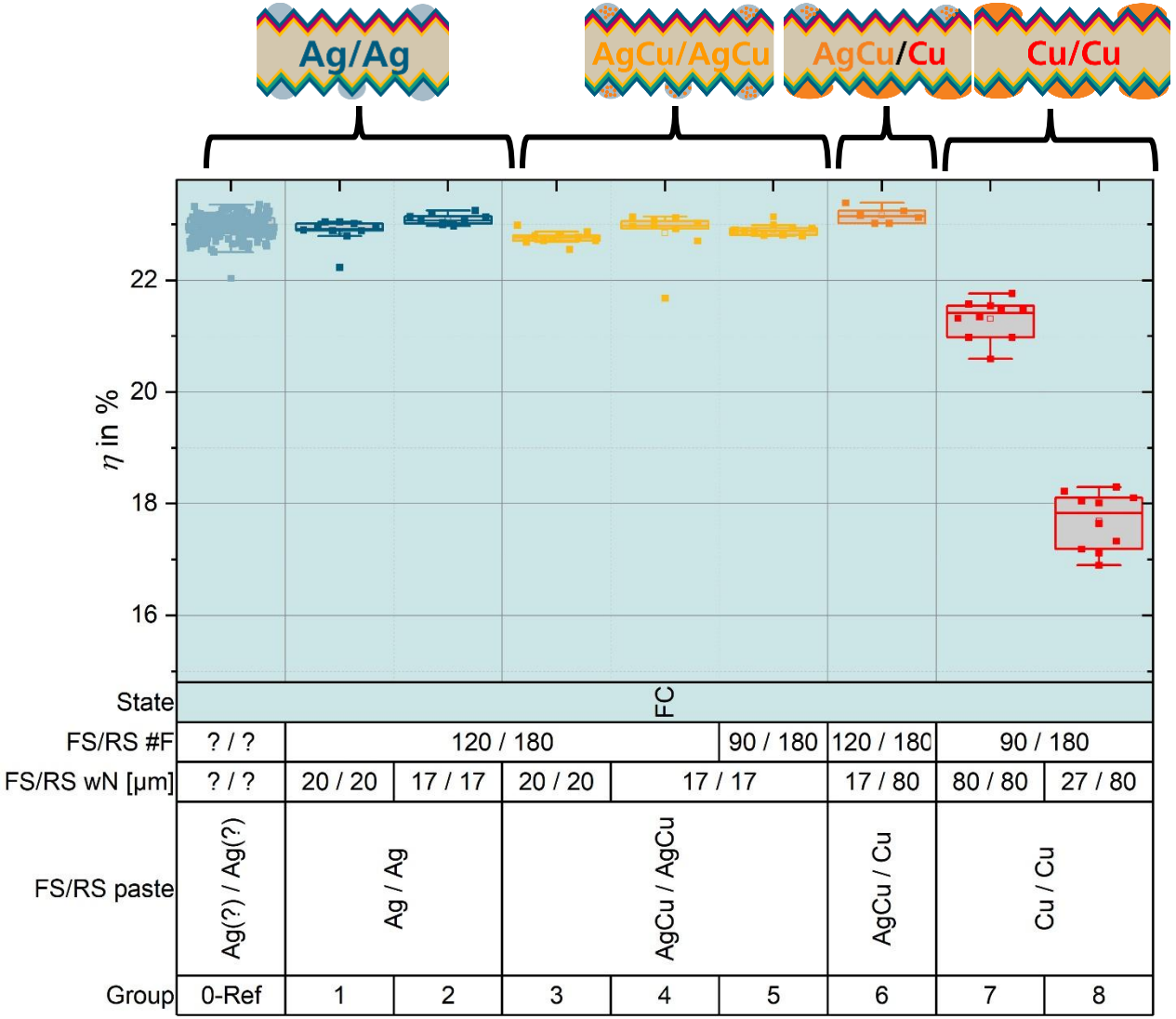
IV Results
Full cell efficiency

- Full cells (FC)[7]
- EL





Cells: 16 contact bars (gold chuck calibration)

[7] S. Pingel et al., SiPV 2025

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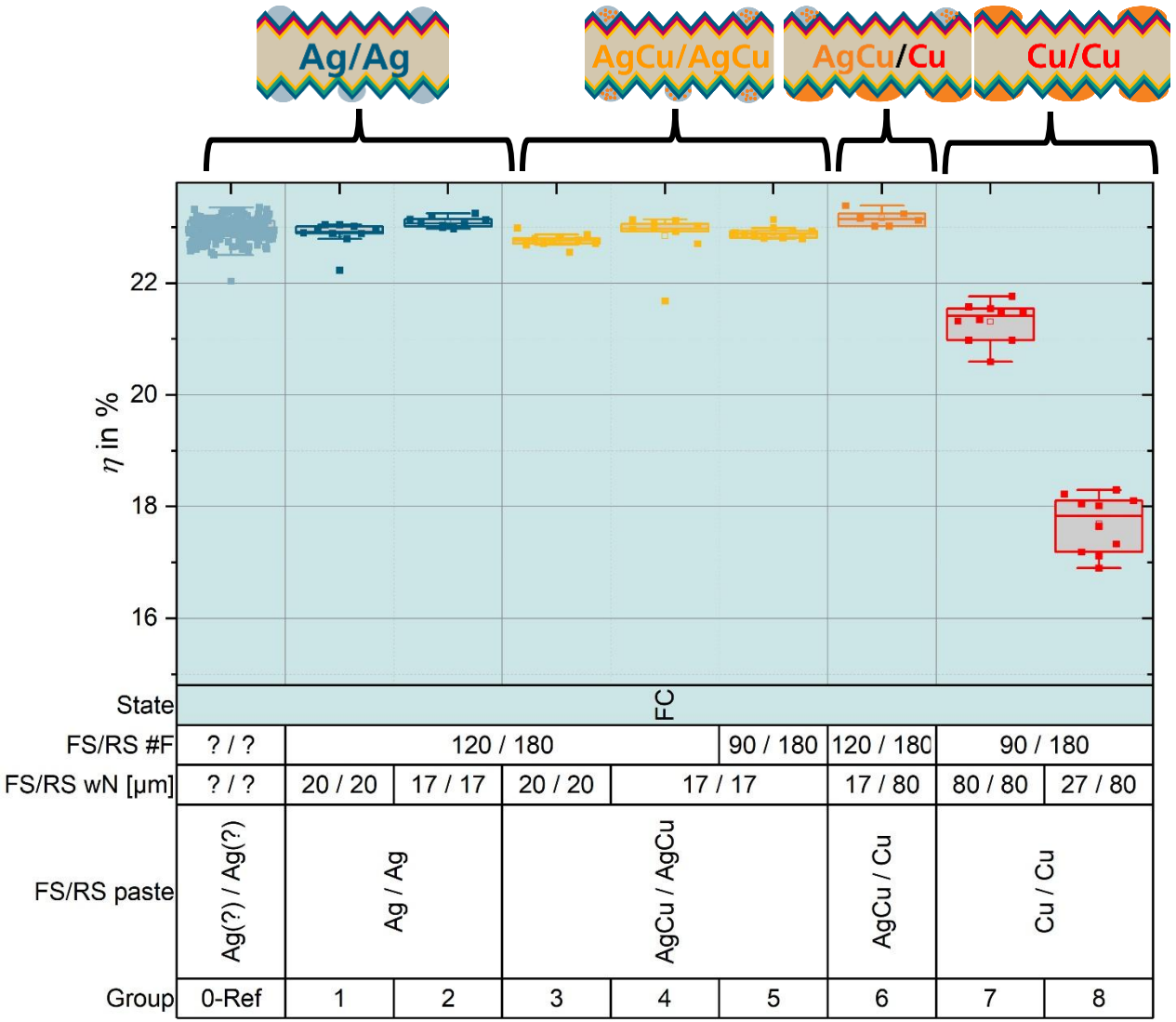
IV Results

Full cell efficiency

- Full cells (FC)[7]

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	FC η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	23.0	0.0%
1	Ag / Ag	20 / 20	120 / 180	22.9	-0.3%
2	Ag / Ag	17 / 17	120 / 180	23.1	0.3%
3	AgCu / AgCu	20 / 20	120 / 180	22.8	-1.0%
4	AgCu / AgCu	17 / 17	120 / 180	23.0	0.0%
5	AgCu / AgCu	17 / 17	90 / 180	22.9	-0.4%
6	AgCu / Cu	17 / 80	120 / 180	23.1	0.7%
7	Cu / Cu	80 / 80	90 / 180	21.4	-6.8%
8	Cu / Cu	27 / 80	90 / 180	17.8	-22.4%

- Similar η for reference and groups 0-6: ± 1%$_{rel.}$
- Low η for pure Cu 7-8



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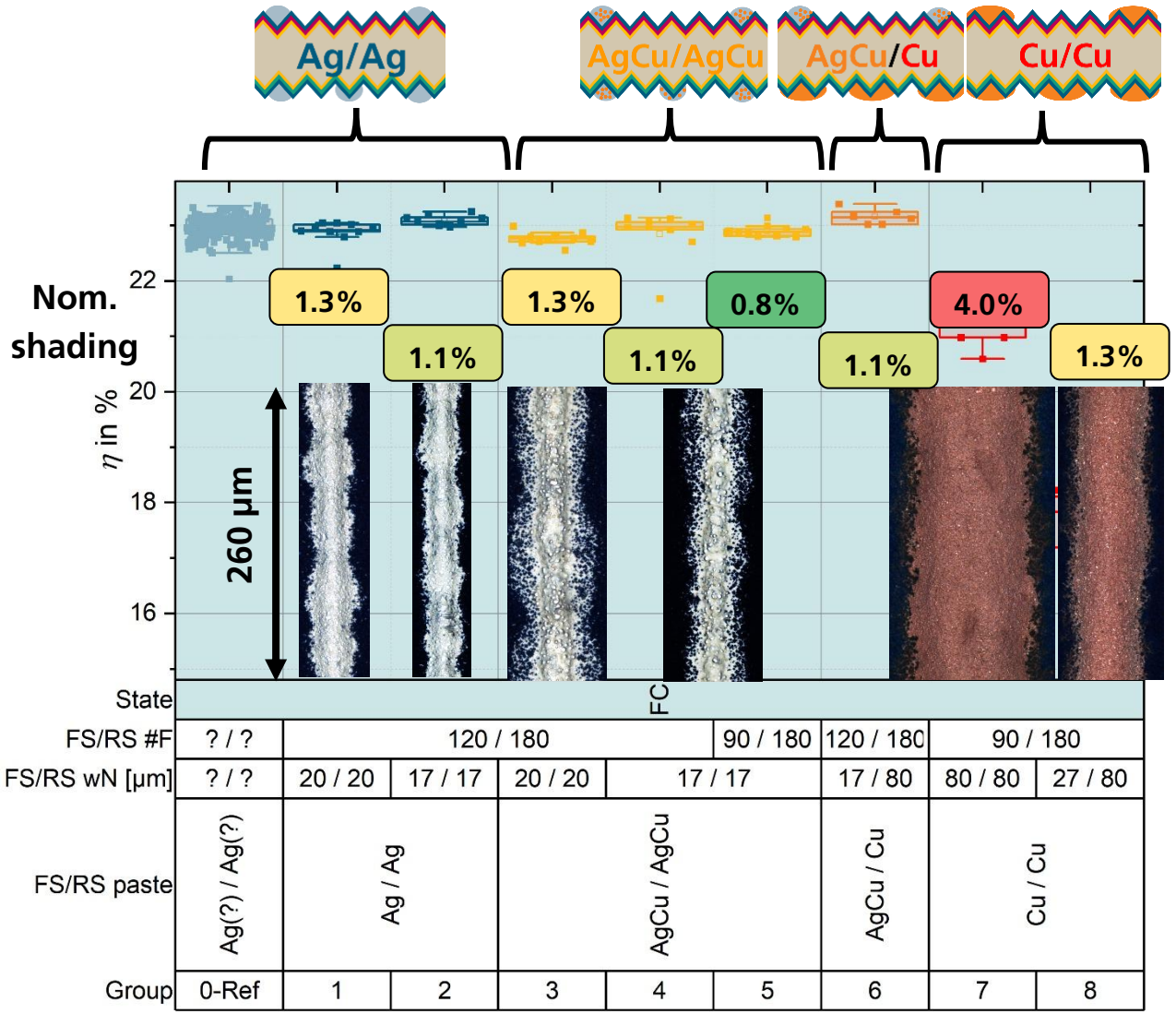
  - Group 7: low J_{SC}
  - Group 8: low J_{SC} and *FF*



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0	Ag(?) / Ag(?)	? / ?	? / ?	23.0	0.0%
1	Ag / Ag	20 / 20	120 / 180	22.9	-0.3%
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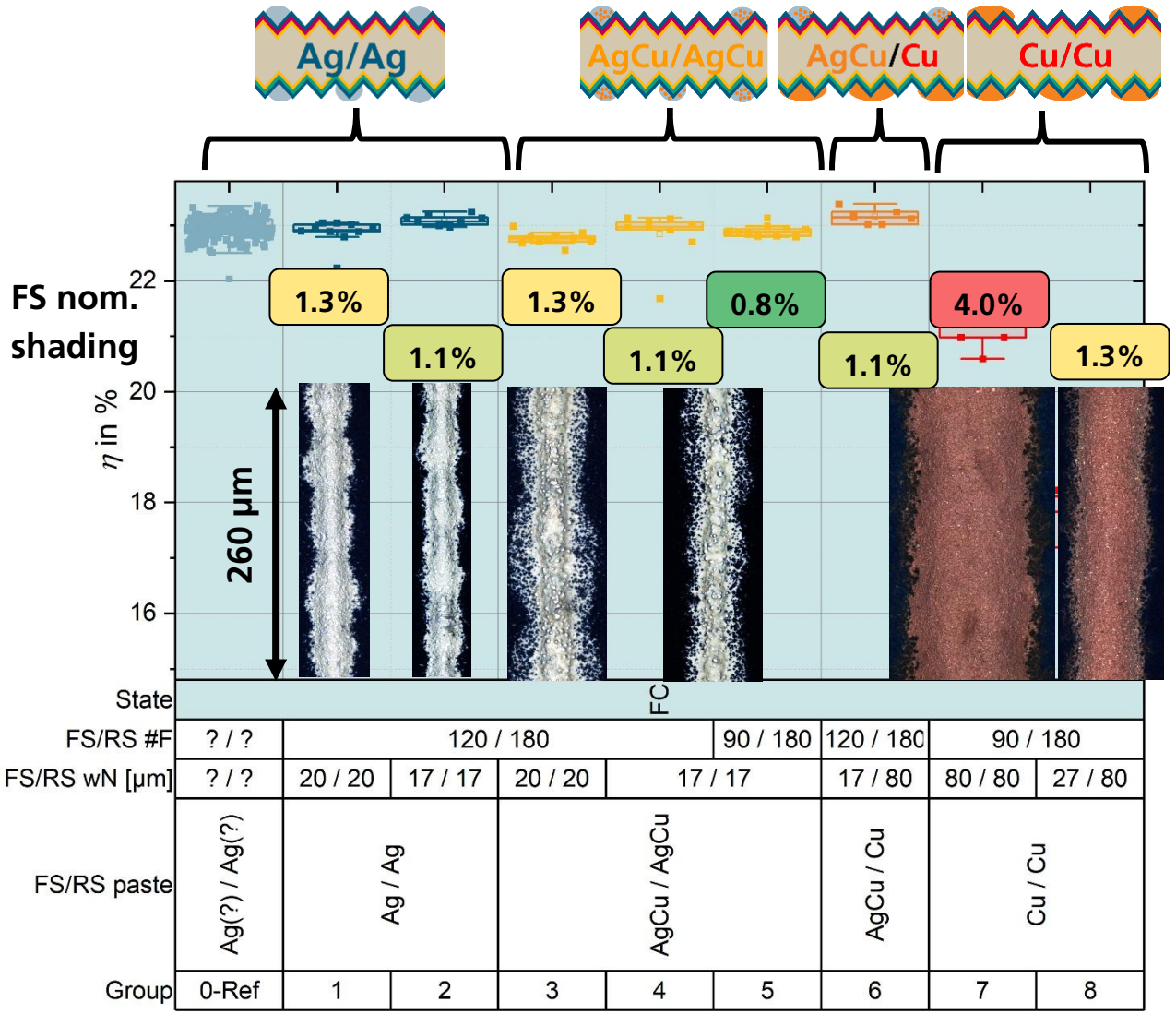
- Similar η for reference and groups 0-6: ± 1%$_{rel.}$
- Low η for pure Cu 7-8
  - Group 7: low J_{SC}
  - Group 8: low J_{SC} and *FF*
- In the following we focus on groups **0,2,5,6,7**



Cells: 16 contact bars (gold chuck calibration)

[7] S. Pingel et al., SiPV 2025

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IV Results
Silver utilization

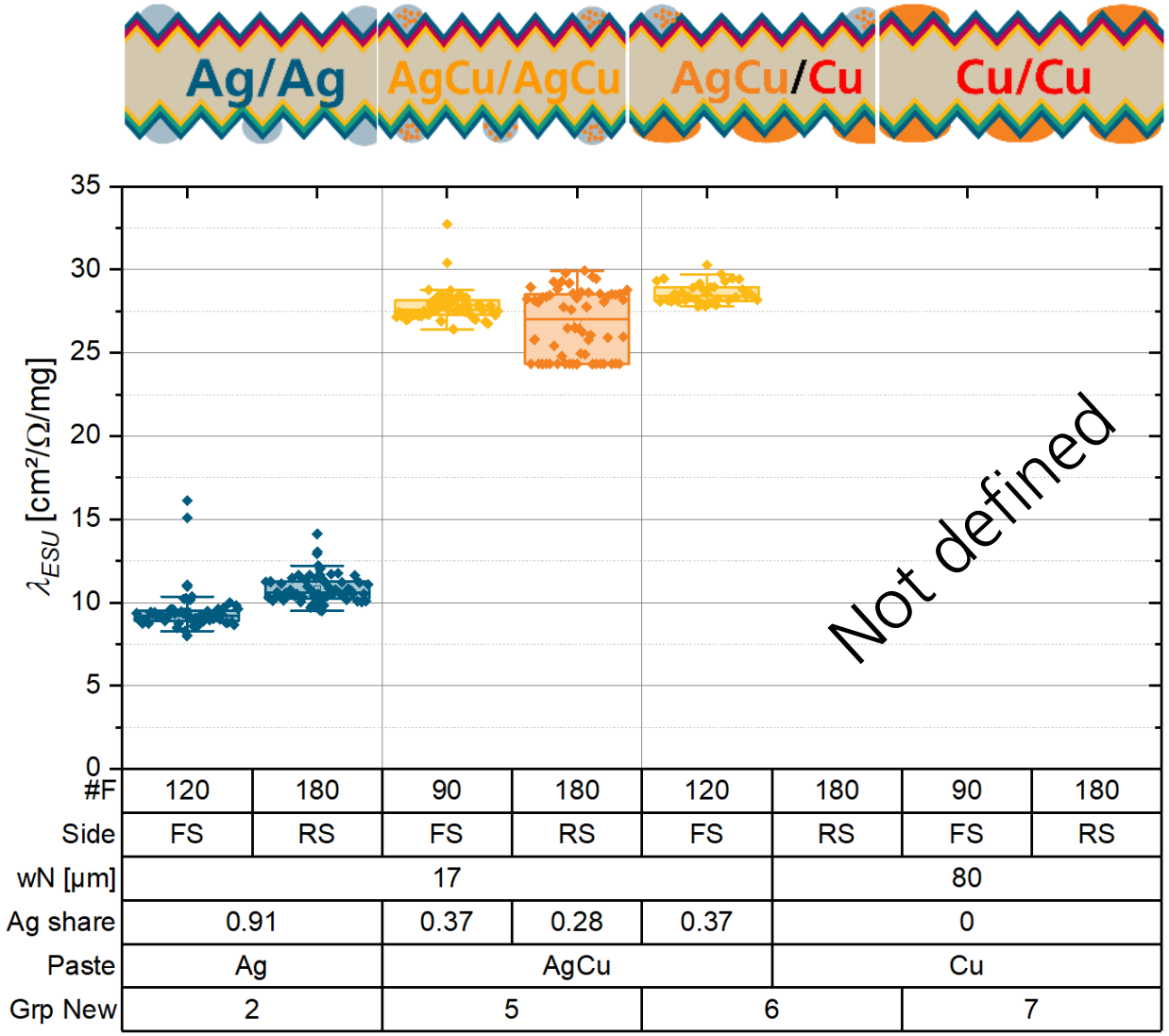
- Full cells (FC)

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	FC η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	23.0	0.0%
2	Ag / Ag	17 / 17	120 / 180	23.1	0.3%
5	AgCu / AgCu	17 / 17	90 / 180	22.9	-0.4%
6	AgCu / Cu	17 / 80	120 / 180	23.1	0.7%
7	Cu / Cu	80 / 80	90 / 180	21.4	-6.8%

Effective Silver Utilization[6,8]

$$\lambda_{ESU} = \frac{l_f}{R_{LINE} \cdot m_{Ag,F}}$$

- Ag (91%)-17µm: ~ 10 cm²/Ωmg ☑
- AgCu (37%)-17µm: ~ 28 cm²/Ωmg ☑
- AgCu(28%) -17µm: ~ 27 cm²/Ωmg ☒
- Cu-80µm not defined since 0 mg Ag ☑



Cells: 16 contact bars (gold chuck calibration)

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[6] S. Pingel et al., 2025, https://doi.org/10.1016/j.solmat.2025.113593
[8] K. Gensowski et al. https://doi.org/10.1016/j.solmat.2022.111871

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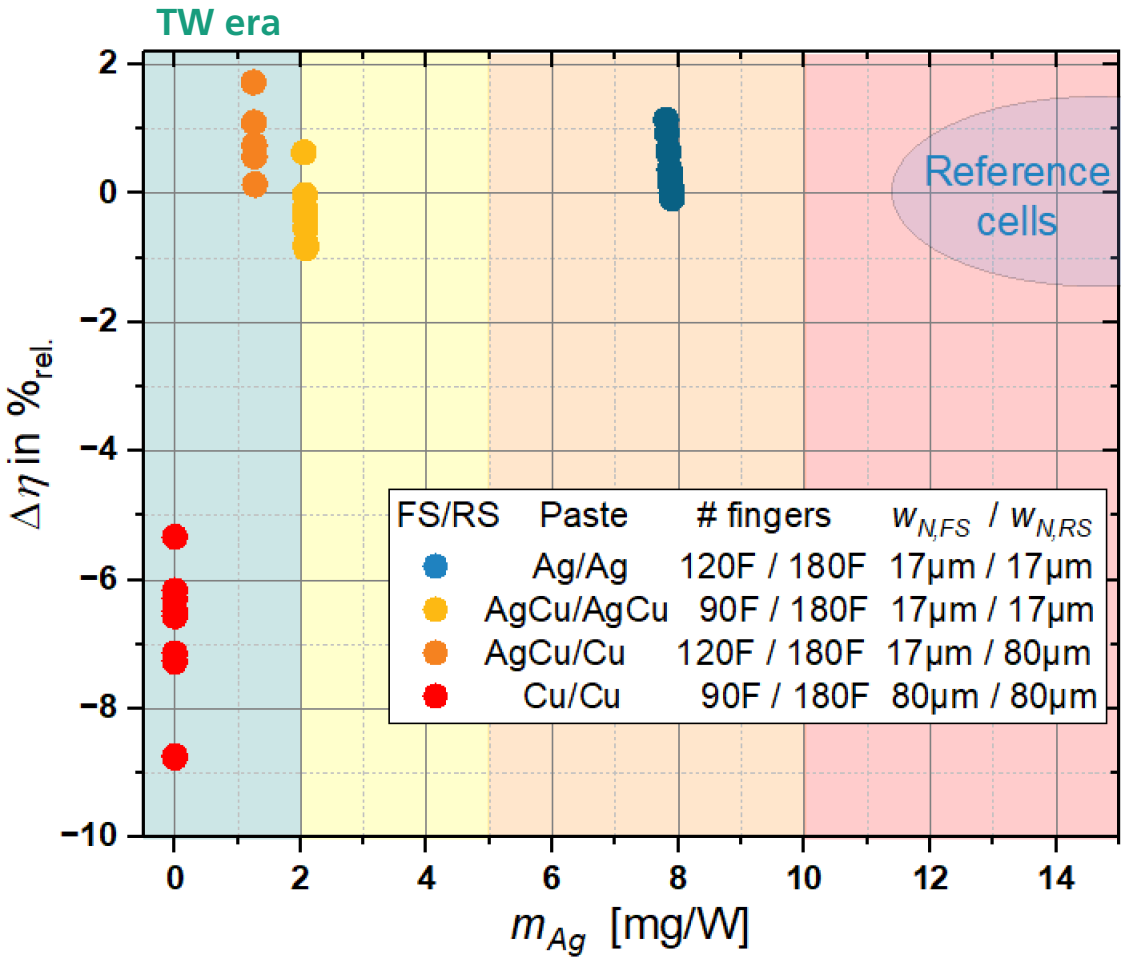
Efficiency and Laydown

Specific silver consumption

- Full cells (FC)

Grp	Paste FS/RS	$w_{N,FS}$ [µm]	# F FS	m_{Ag} [mg/W]
0	Ag(?) / Ag(?)	?	?	~12-17
2	Ag / Ag	17	120	~ 8.0
5	AgCu / AgCu	17	90	**~ 2.1**
6	AgCu / Cu	17	120	**~ 1.4**
7	Cu / Cu	80	90	0

- **TW era** compatible SHJ solar cells are achieved with
  - AgCu / AgCu
  - AgCu / Cu
- Without significantly compromising the η



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3. Module Integration & Reliability Testing

Modules Process Plan

	Ag/Ag		AgCu/AgCu	AgCu/Cu	Cu/Cu
Grp	**0**	**2**	**5**	**6**	**7**
Type	Ind. cell	SHJ M10 industrial precursor			
RS	**Ag?**	**Ag (91%)**	**AgCu (28%)**	**Cu (0%)**	
FS	**Ag?**	**Ag (91%)**	**AgCu (37%)**		**Cu (0%)**
Char	**IV** 0BB cells				
Halfcut	Thermal Laser Separation (TLS): **IV**				
Module Integration Testing	FS + RS soldering 16 Cu-core wires				
	Cross connection | Layup: Glass/POE/String/POE/Glass incl. Edge Sealant | Lamination				
	IV* | aTC200 (-40°C/+85°C) | **IV***				

Cells: FS+RS 16 contact bars (gold chuck calibration)
***Modules: IV measurement relative to calibrated reference**

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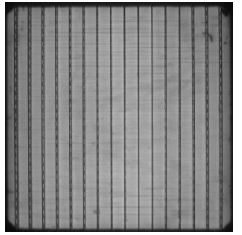
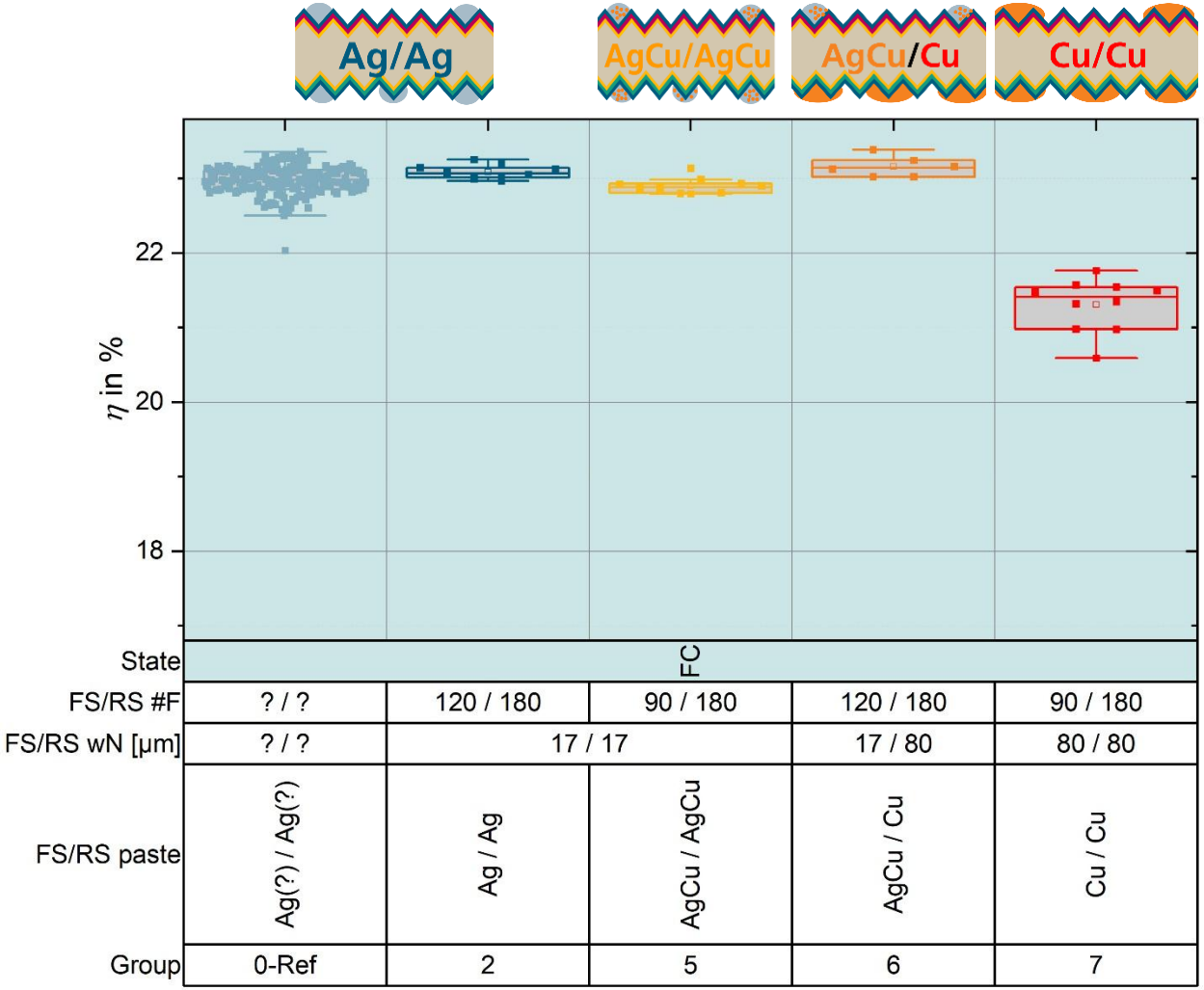
IV Results
Full Cell



- **Full Cells[7]**

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	FC η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	23.0	0.0%
2	Ag / Ag	17 / 17	120 / 180	23.1	0.3%
5	AgCu / AgCu	17 / 17	90 / 180	22.9	-0.4%
6	AgCu / Cu	17 / 80	120 / 180	23.1	0.7%
7	Cu / Cu	80 / 80	90 / 180	21.4	-6.8%

- Similar η for reference and groups 0,2,5,6: ± 1%$_{rel.}$
- Low η for pure Cu 7



Cells: 16 contact bars (gold chuck calibration)

[7] S. Pingel et al., SiPV 2025

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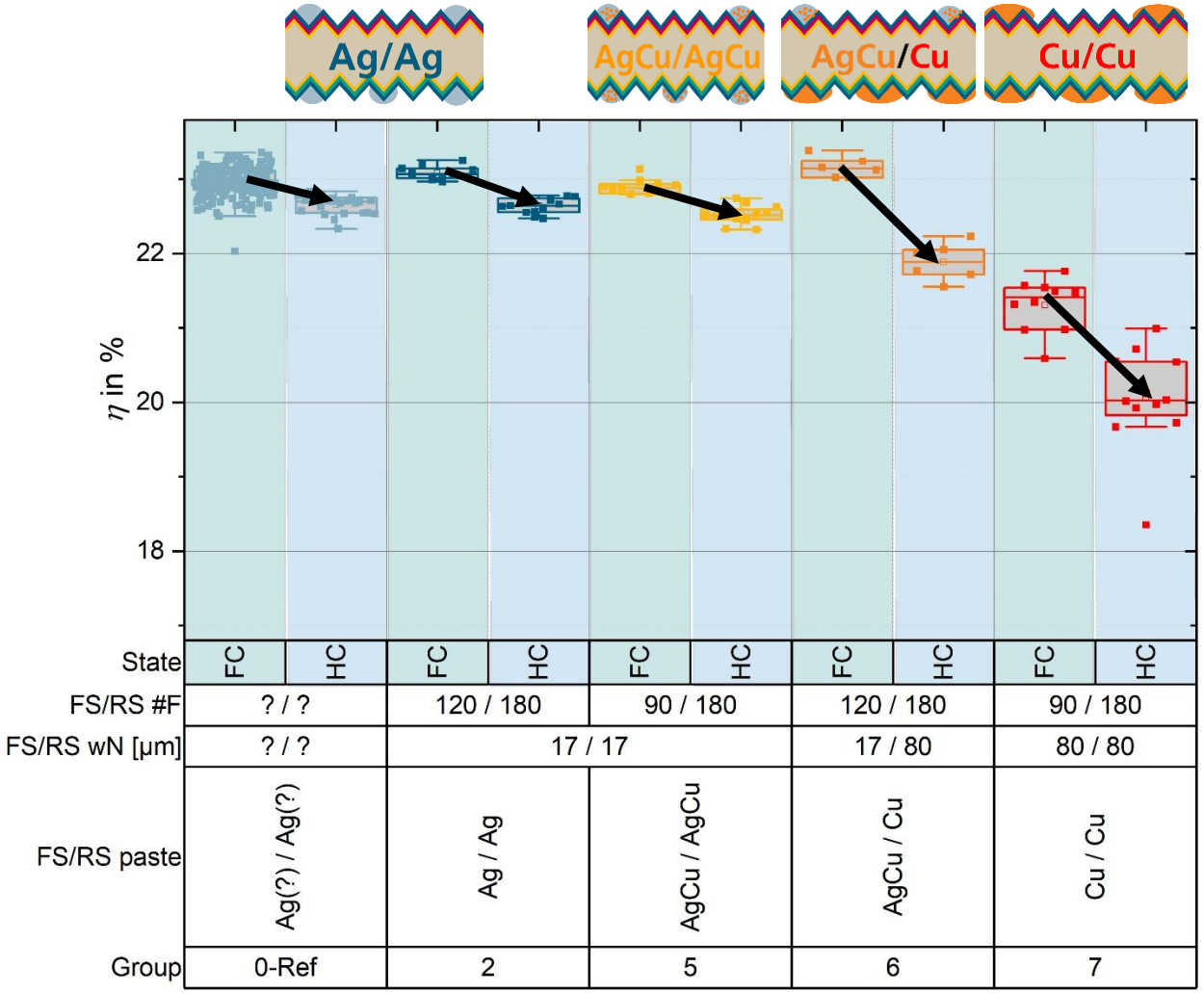
IV Results

Full Cell, Half-cut Cell

- **Full cells → Half-Cut cells**

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	FC η in %	HC η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	23.0	22.7	-1.2%
2	Ag / Ag	17 / 17	120 / 180	23.1	22.6	-1.8%
5	AgCu / AgCu	17 / 17	90 / 180	22.9	22.5	-1.6%
6	AgCu / Cu	17 / 80	120 / 180	23.1	21.9	-5.4%
7	Cu / Cu	80 / 80	90 / 180	21.4	20.0	-6.5%

- Groups 0-5 rel. η-loss 1-2%$_{rel.}$
- Groups 6-7 rel. η-loss ~6%$_{rel.}$
  - R_S-increase - likely oxidation of Cu



Cells: 16 contact bars (gold chuck calibration)

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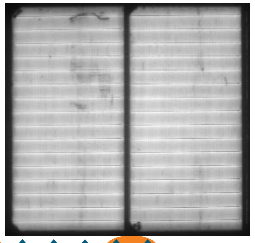
IV Results

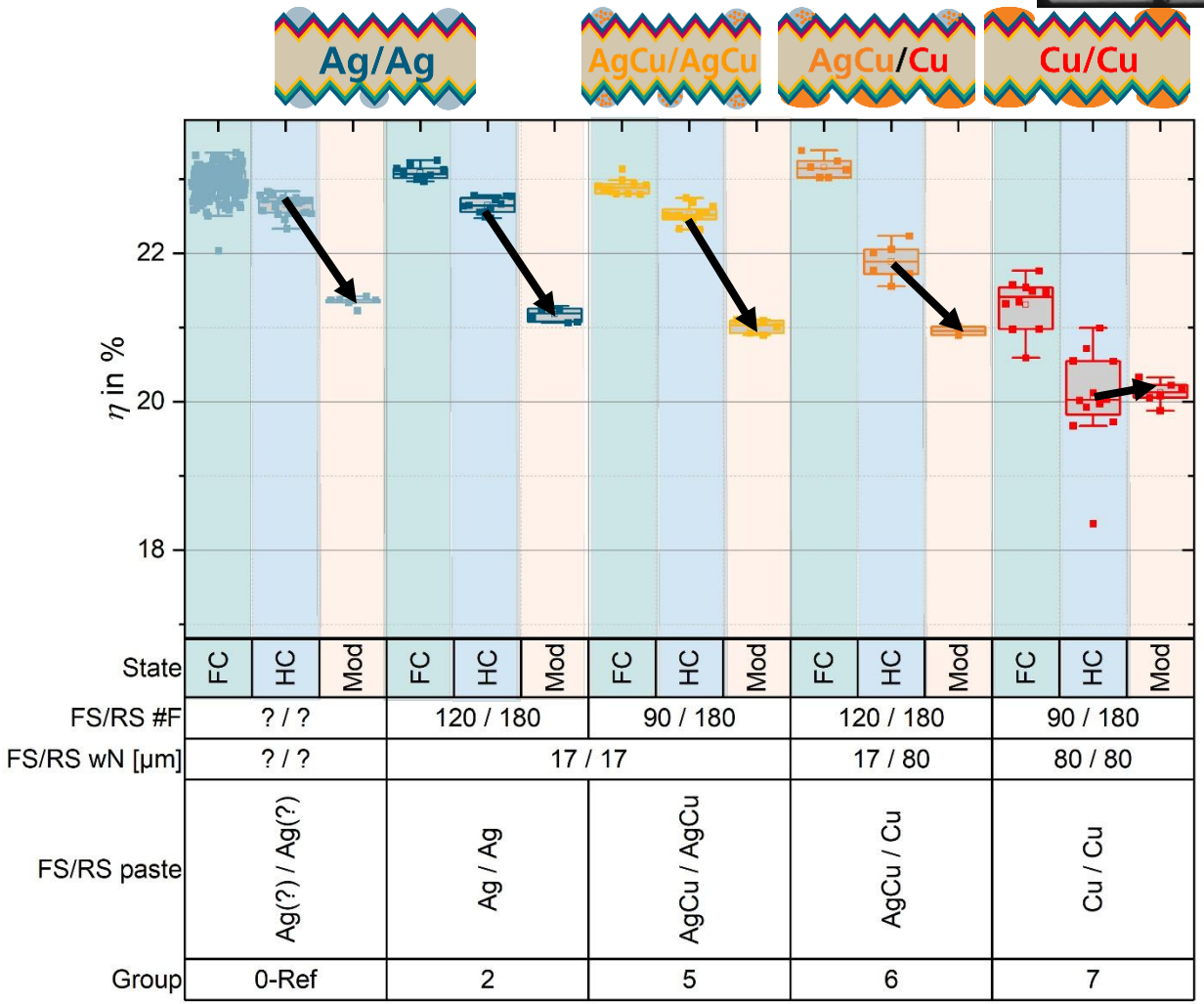
Full Cell, Half-cut Cell, Module



- **Module integration (2x HC)**, no Callab IV

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	HC η in %	MOD η in %	CTM in %
0	Ag(?) / Ag(?)	? / ?	? / ?	22.7	21.4	94.1%
2	Ag / Ag	17 / 17	120 / 180	22.6	21.2	93.6%
5	AgCu / AgCu	17 / 17	90 / 180	22.5	21.0	93.4%
6	AgCu / Cu	17 / 80	120 / 180	21.9	21.0	95.7%
7	Cu / Cu	80 / 80	90 / 180	20.0	20.1	100.5%

- Groups 0-5 CTM factor 93-94%
- Groups 6/7 CTM factor 96% / 100%
  - R_S-increase was compensated during module integration (likely only surface oxidation)



Cells: 16 contact bars (gold chuck calibration)
Modules: IV measurement relative to calibrated reference

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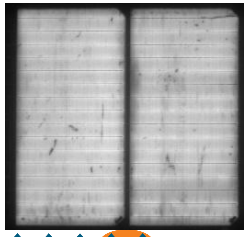
IV Results

Full Cell, Half-cut Cell, Module, aTC200

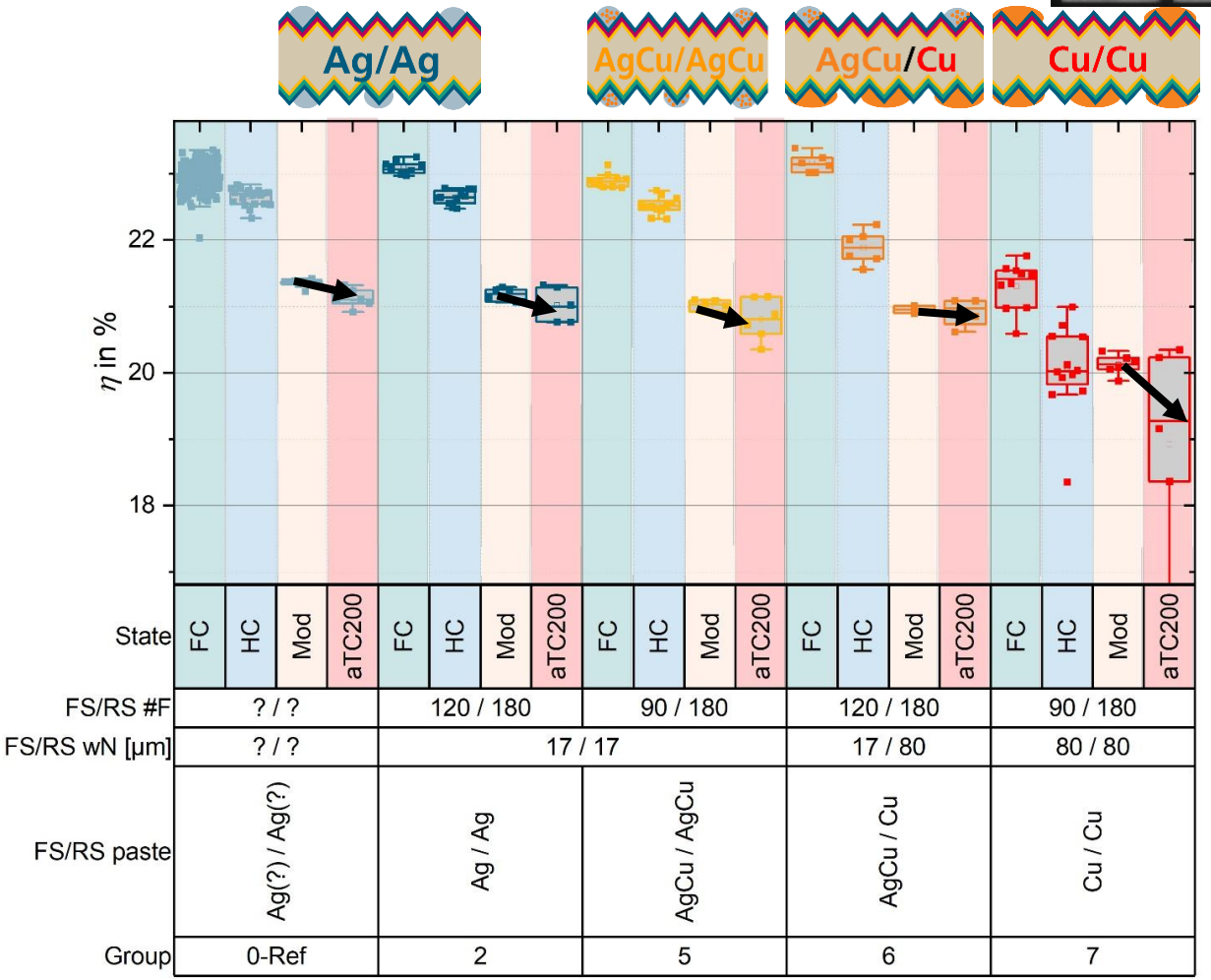


- **Module aTC testing**, no Callab IV

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	MOD η in %	aTC200 η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	21.4	21.1	-1.4%
2	Ag / Ag	17 / 17	120 / 180	21.1	20.8	-1.4%
5	AgCu / AgCu	17 / 17	90 / 180	21.0	20.7	-1.0%
6	AgCu / Cu	17 / 80	120 / 180	21.0	20.7	-1.5%
7	Cu / Cu	80 / 80	90 / 180	20.1	18.8	-6.5%

- Group 0-6 Med. η ↘ by 1-2%$_{rel.}$ (all similar as Ag!)
- Group 7 pure Cu less stable η ↘ by ~ 7%$_{rel.}$

- **TW era** compatible group 5 & 6
  - Successfully introduced into modules
  - No more degradation than the references



Cells: 16 contact bars (gold chuck calibration)
Modules: IV measurement relative to calibrated reference

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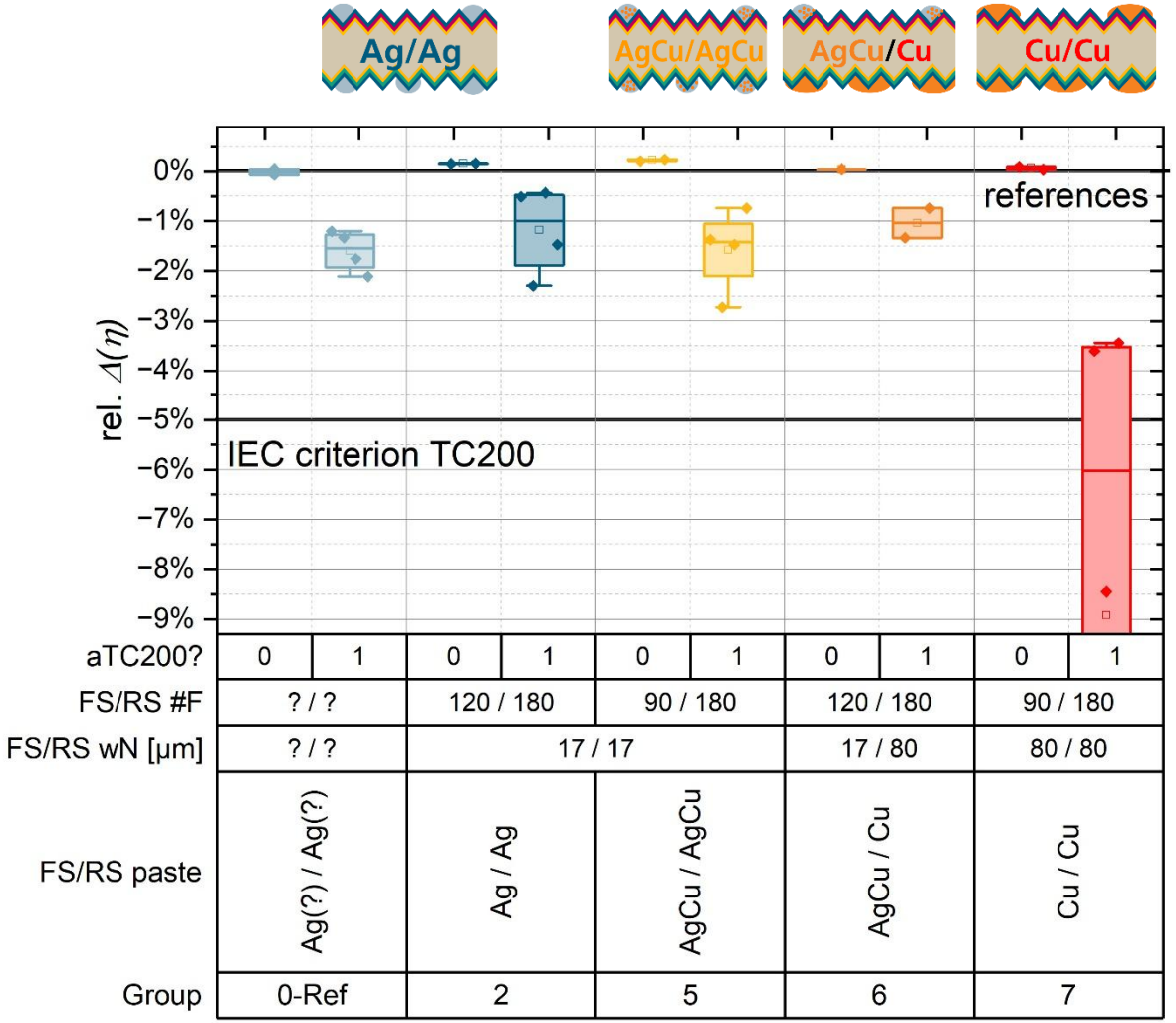
IV Results

Full Cell, Half-cut Cell, Module, aTC200

- **Module aTC testing**

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	MOD η in %	aTC200 η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	21.4	21.1	-1.4%
2	Ag / Ag	17 / 17	120 / 180	21.1	20.8	-1.4%
5	AgCu / AgCu	17 / 17	90 / 180	21.0	20.7	-1.0%
6	AgCu / Cu	17 / 80	120 / 180	21.0	20.7	-1.5%
7	Cu / Cu	80 / 80	90 / 180	20.1	18.8	-6.5%

- Group 0-6 Med. η ↘ by 1-2%$_{rel.}$ (all similar as Ag!)
- Group 7 pure Cu less stable η ↘ by ~ 7%$_{rel.}$
- Direct Module by module comparison
  - Most samples stay below 2%$_{rel.}$ in aTC200
  - Less then allowed degradation acc. to IEC61215
- What are the relevant loss channels?



Cells: 16 contact bars (gold chuck calibration)
Modules: IV measurement relative to calibrated reference

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IV Results

Full Cell, Half-cut Cell, Module, aTC200

- **Module aTC testing**

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	MOD η in %	aTC200 η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	21.4	21.1	-1.4%
2	Ag / Ag	17 / 17	120 / 180	21.1	20.8	-1.4%
5	AgCu / AgCu	17 / 17	90 / 180	21.0	20.7	-1.0%
6	AgCu / Cu	17 / 80	120 / 180	21.0	20.7	-1.5%
7	Cu / Cu	80 / 80	90 / 180	20.1	18.8	-6.5%

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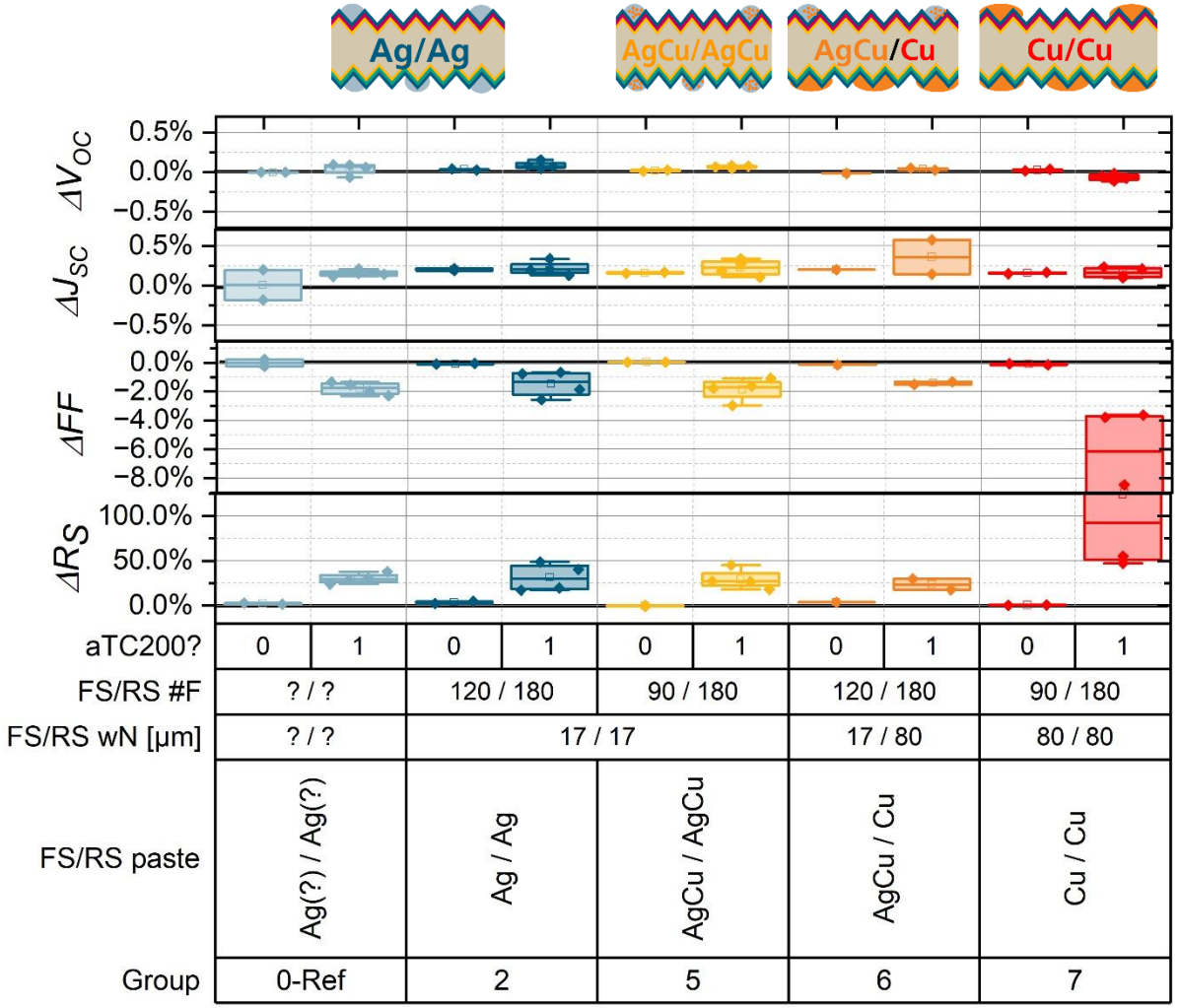
- What are the relevant loss channels?
  - V_{OC} and J_{SC} stable
  - *FF* degradation due to R_S increase (0-6: ~25%)



Cells: 16 contact bars (gold chuck calibration)
Modules: IV measurement relative to calibrated reference

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IV Results

Full Cell, Half-cut Cell, Module, aTC200

- **Module aTC testing**

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS / RS	MOD η in %	aTC200 η in %	$\Delta_{rel.}$
0	Ag(?) / Ag(?)	? / ?	? / ?	21.4	21.1	-1.4%
2	Ag / Ag	17 / 17	120 / 180	21.1	20.8	-1.4%
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6	AgCu / Cu	17 / 80	120 / 180	21.0	20.7	-1.5%
7	Cu / Cu	80 / 80	90 / 180	20.1	18.8	-6.5%

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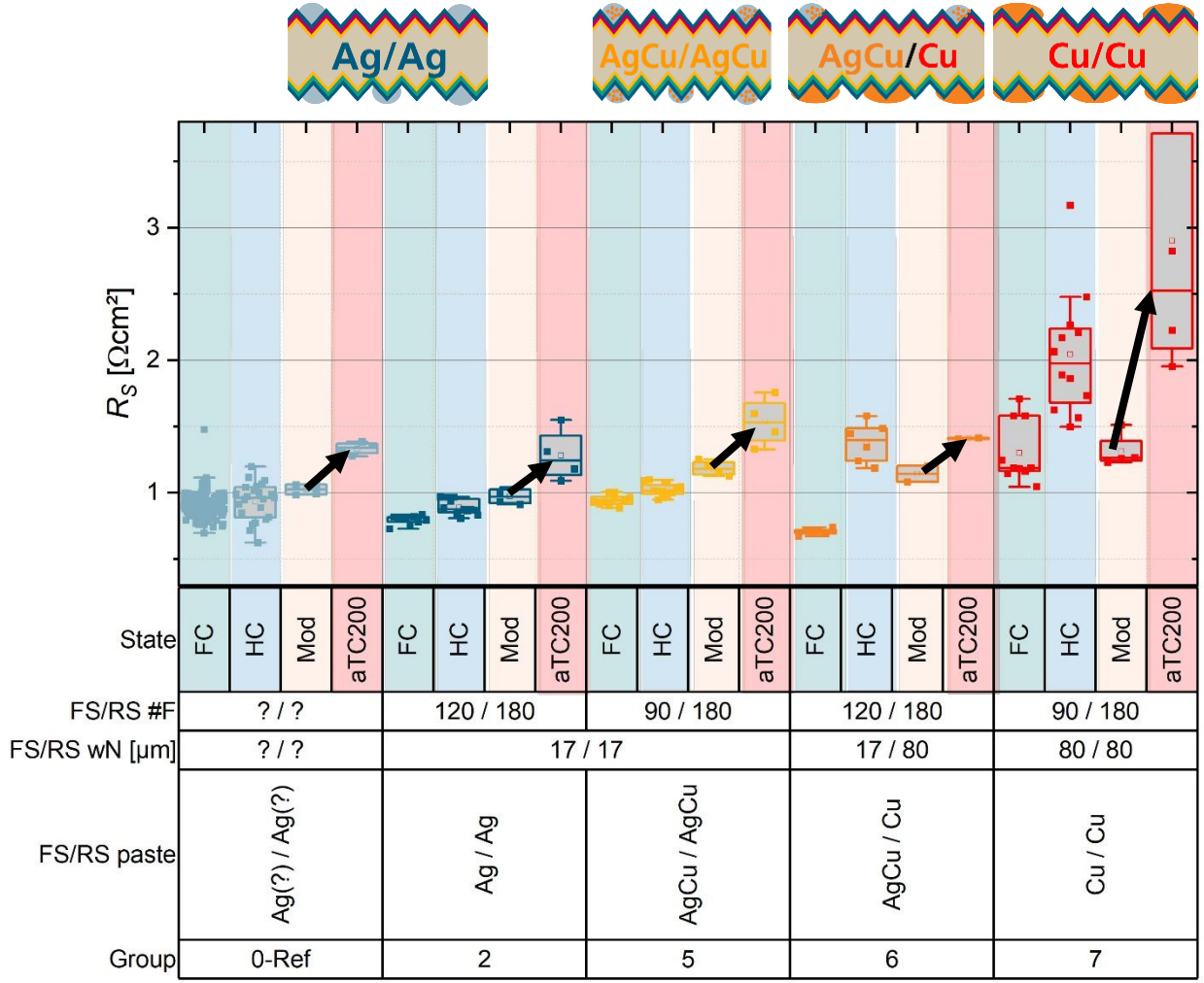

Cells: 16 contact bars (gold chuck calibration)
Modules: IV measurement relative to calibrated reference

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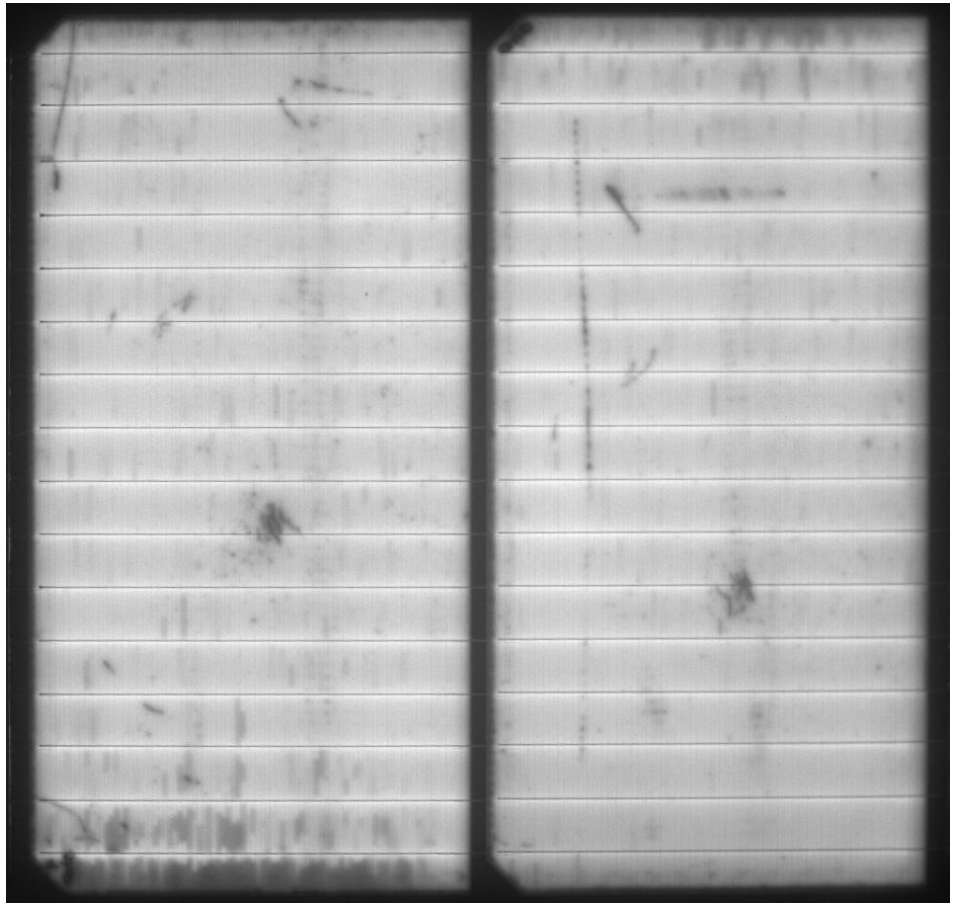
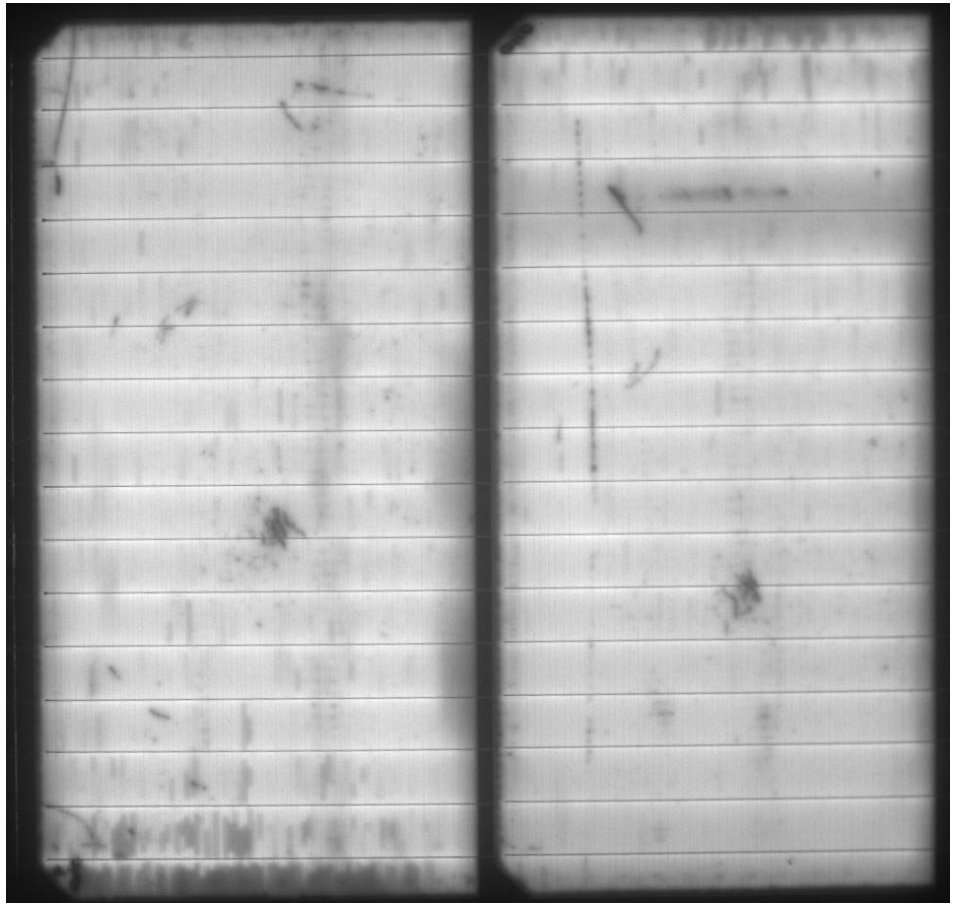
EL images

Grp 2: Ag w_N = 17 µm 120F / 180F



initial



aTC200

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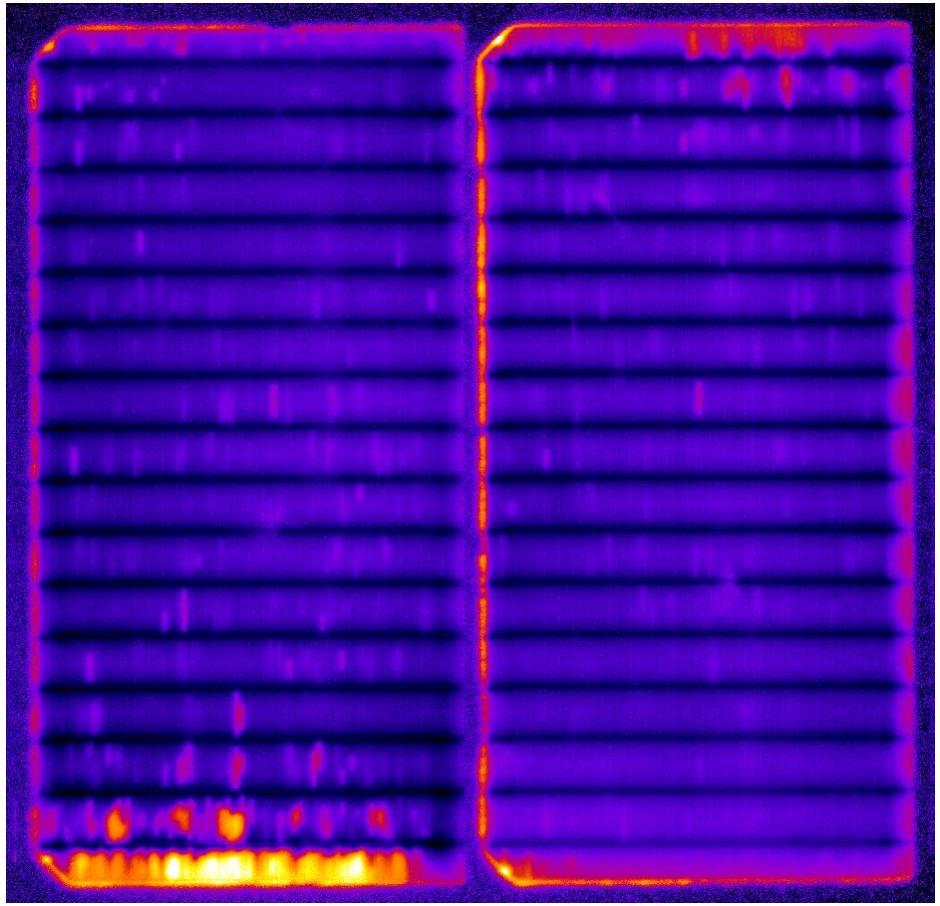
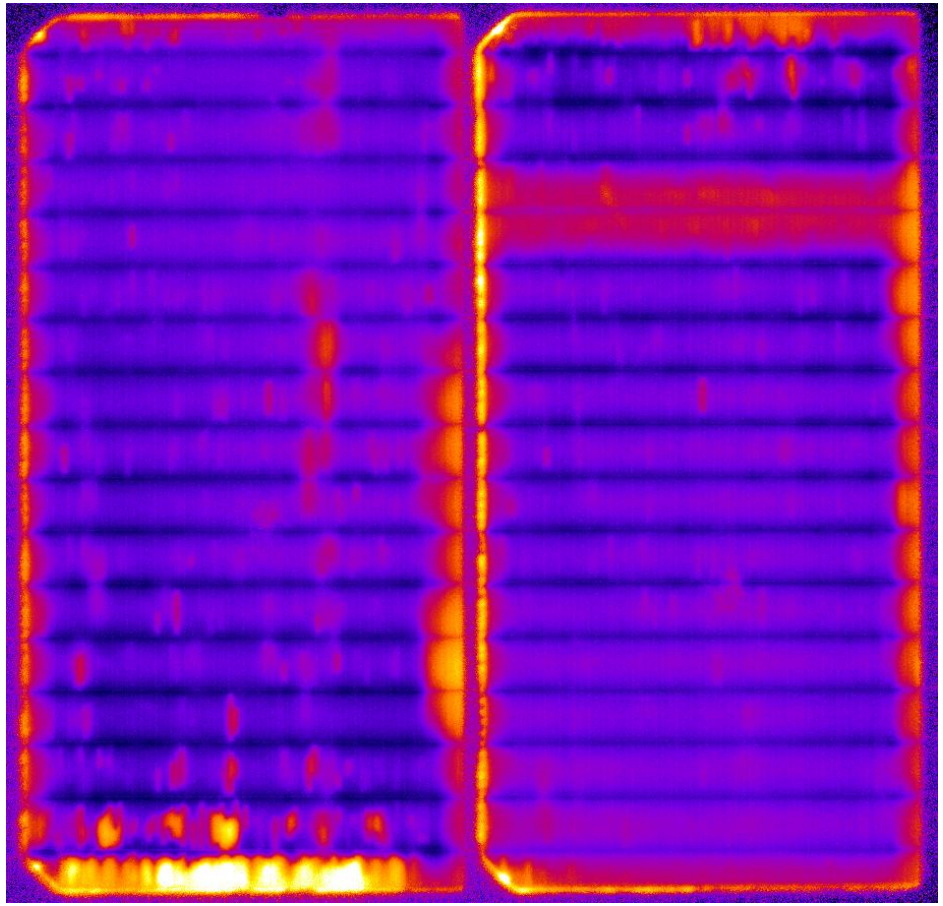
CDCR Series Resistance Analysis

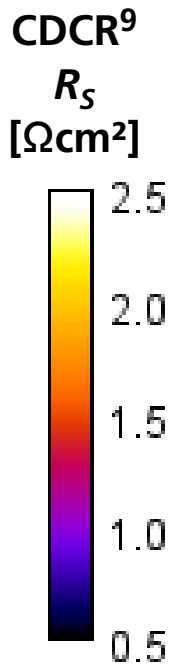
Grp 2: Ag w_N = 17 µm 120F / 180F



initial



aTC200



[9] M. Glatthaar et al., https://doi.org/10.1002/pssr.200903290

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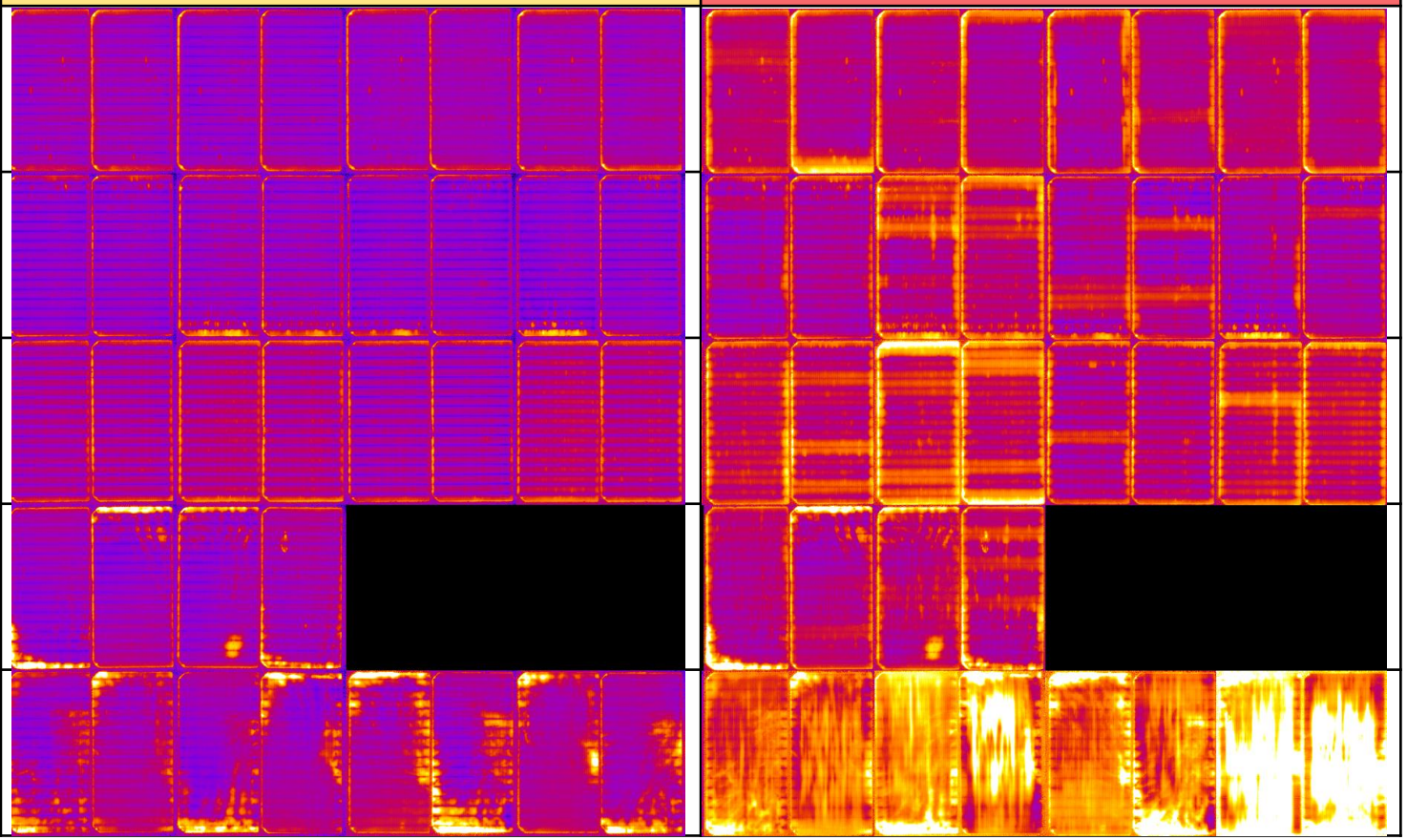
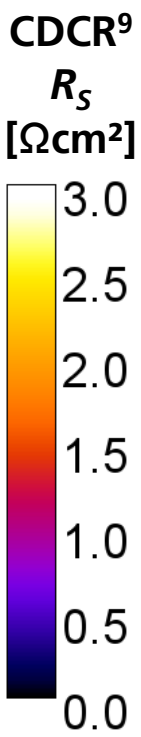
CDCR Series Resistance Analysis

Initial and post aTC200

Grp	Paste FS/RS	w_N [µm] FS/RS	#F FS/RS	inital	post aTC200
0	Ag(?) / Ag(?)	? / ?	? / ?		
2	Ag / Ag	17 / 17	120 / 180		
5	AgCu / AgCu	17 / 17	90 / 180		
6	AgCu / Cu	17 / 80	120 / 180		
7	Cu / Cu	80 / 80	90 / 180		





[9] M. Glatthaar et al., https://doi.org/10.1002/pssr.200903290

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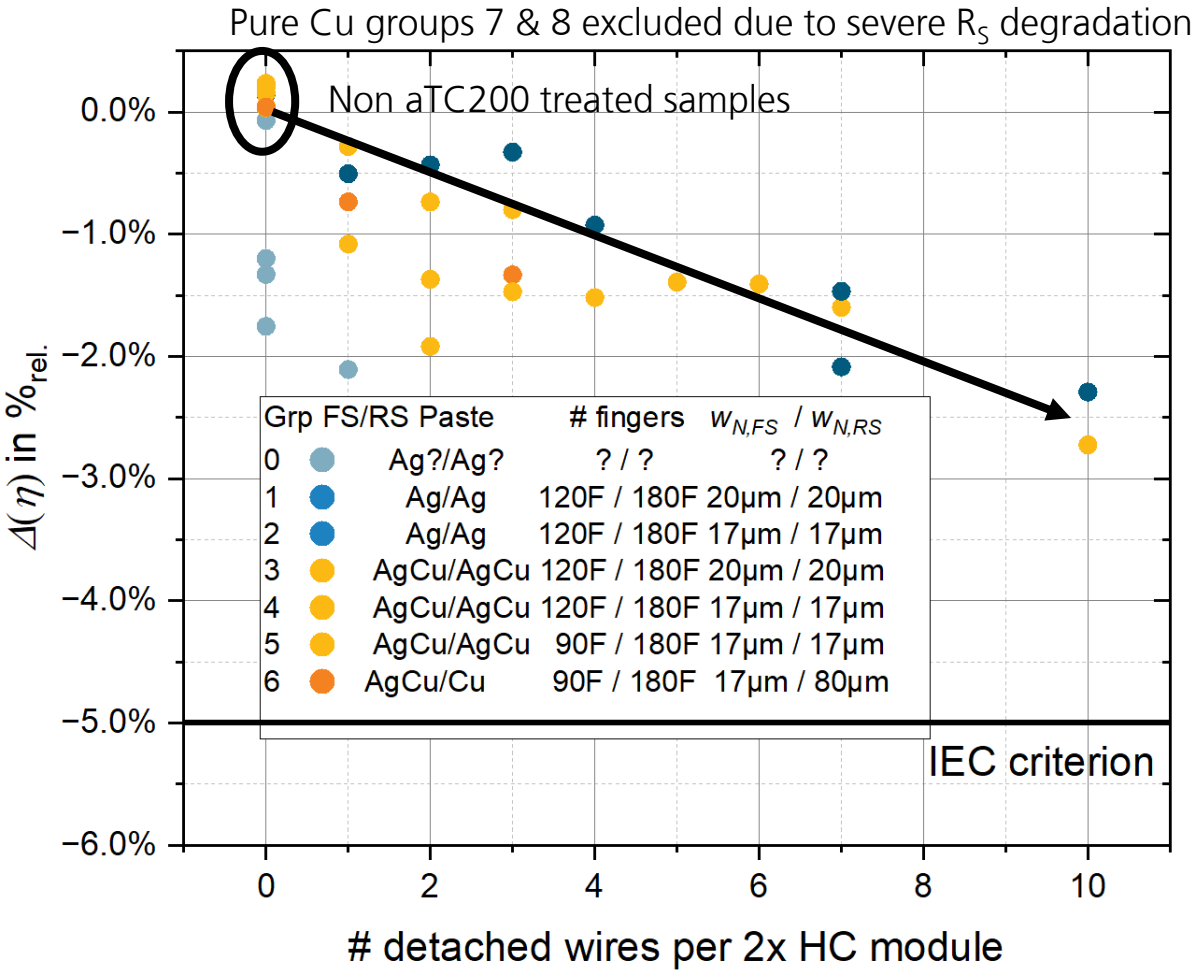
Correlation Wire Detachment Rate to Degradation

Initial and post aTC200

- Count of (partially) detached wires after aTC200
  - Up to 10 per 2-HC module affected
- Correlation to η-degradation
  - Count ↗ leads to degradation ↗ (~ 0.25% / wire)
  - Other forms of R_S degradation present (0-Ref)
- Further research necessary for root cause analysis of wire detachment
  - Fine Line printed fingers to weak?
  - Stress during interconnection?
  - …

Groups 1-6 degrade less than TC200 IEC criterion (<5%) but substantial optimization potential



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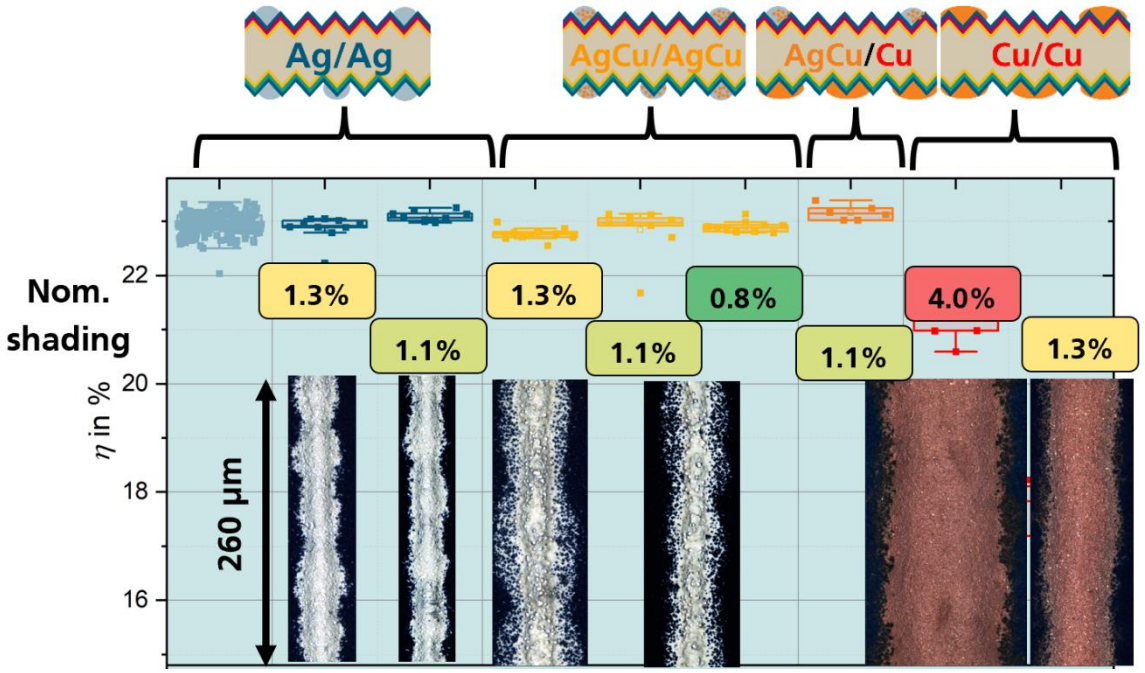
Summary & Outlook

Summary

- Successfully fine-line printed SHJ cells with advanced screens and pastes: **Ag (91%)**, **AgCu (37%** and **28%)**
- Promising λ_{ESU} 25-30 achieved for fine **AgCu** fingers



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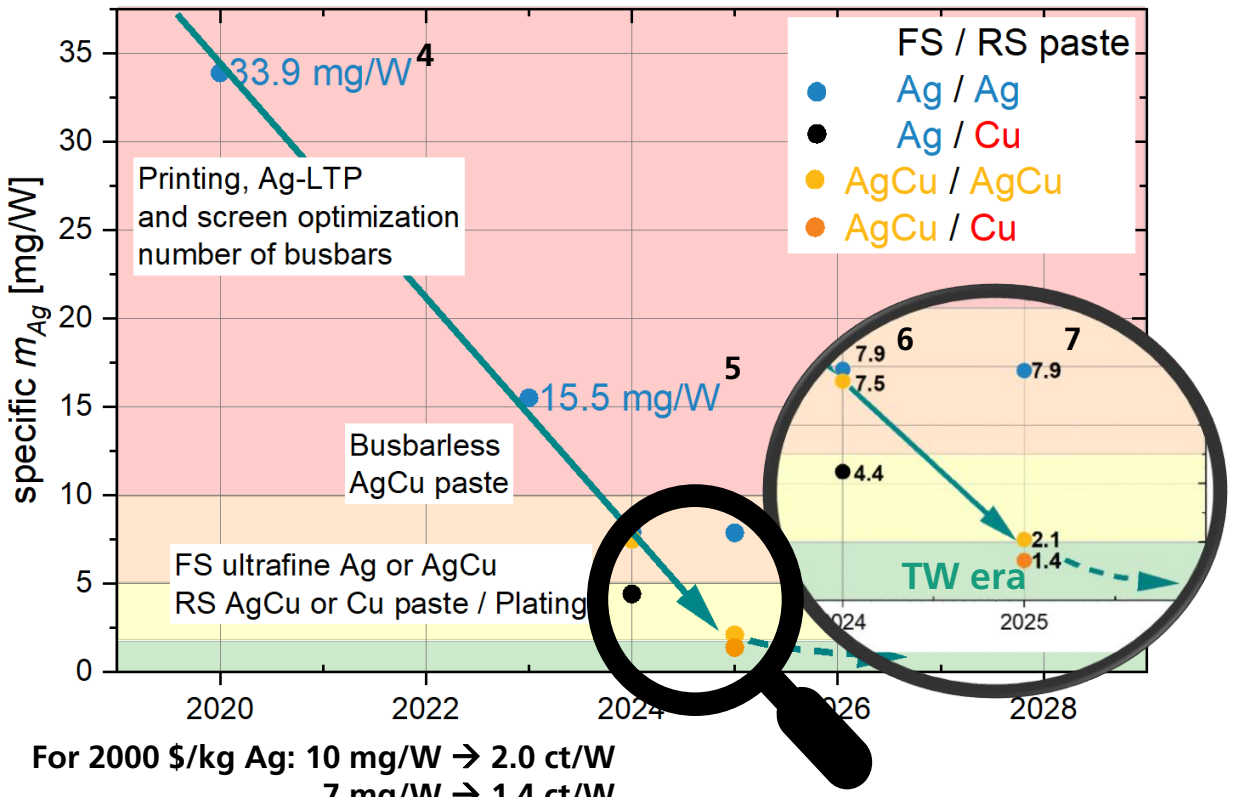
  - **AgCu / AgCu:** m_{Ag} ~ 2.1 mg/W; η ➔ vs. **Ag** Ref
  - **AgCu / Cu** m_{Ag} ~ 1.4 mg/W; η ↗ compared to **Ag** Ref

  Metallization costs absolutely **competitive to TOPCon**



For 2000 $/kg Ag: 10 mg/W → 2.0 ct/W
7 mg/W → 1.4 ct/W
2 mg/W → 0.4 ct/W

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[4] Y. Zhang et al., EES 2021 https://doi.org/10.1039/D1EE01814K
[5] Y. Chang et al., 2024, https://doi.org/10.1002/pip.3799
[6] S. Pingel et al., 2025,https://doi.org/10.1016/j.solmat.2025.113593
[7] S. Pingel et al., SiPV 2025 & this workshop

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Summary & Outlook

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- Successfully fine-line printed SHJ cells with advanced screens and pastes: **Ag (91%)**, **AgCu (37%** and **28%)**
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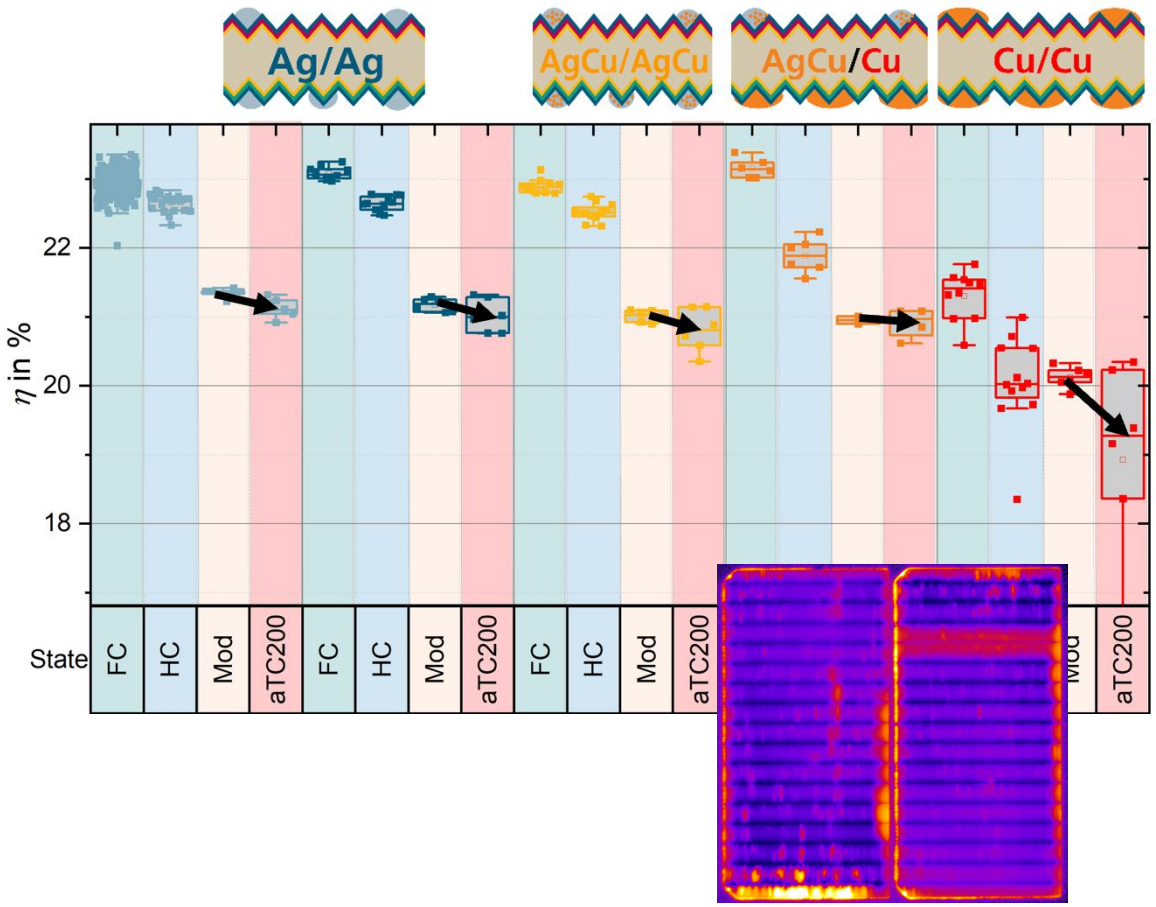
- **Integration into modules**
  - Cutting and CTM losses investigated
  - aTC-testing, better than IEC TC200 criterion ☑
  - Optimization potential!

Ag is not limiting SHJ cell production in TW era



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Summary & Outlook

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  - **AgCu / AgCu:** m_{Ag} ~ 2.1 mg/W; η ➔ vs. **Ag** Ref
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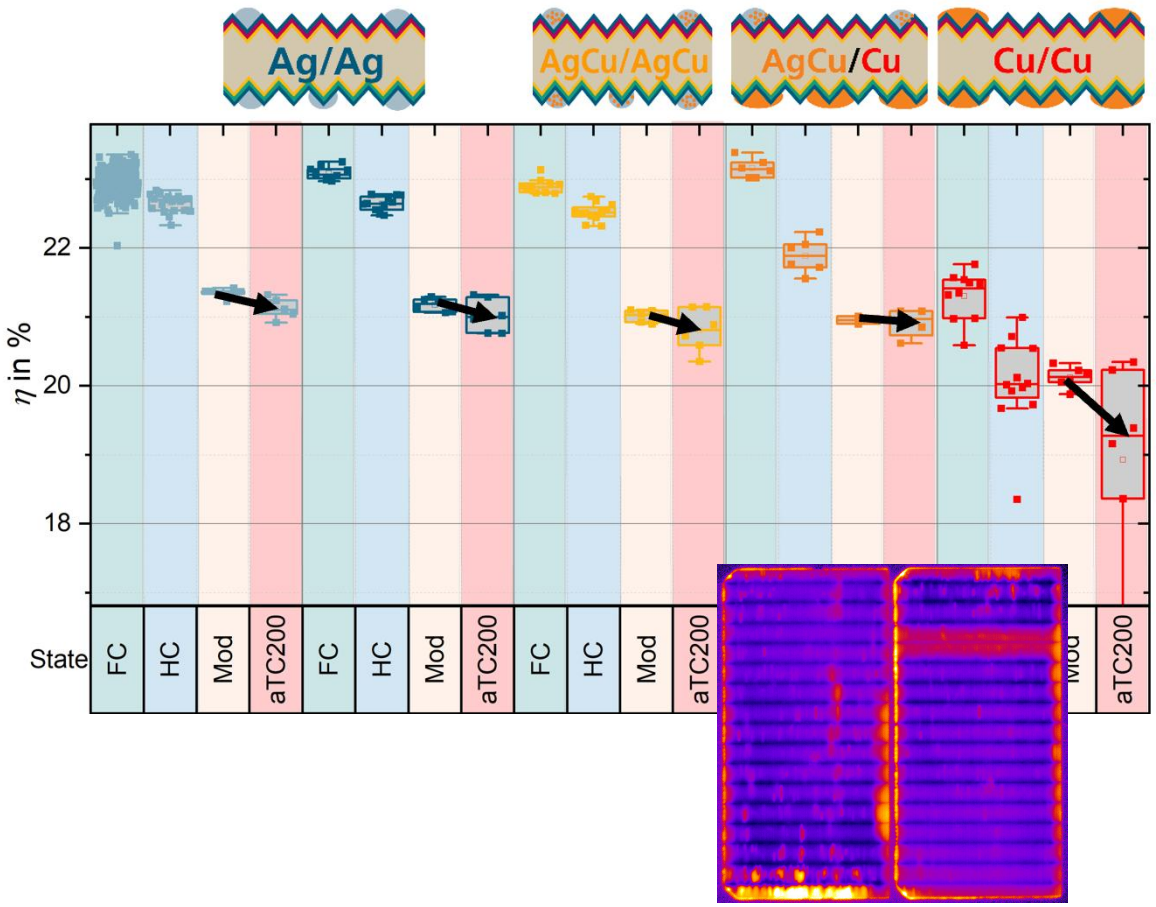
  - Cutting and CTM losses investigated
  - aTC-testing, better than IEC TC200 criterion ☑
  - Optimization potential!

Ag is not limiting SHJ cell production in TW era

Outlook: Printing finer: w_N = 16 ↘ 10 µm (η↗, costs ↘)
Address Indium and Bismuth consumption



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Thank you for your attention!

Department for Metallization and Structuring Technologies

Department for Quality Assurance, Characterization and Simulation

Division Photovoltaics
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- Industry partners
- Federal Ministry for Economic Affairs and Climate Action

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