

Transition From Silver- to Copper-Based Screen Printed SHJ Solar Cells

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²now with ASYS-Group

Metallization Workshop 2024, Chambéry
October 24th, 2024

www.ise.fraunhofer.de

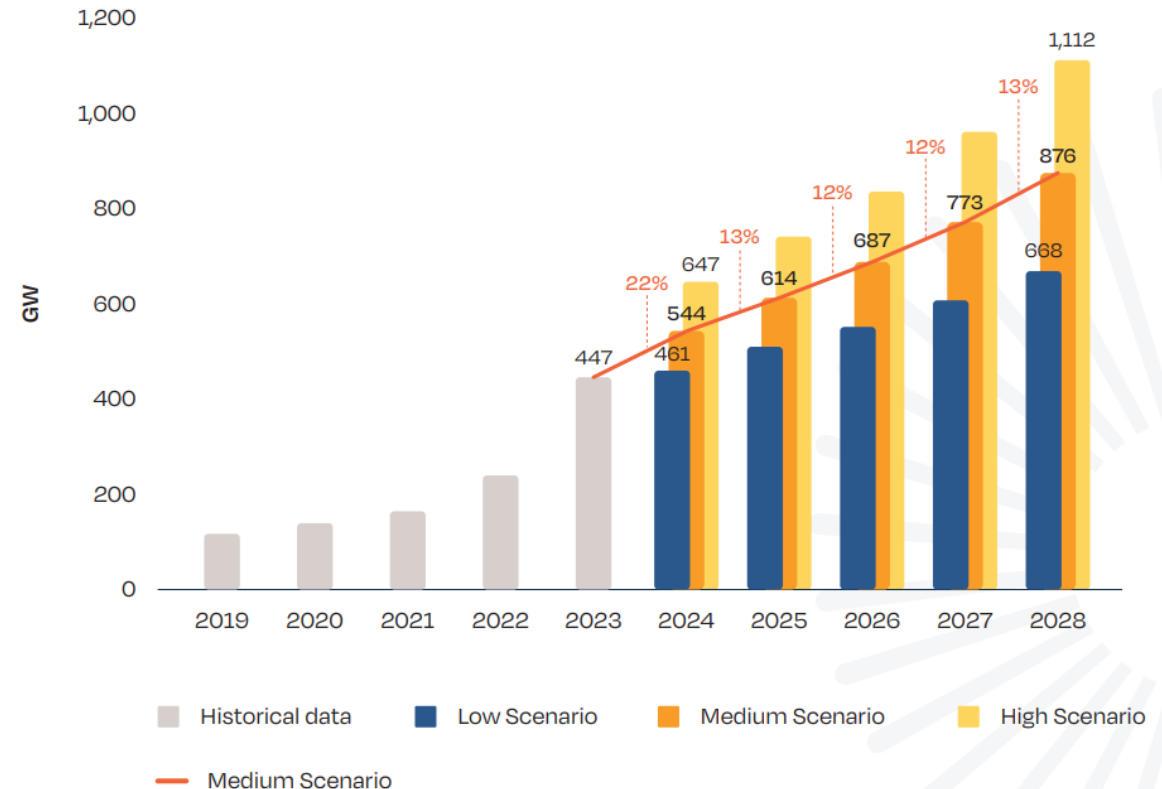
Background and Motivation

Rapid growth of the PV Industry – Risk and Challenges

Rapid growth of PV:

- Installed capacity 2023: **447 GW_p**¹

FIGURE 4 WORLD ANNUAL SOLAR PV MARKET SCENARIOS 2024-2028



Forecast of the globally installed PV capacity until 2028²

¹Solar Power Europe 2024

² https://api.solarpowereurope.org/uploads/Global_Market_Outlook_for_Solar_Power_2024_a083b6dcd5.pdf

³J. Bartsch et al., PV International 48, 2021

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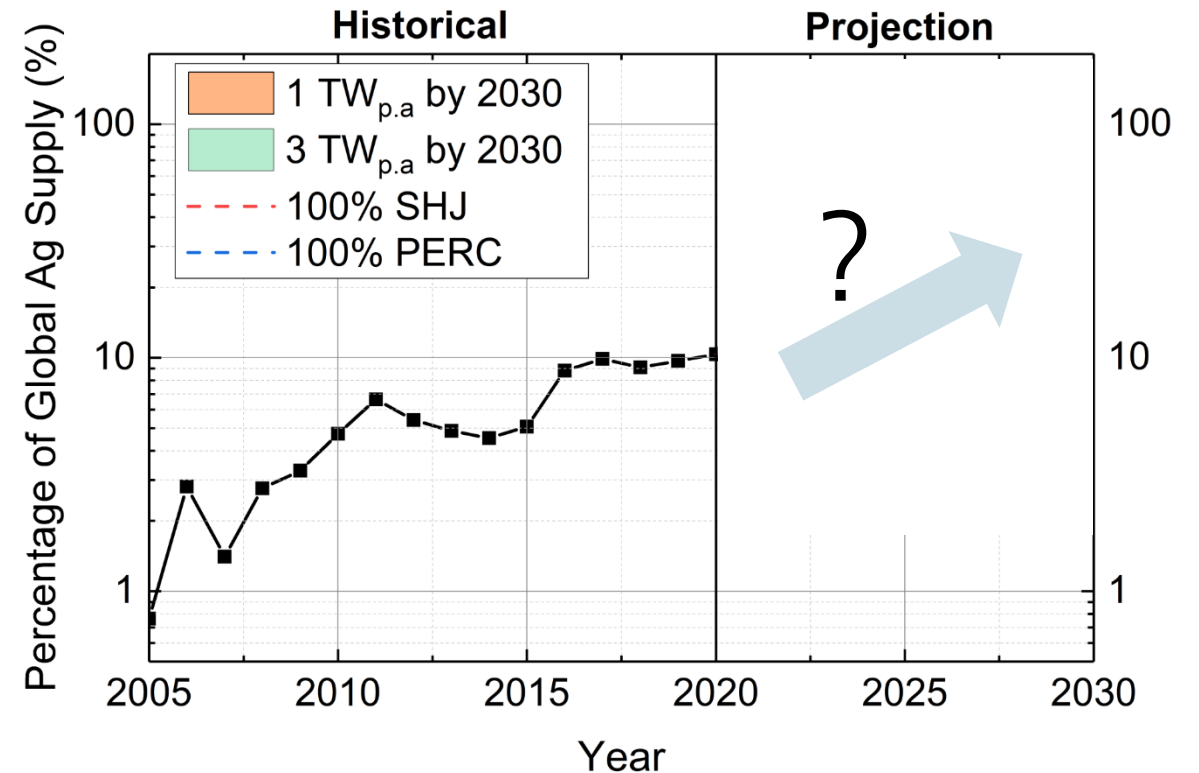
Rapid growth of the PV Industry – Risk and Challenges

Rapid growth of PV:

- Installed capacity 2023: **447 GW_p**¹

Risk and Challenge:

- Rising demand for scarce material (**Ag**, Bi, In...)



Development of global silver consumption until 2030 with a projected yearly increase of 1 or 3 TW/year³

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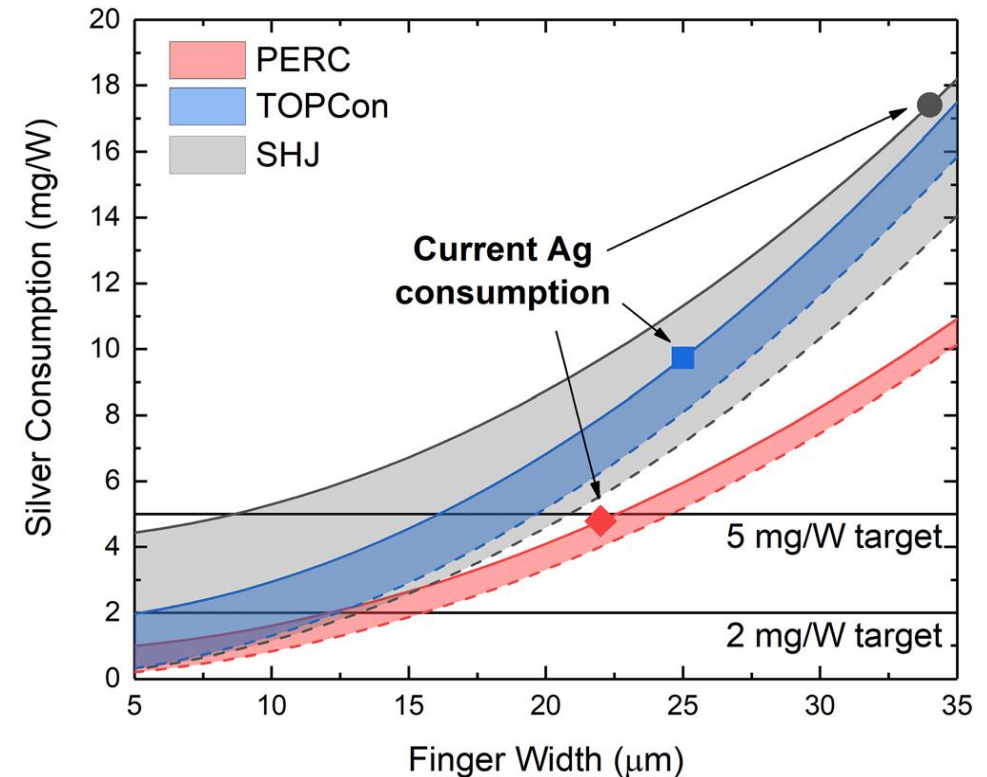
Rapid growth of the PV Industry – Risk and Challenges

Rapid growth of PV:

- Installed capacity 2023: **447 GW_p**¹

Risk and Challenge:

- Rising demand for scarce material (**Ag**, Bi, In...)
- Most critical resource: Silver usage in metallization
- Today: 5 mg/W (PERC) – **17 mg/W (SHJ) Ag** is used⁴



Calculated silver consumption as a function of printed width of ag fingers in industrial screen-printed PERC, TOPCon and SHJ solar cells. Solid lines show the total silver consumption in the finger, busbar and soldering tab regions, and dash lines show finger silver consumption only⁴

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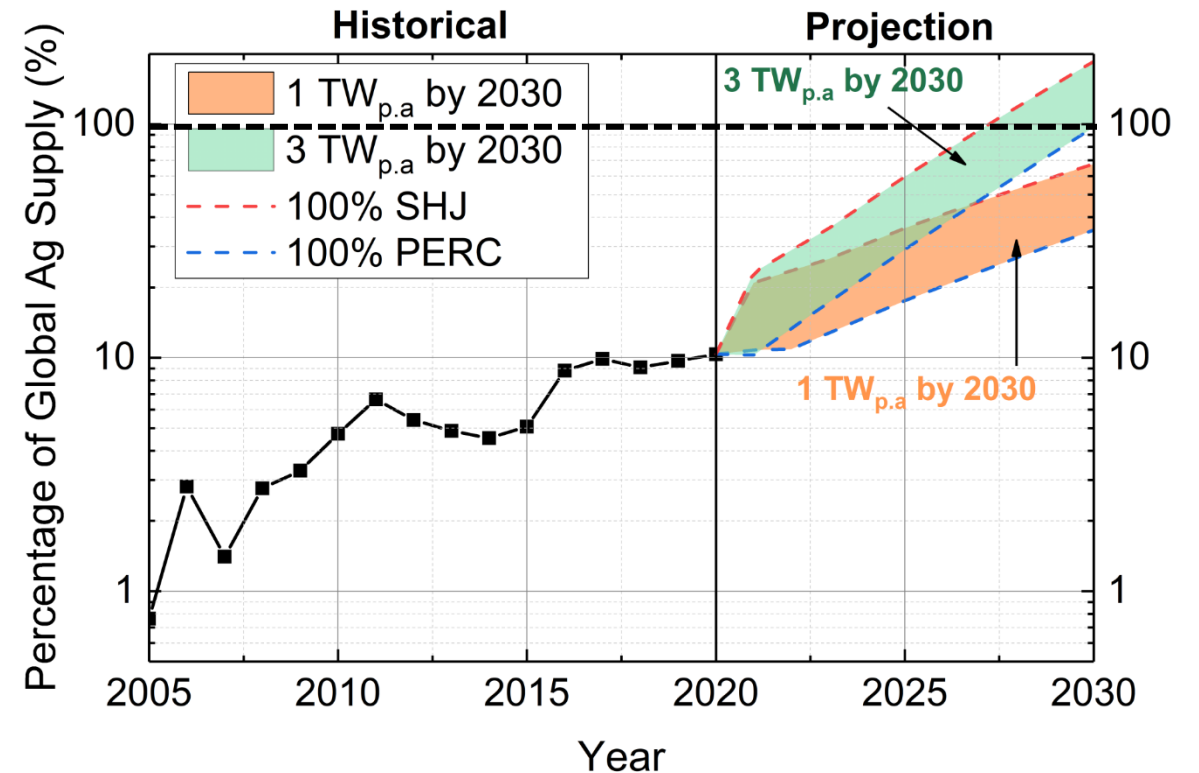
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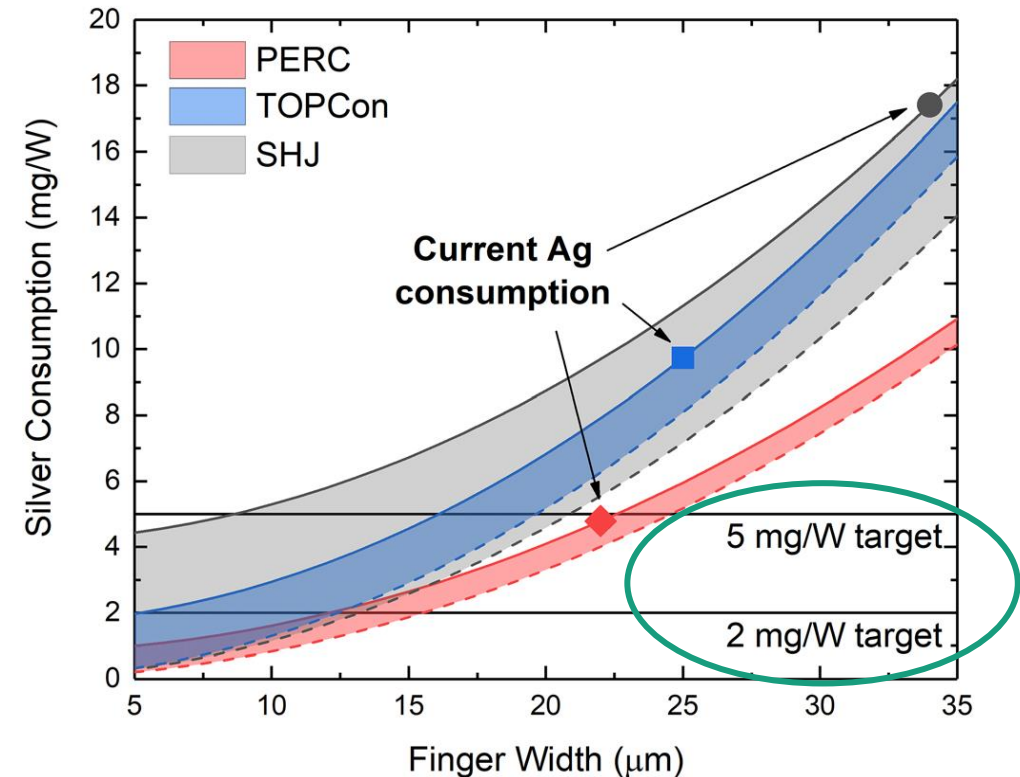
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- Installed capacity 2023: **447 GW_p**¹

Risk and Challenge:

- Rising demand for scarce material (**Ag**, Bi, In...)
- Most critical resource: Silver usage in metallization
- Today: 5 mg/W (PERC) – **17 mg/W (SHJ) Ag** is used⁴
- Sustainable TW production: reducing Ag usage to **5** or even **2 mg/W**⁵⁻⁷

→ **Silver has to be reduced or replaced!**



Calculated silver consumption as a function of printed width of ag fingers in industrial screen-printed PERC, TOPCon and SHJ solar cells. Solid lines show the total silver consumption in the finger, busbar and soldering tab regions, and dash lines show finger silver consumption only⁴

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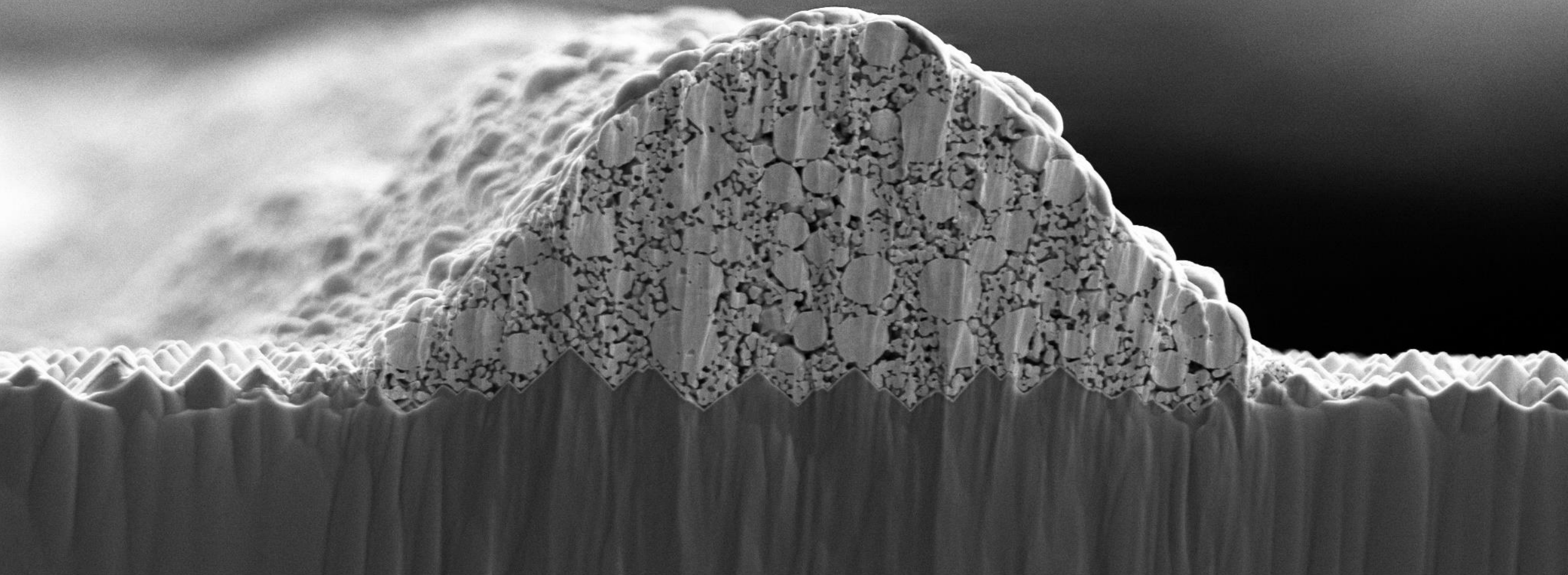
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⁵Verlinden PJ. J Renew Sustain Energy. 2020

⁶Y. Zhang, EES 2021

<https://doi.org/10.1039/D1EE01814K>

⁷Hallam B et al., Prog Photovolt: Res Appl. 2022



10 μm

EHT = 5.00 kV

WD = 5.0 mm

Mag = 3.01 K X

Fraunhofer ISE

Stage at T = 0.0 °

Detector = SE2

Ag and AgCu LT-Paste Screening

Testlayout

Ag $w_N =$
18 μm
21 μm
24 μm
27 μm

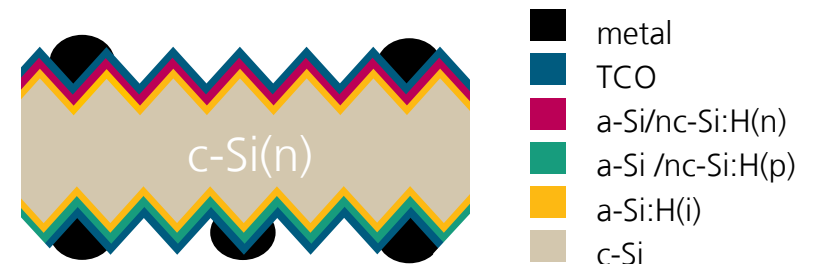
Ag/Cu or Ag $w_N =$
30 μm
35 μm
40 μm
45 μm

Ag and AgCu LT-Paste Screening

- Low temperature pastes (LTP) based on silver (Ag) or silver-coated copper (AgCu) particles

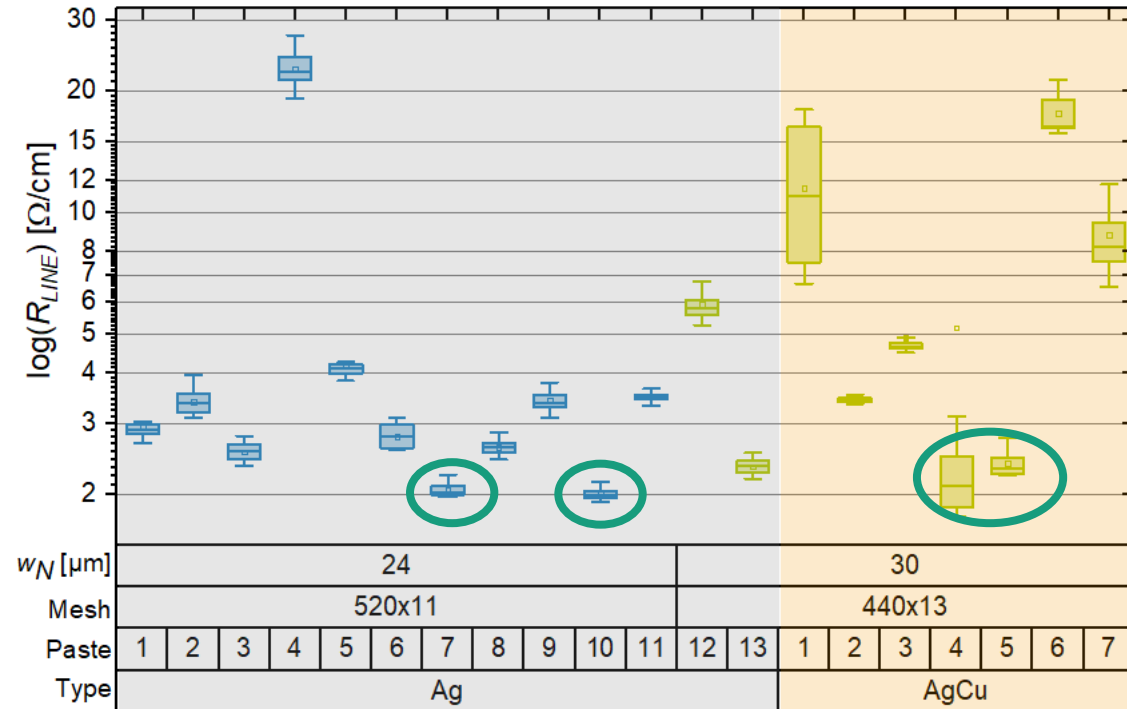
#SHJ precursors	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10		
Preparation	Randomize & Label																					
FS	Finger	Reference FS screen and Ag paste Drying 200°C, 1.5 min																				
	BB	5BB print Drying 200°C, 1.5 min																				
RS	#20 pastes	Ag 01	Ag 02	Ag 03	Ag 04	Ag 05	Ag 06	Ag 07	Ag 08	Ag 09	Ag 10	Ag 11	Ag 12	Ag 13	AgCu 1	AgCu 2	AgCu 3	AgCu 4	AgCu 5	AgCu 6	AgCu 7	
	Finger	520x11 $w_N = 18-27 \mu m$											430x13 $w_N = 30-45 \mu m$									
	BB	Drying 200°C, 1.5 min 5BB print											Curing 220°C, 1.5 min									
Char	5BB R _{LINE}																					
	LEXT: $w_f A_{fr}$ TLM: ρ_c																					

- Balance → laydown M for each paste & screen combination



Ag and AgCu LT-Paste Screening

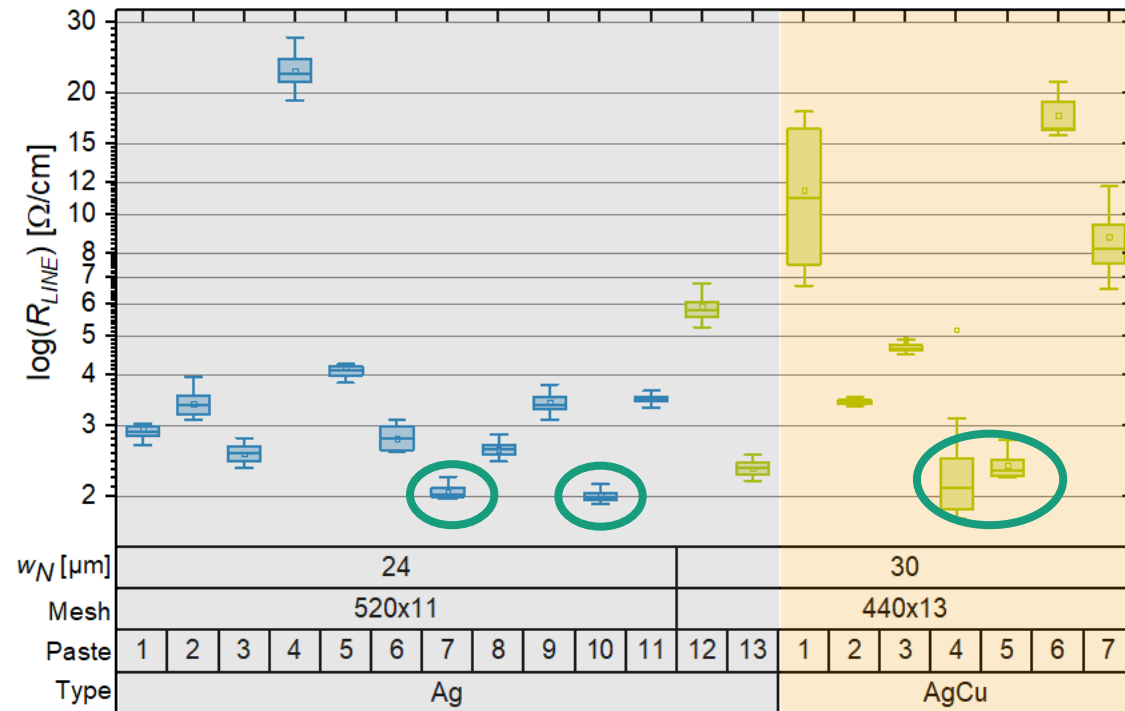
R_{LINE}



- Most Ag pastes: good R_{LINE} for $w_N \geq 21 \mu\text{m}$
- Not all AgCu are compatible with $w_N = 30 \mu\text{m}$
- AgCu4/5 and Ag7/10 $w_N = 24 \mu\text{m}$ at $R_{LINE} \sim 2 \Omega/\text{cm}$

Ag and AgCu LT-Paste Screening

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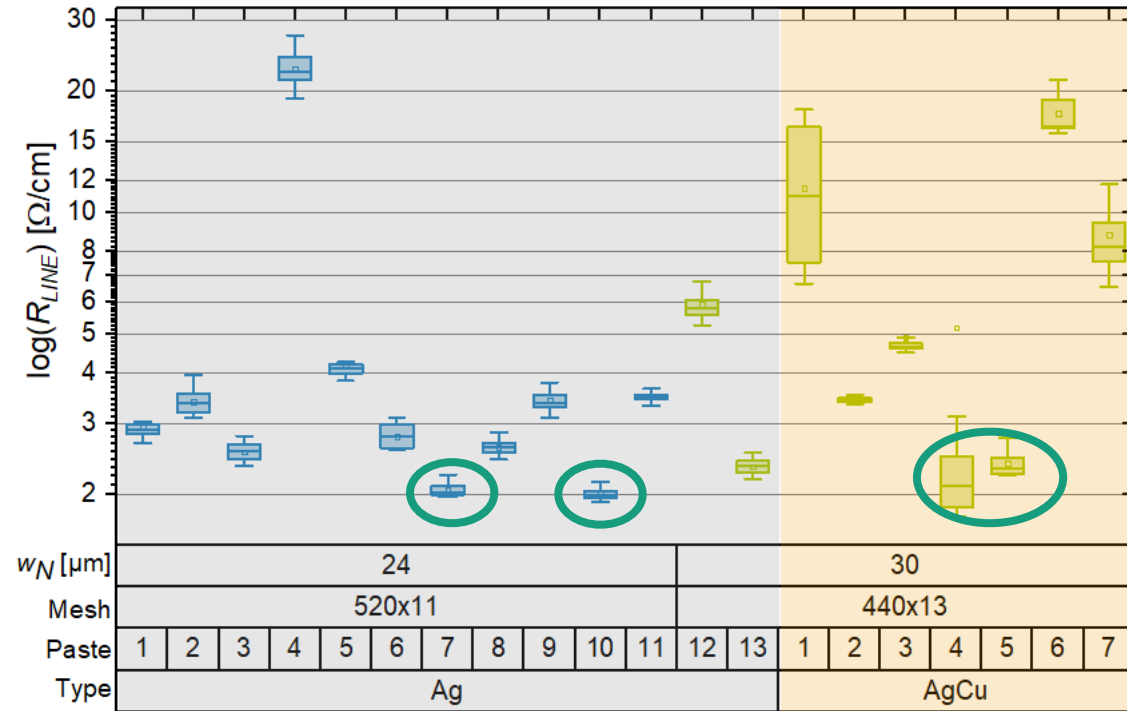
Effective Silver Usage⁸:

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

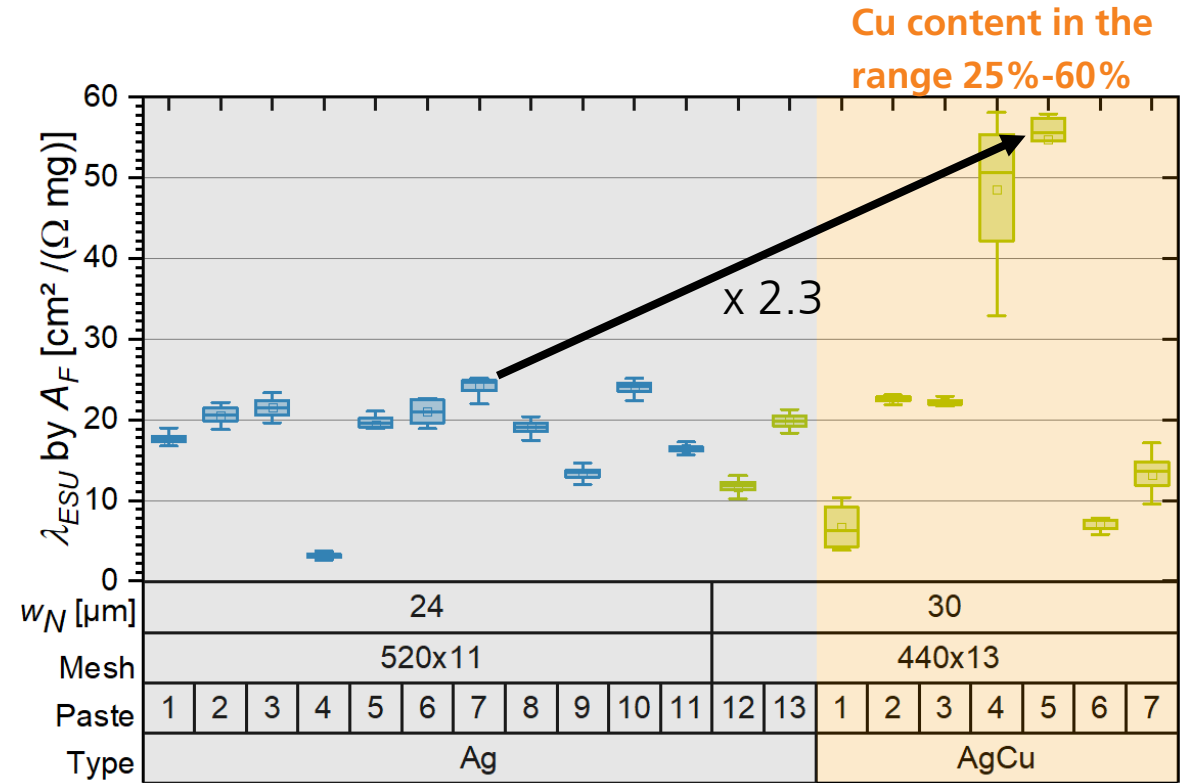
- $m_{Ag,F} / l_f$ is estimated from M scaled with A_F

Ag and AgCu LT-Paste Screening

R_{LINE} and λ_{ESU}



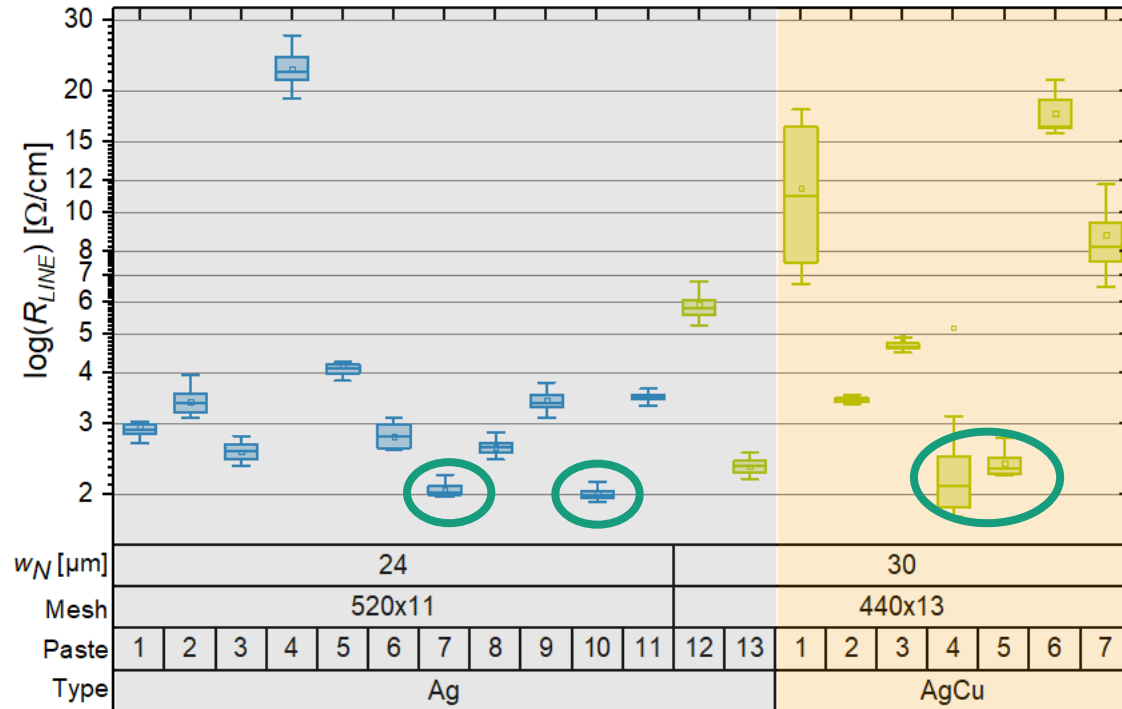
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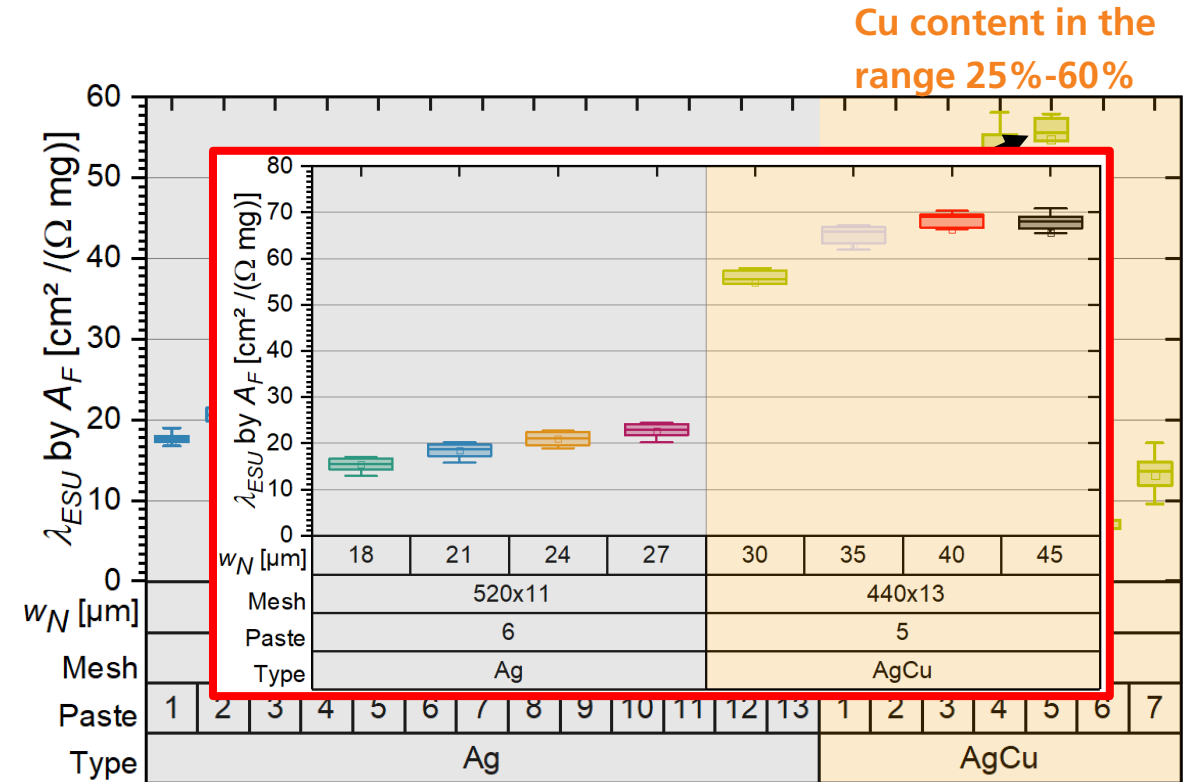
- Effective silver usage λ_{ESU} ⁸ calculated on basis of laydown M and finger cross-section A_F
- AgCu5: Cu \nearrow + R_{LINE} \searrow lead to $\lambda_{ESU} = 56 \text{ cm}^2/(\Omega \text{ mg})$

Ag and AgCu LT-Paste Screening

R_{LINE} and λ_{ESU}



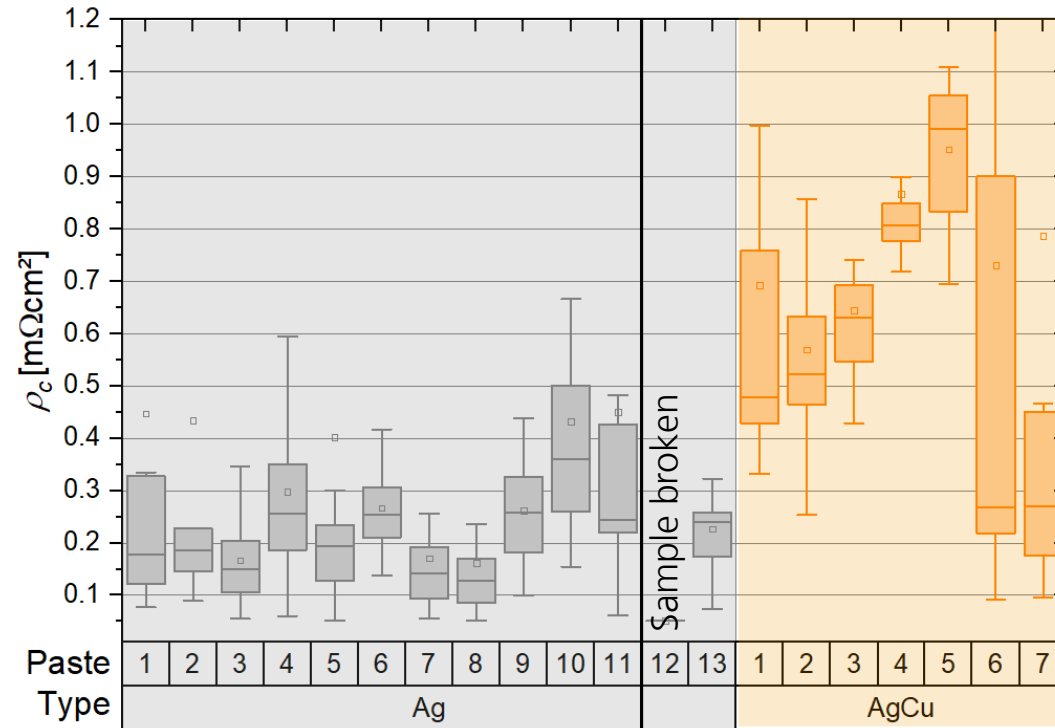
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- Effective silver usage λ_{ESU} calculated on basis of laydown M and finger cross-section A_F
- AgCu5: Cu \nearrow + $R_{LINE} \searrow$ lead to $\lambda_{ESU} = 56 \text{ cm}^2/(\Omega \text{ mg})$
- Wider $w_N \rightarrow$ improved λ_{ESU} , more uniform fingers

Ag and AgCu LT-Paste Screening

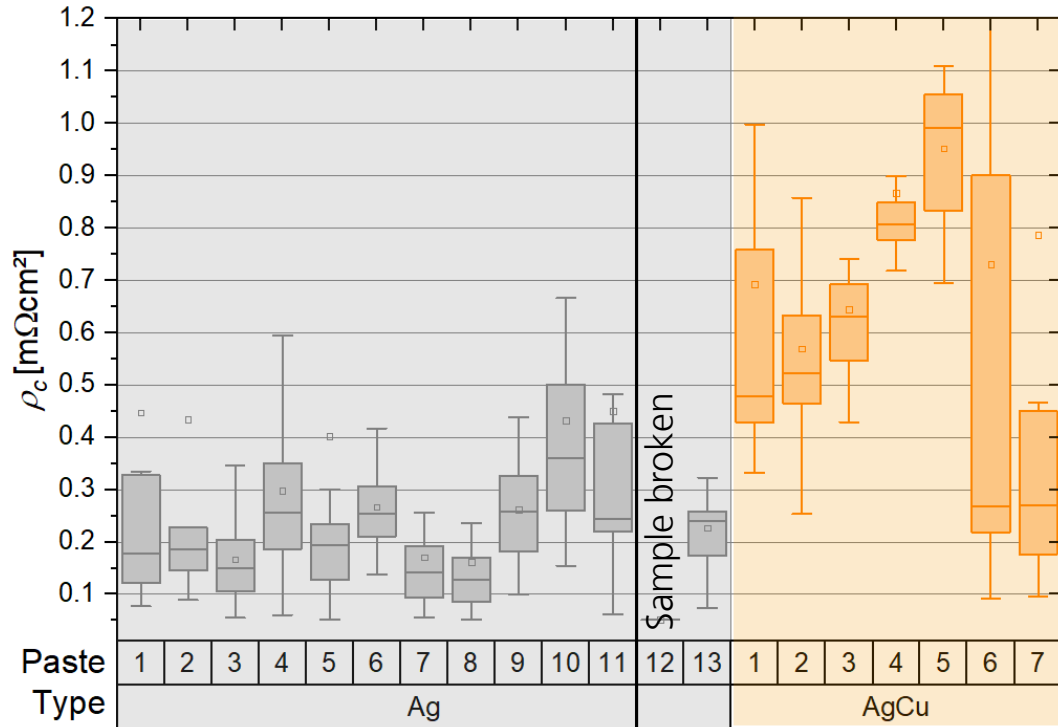
ρ_c



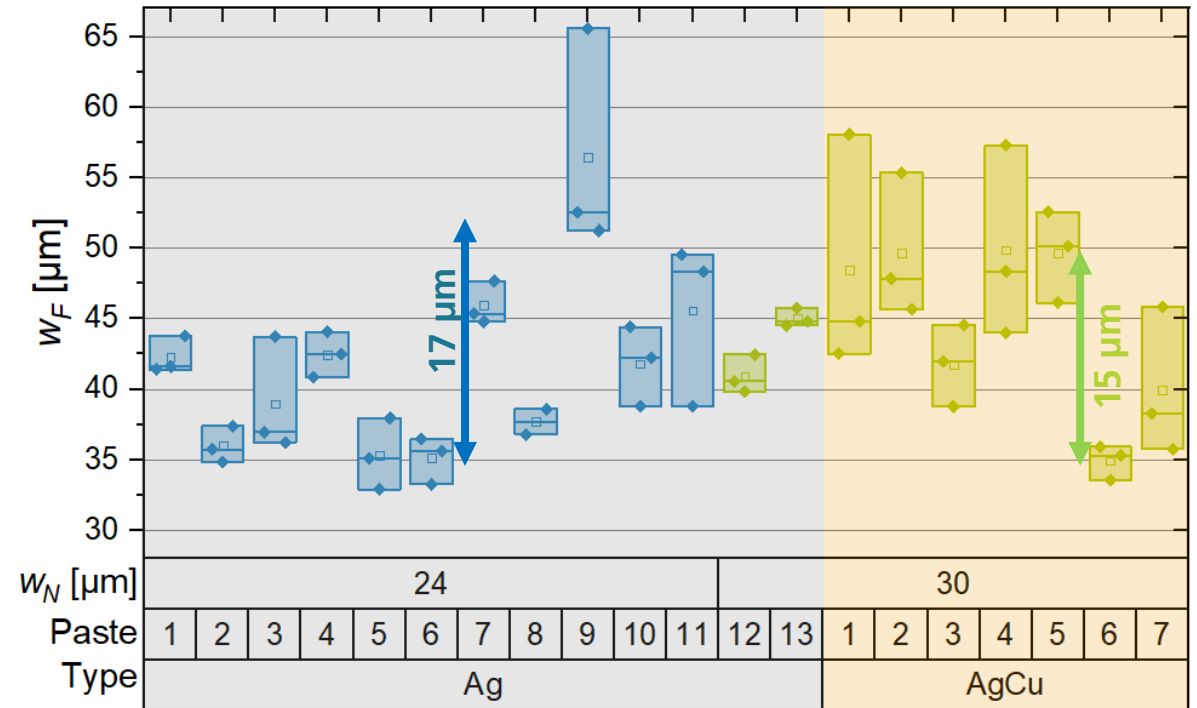
- Ag pastes achieve extremely low $\rho_c < 0.5 \text{ m}\Omega\text{cm}^2$
- AgCu paste low but higher $\rho_c < 1.0 \text{ m}\Omega\text{cm}^2$
 AgCu4/5 with $\rho_c \nearrow$, $R_{\text{LINE}} \searrow$, due to particle size?

Ag and AgCu LT-Paste Screening

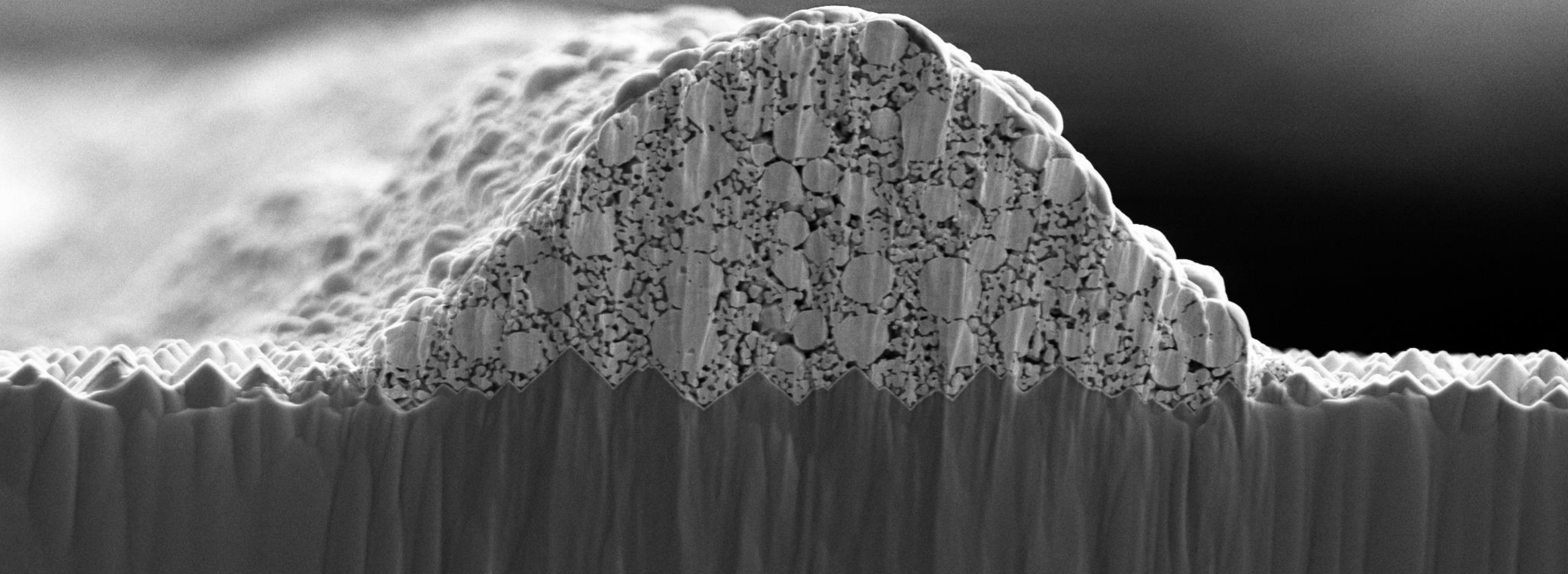
ρ_c and w_F



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- AgCu4/5 with $\rho_c \nearrow$, $R_{\text{LINE}} \searrow$, due to particle size?



- Pastes vary substantially in printed w_F for constant w_N
- Best w_F for Ag (24 μm) and AgCu (30 μm) similar



10 μm

EHT = 5.00 kV

WD = 5.0 mm

Mag = 3.01 K X

Fraunhofer ISE

Stage at T = 0.0 °

Detector = SE2

Bifacial GridMaster Simulation

GridMaster¹⁰ simulation

- M10 SHJ precursor data is held constant ($\eta = 25.5\%$ w/o metallization related losses)
- Base: grid finger data from paste screening
- Per data set: pitch $p_{F,FS}$ and $p_{F,RS}$ variation
- Simulation of Cell IV with 20 contacts (pitch 9.1 mm)
- Irradiation: FS 1.0 sun, RS 0.1 sun
- Ag consumption per finger is estimated scaling the laydown M for each w_N by A_F taking the Ag content into account
- Simple cost model for paste price and comparison to a reference cell

→ η , Ag consumption and costs

→ η - and cost- optimum

Reference⁴:

specific $m_{Ag} \sim 15.5$ mg/W

Assumed:

$\eta = 24.5\%$

Ag paste: 92% Ag content

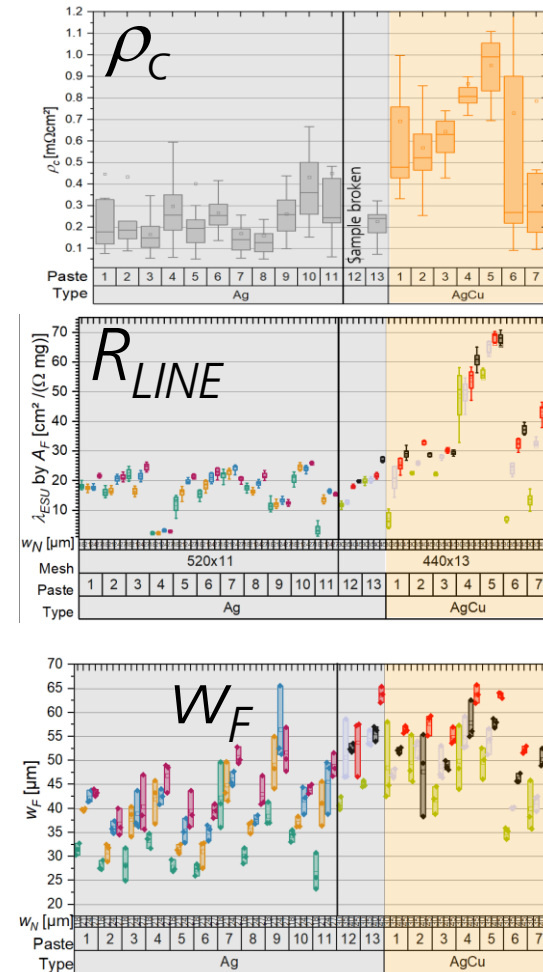
Simple cost model based on data in AgCu⁹:

Ag: 1000 €/kg

AgCu: 200 €/kg

Paste production: +30%

Cell value: 0.10 ct€/Wp



Bifacial GridMaster Simulation

Efficiency versus cost optimization

GridMaster¹⁰ simulation - Results

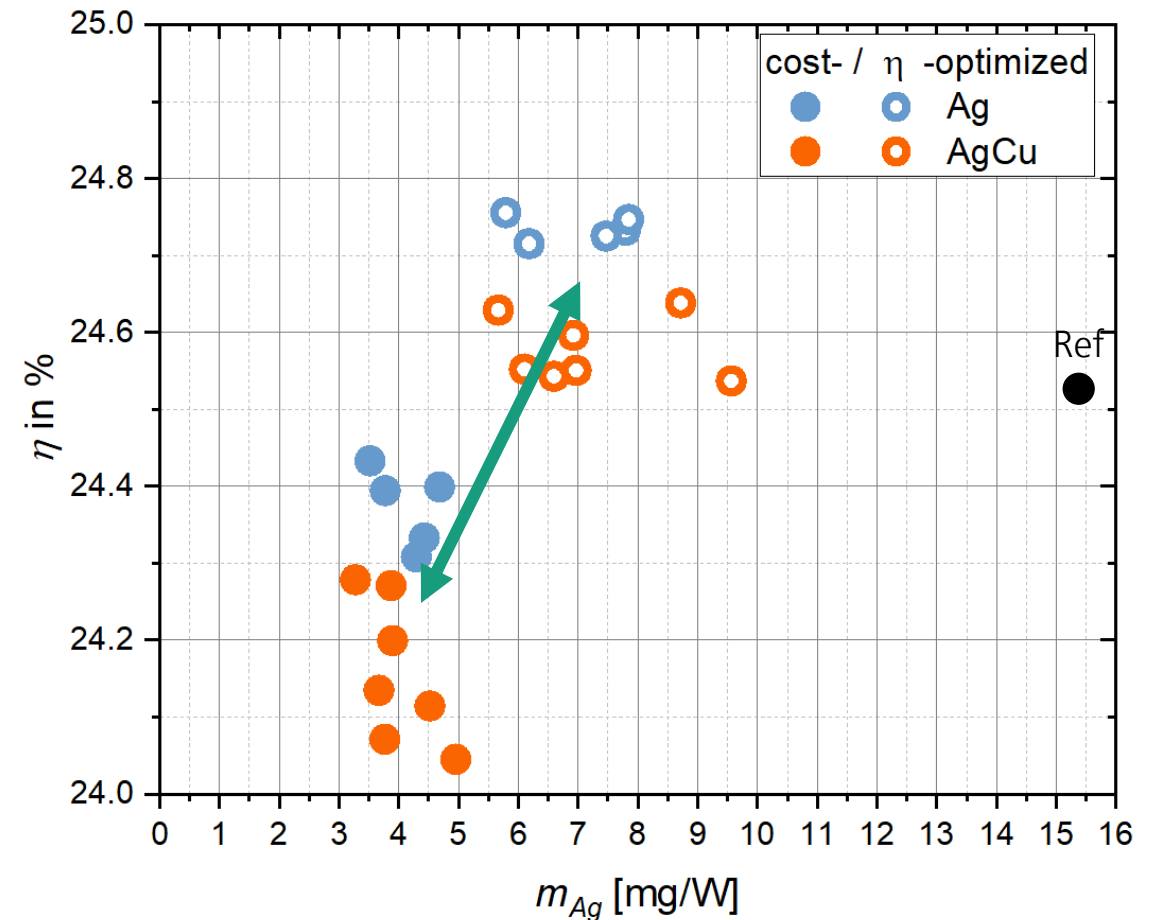
Gap between η - versus cost-optimization

- η : +0.4%_{abs} ↗
- m_{Ag} : +3 mg/W ↗

Gap increases if

- Ag price ↗
- Value of Cell €/Wp ↘

→ Chance for **low Ag or Ag-free technologies** to step in



Ag and AgCu LTP on SHJ Cells



Ag and AgCu LTP Applied on SHJ Solar Cells

Variations paste combinations FS / RS

Ag / Ag



Ag / AgCu



AgCu / AgCu



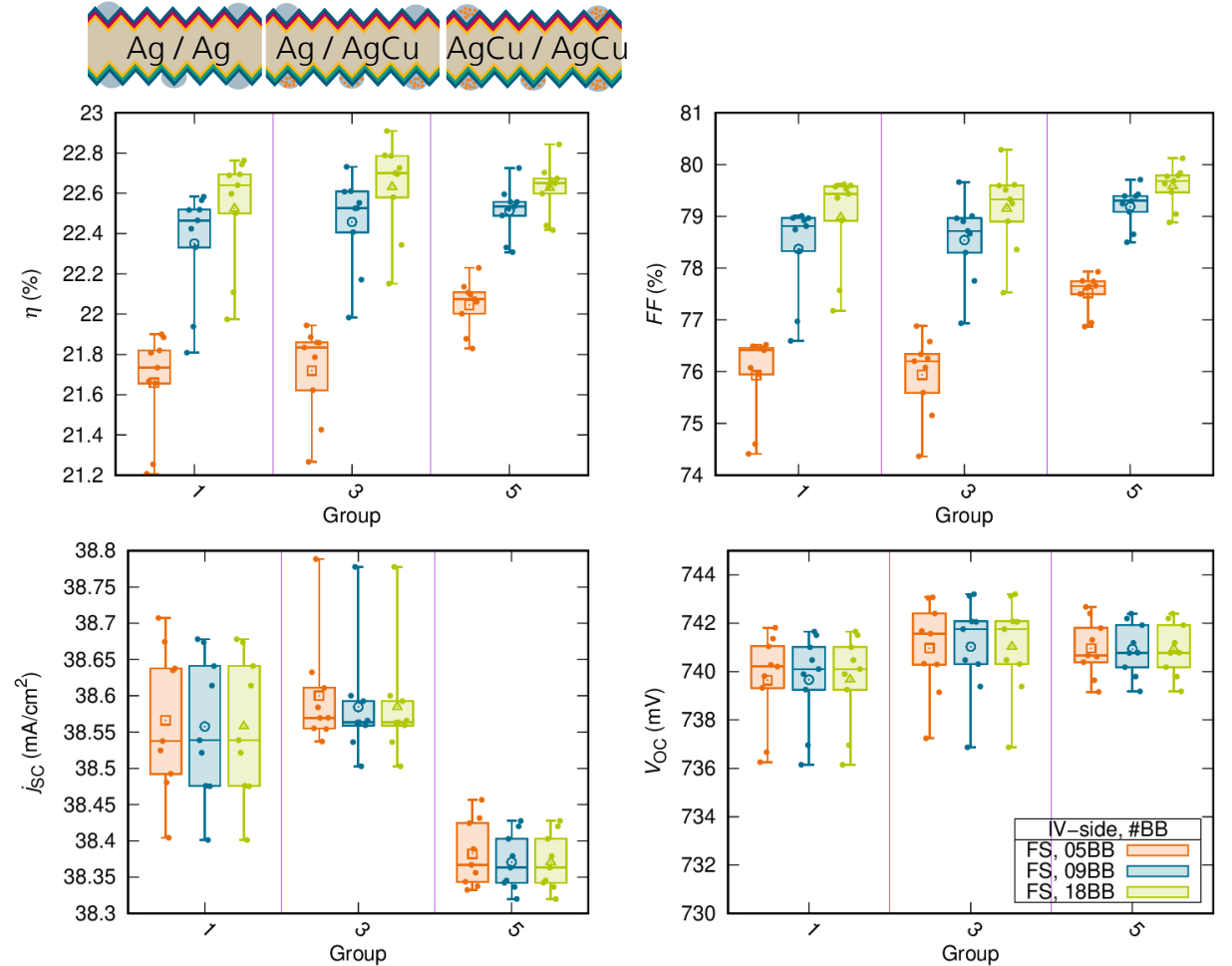
- 0BB FS screen: 80F $w_N = 25\mu\text{m}$ 430x13x0
- 12BB RS screen: 162F $w_N = 25\mu\text{m}$ 430x13x0

Ag and AgCu LTP Applied on SHJ Solar Cells

IV data

Variations paste combinations FS / RS

- Ag / Ag
- Ag / AgCu
- AgCu / AgCu
- **0BB FS screen:** 80F $w_N = 25\mu\text{m}$ 430x13x0
- **12BB RS screen:** 162F $w_N = 25\mu\text{m}$ 430x13x0
- **IV data**
 - **5BB** and **9BB** measurement
 - **9BB** → **18BB** correction¹¹ based on $R_{LINE,5BB}$

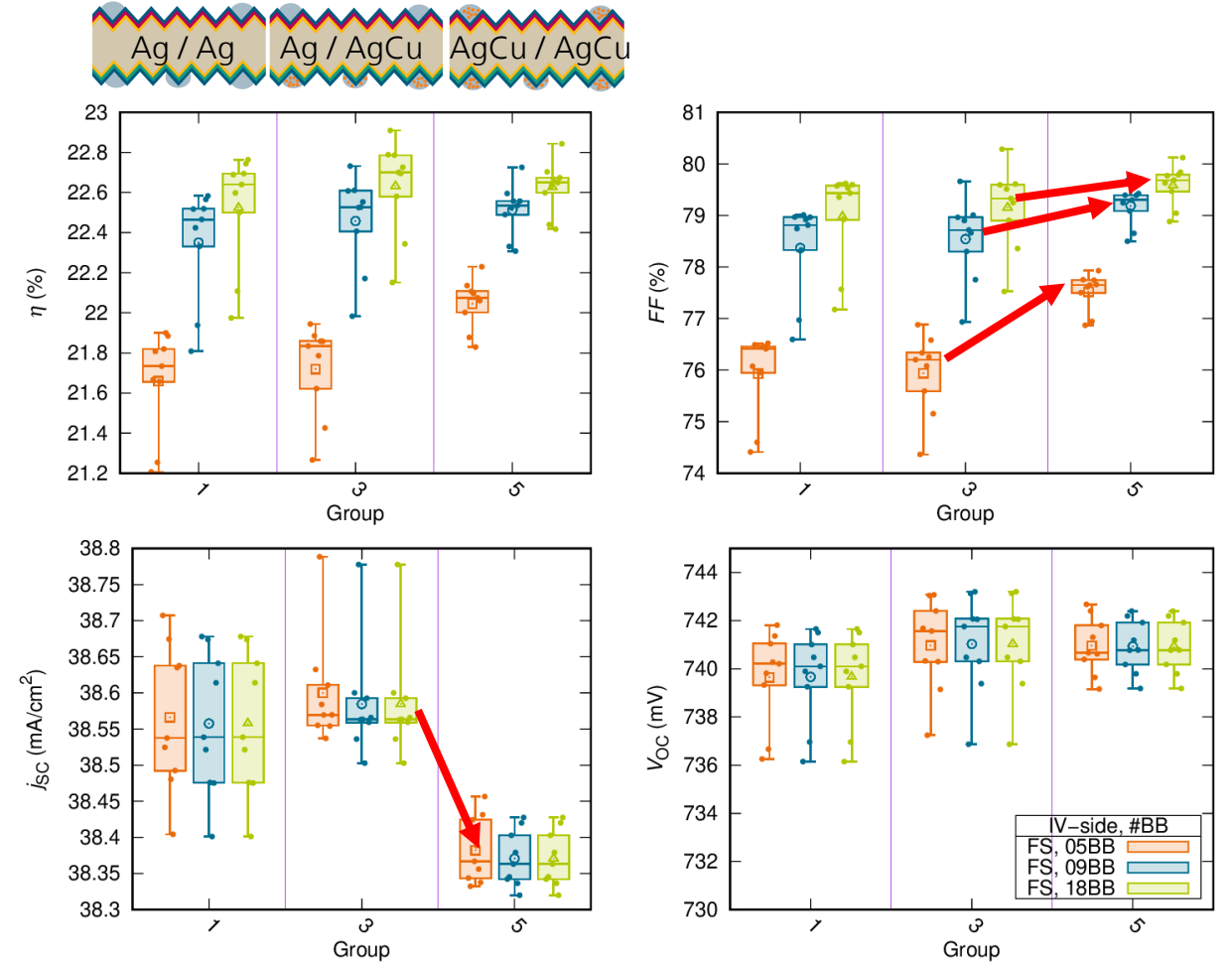


Ag and AgCu LTP Applied on SHJ Solar Cells

IV data

Results AgCu compared to Ag

- AgCu paste compatible with $w_N = 25\mu\text{m}$
- Shading ↗: $J_{SC} -0.2 \text{ mA/cm}^2$
- FF ↗ due to R_{LINE} ↘
 - #wires ↗ effect of R_{LINE} on FF ↘



Ag and AgCu LTP Applied on SHJ Solar Cells

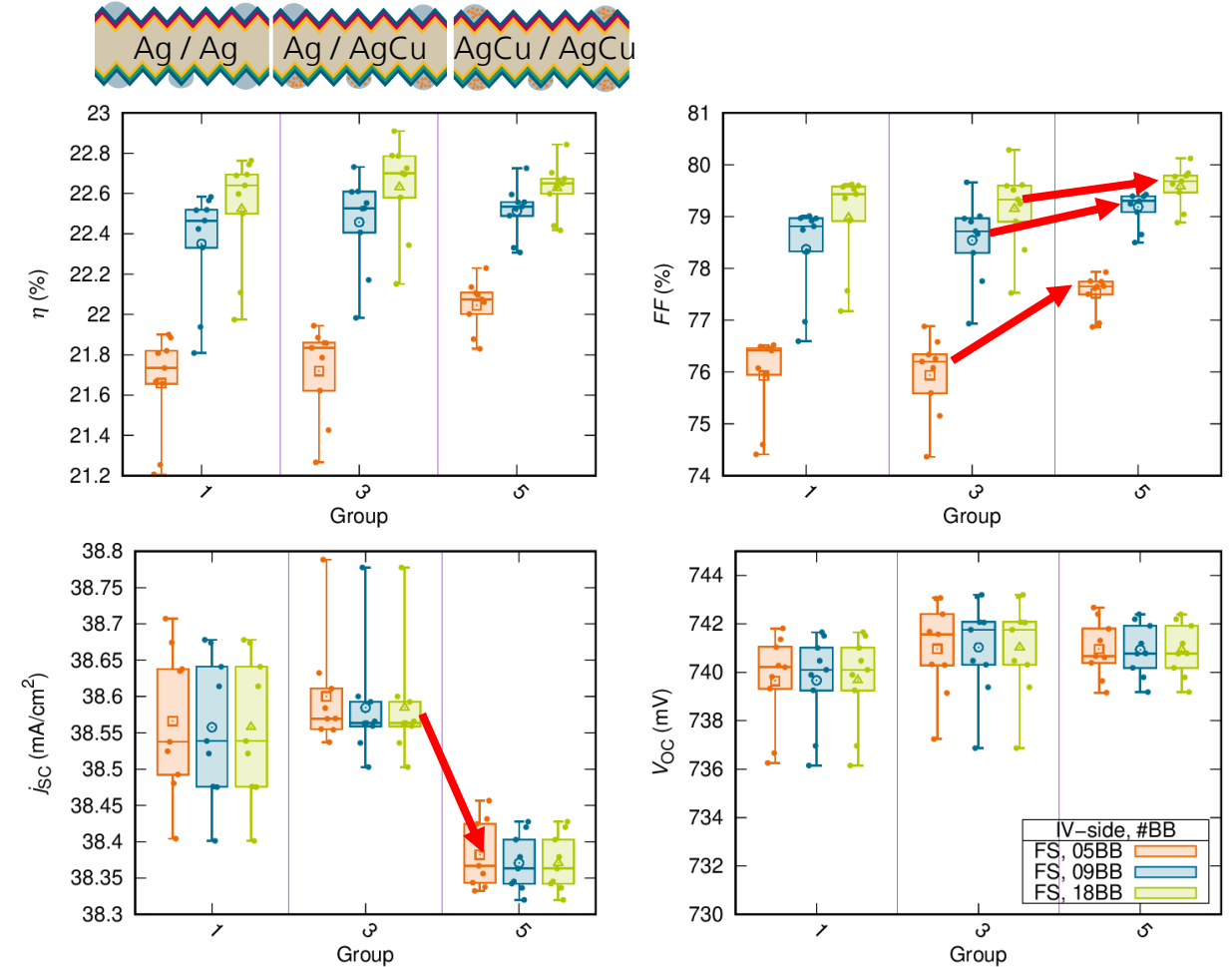
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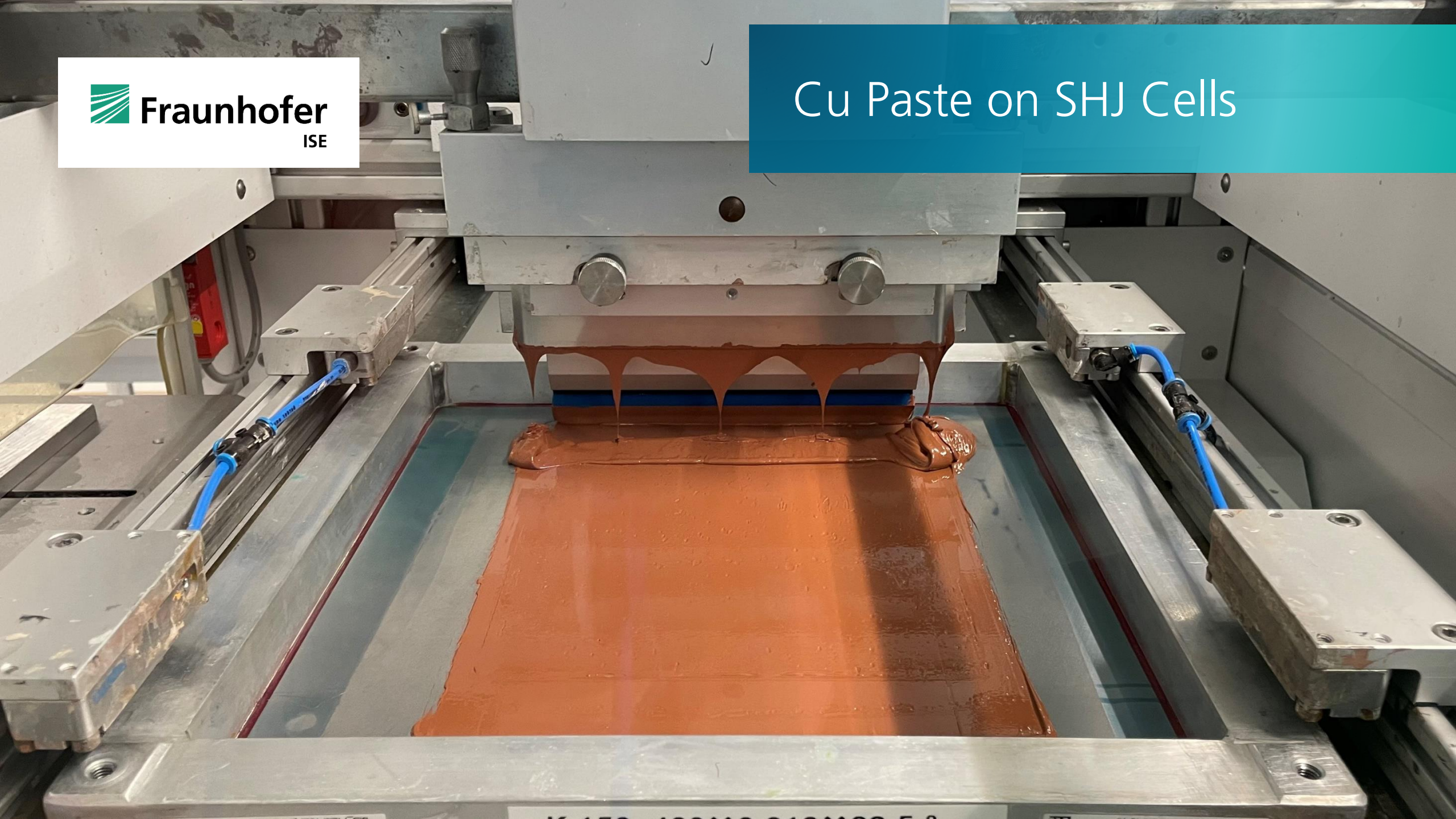
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- **FF** \nearrow due to $R_{LINE} \searrow$
 - #wires \nearrow effect of R_{LINE} on $FF \searrow$
- Specific m_{Ag} FS 0BB RS 12BB:
 - Ag / Ag $< 10 \text{ mg/W}^*$
 - Ag / AgCu $< 10 \text{ mg/W}^*$
 - **AgCu / AgCu: 7.5 mg/W**

Ag/Cu: big step towards $< 5 \text{ mg}_{Ag}/\text{W}$

Further reduction with finer lines and no BB




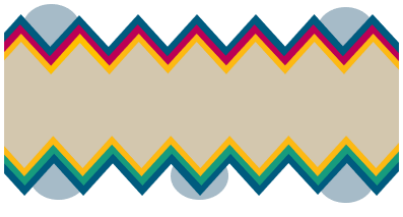




Cu Pastes Applied on SHJ Solar Cells

Paste selection:

- Ag and Cu LTP on SHJ M6 precursors

Variations on RS:

Paste / screen	162F/80 μ m	162F/25 μ m
Ag / Ag		
Ag / Cu		

Cu Pastes Applied on SHJ Solar Cells

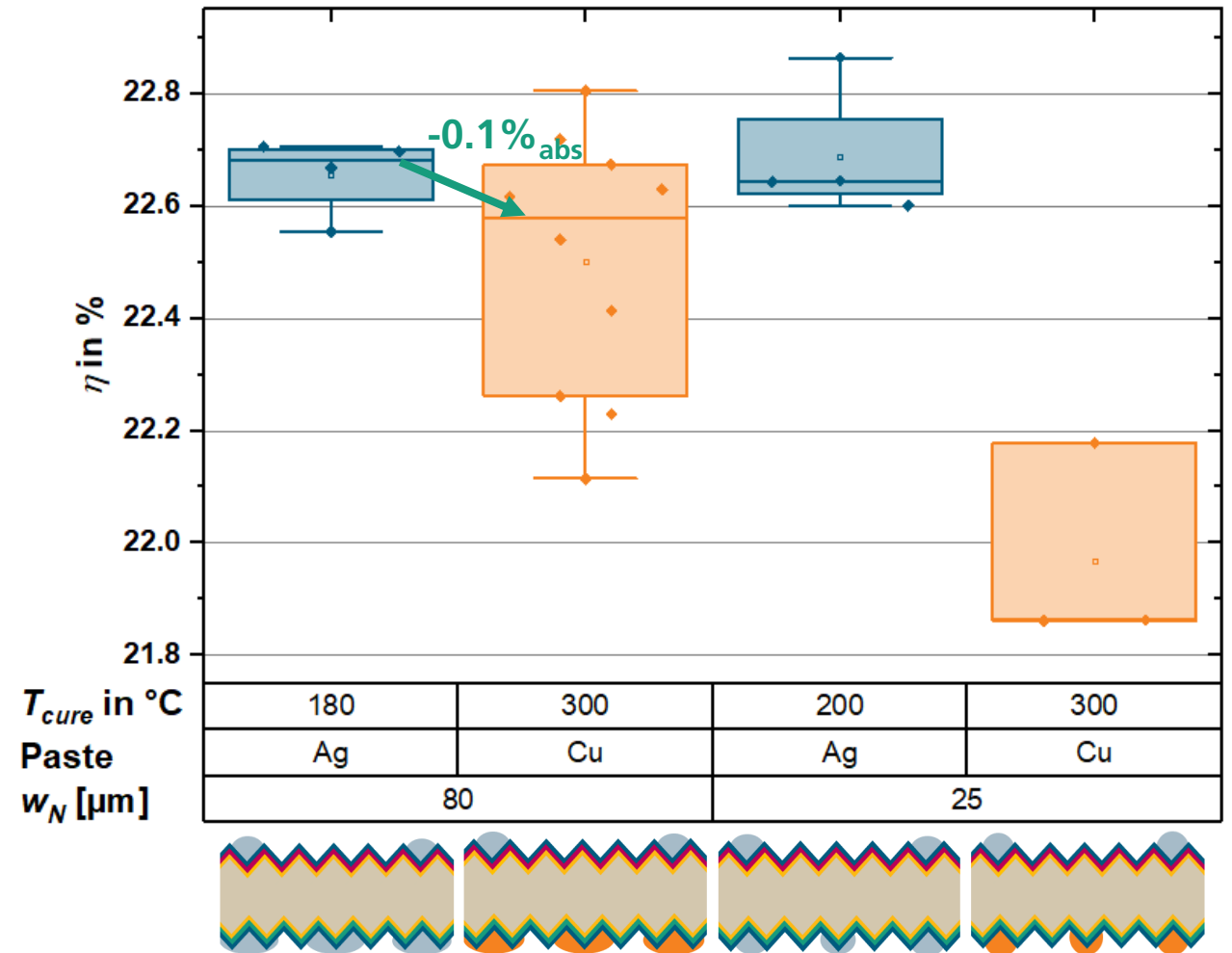
FS constant with Ag 126F / 22 μ m (30 mg LTP Ag)

Variations:

- **RS** with 162 fingers varied:
 - Ag or Cu LTP
 - $w_N = 80 \mu\text{m}$ or $25 \mu\text{m}$

Results:

- Cu with $w_N = 80 \mu\text{m}$ η -0.1%_{abs} vs Ag



9BB IV on conductive chuck, BC calibration

Cu Pastes Applied on SHJ Solar Cells

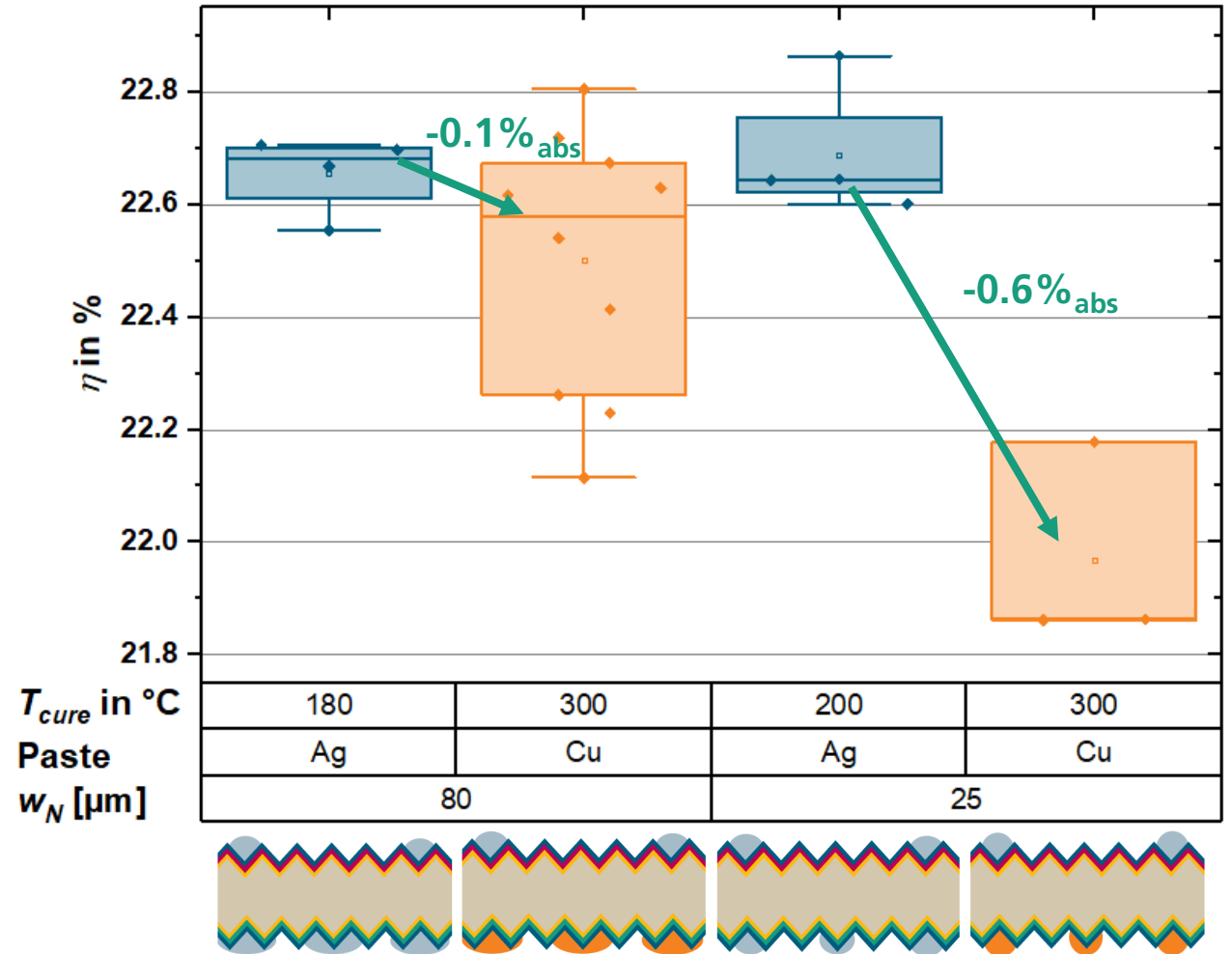
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- Cu with $w_N = 80 \mu\text{m}$ η $-0.1\%_{\text{abs}}$ vs Ag
- Cu with $w_N = 25 \mu\text{m}$ η $-0.6\%_{\text{abs}}$ vs Ag
indicate a high ρ_c ($4.9 \text{ m}\Omega\text{cm}^2$ for $w_N = 80 \mu\text{m}$)



9BB IV on conductive chuck, BC calibration

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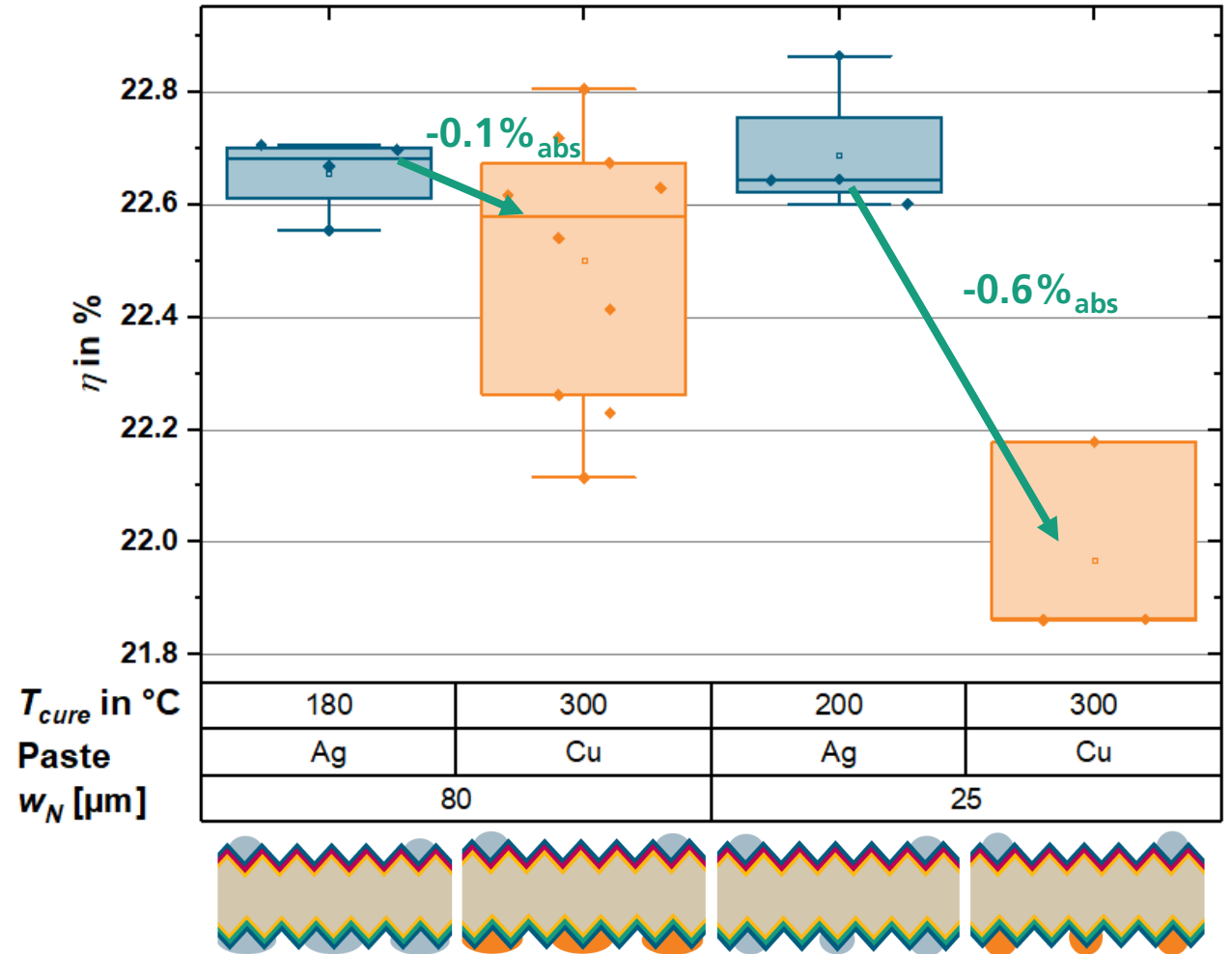
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Results:

- Cu with $w_N = 80 \mu\text{m}$ η -0.1%_{abs} vs Ag
 $m_{\text{Ag}} \sim 4.4 \text{ mg}_{\text{Ag}}/\text{W}$
- Cu with $w_N = 25 \mu\text{m}$ η -0.6%_{abs} vs Ag
 indicate a high ρ_c (4.9 m Ω cm² for $w_N = 80 \mu\text{m}$)
 $m_{\text{Ag}} \sim 4.6 \text{ mg}_{\text{Ag}}/\text{W}$
Cu paste on the RS enables $< 5 \text{ mg}_{\text{Ag}}/\text{W}$



Cu Pastes Applied on SHJ Solar Cells

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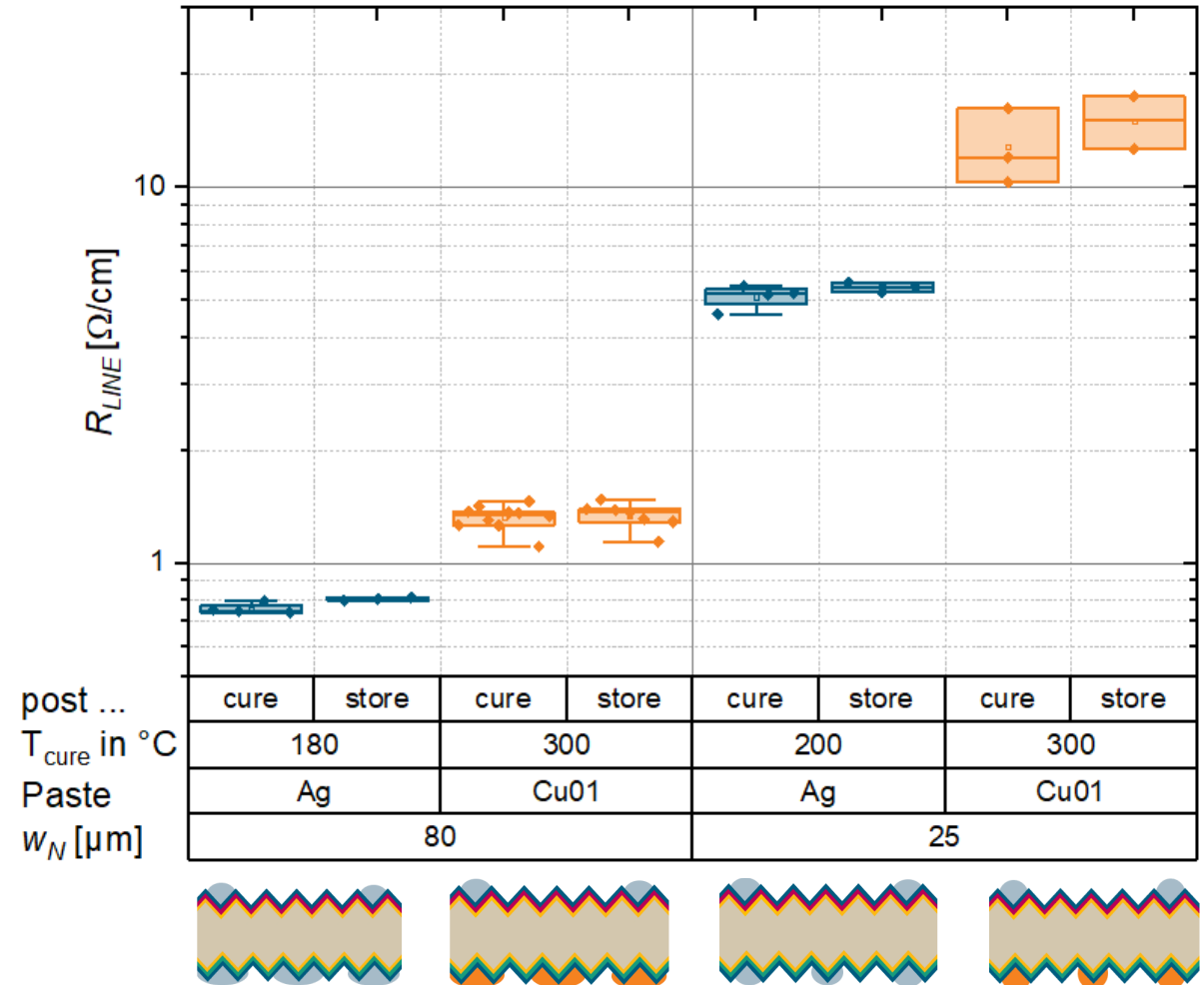
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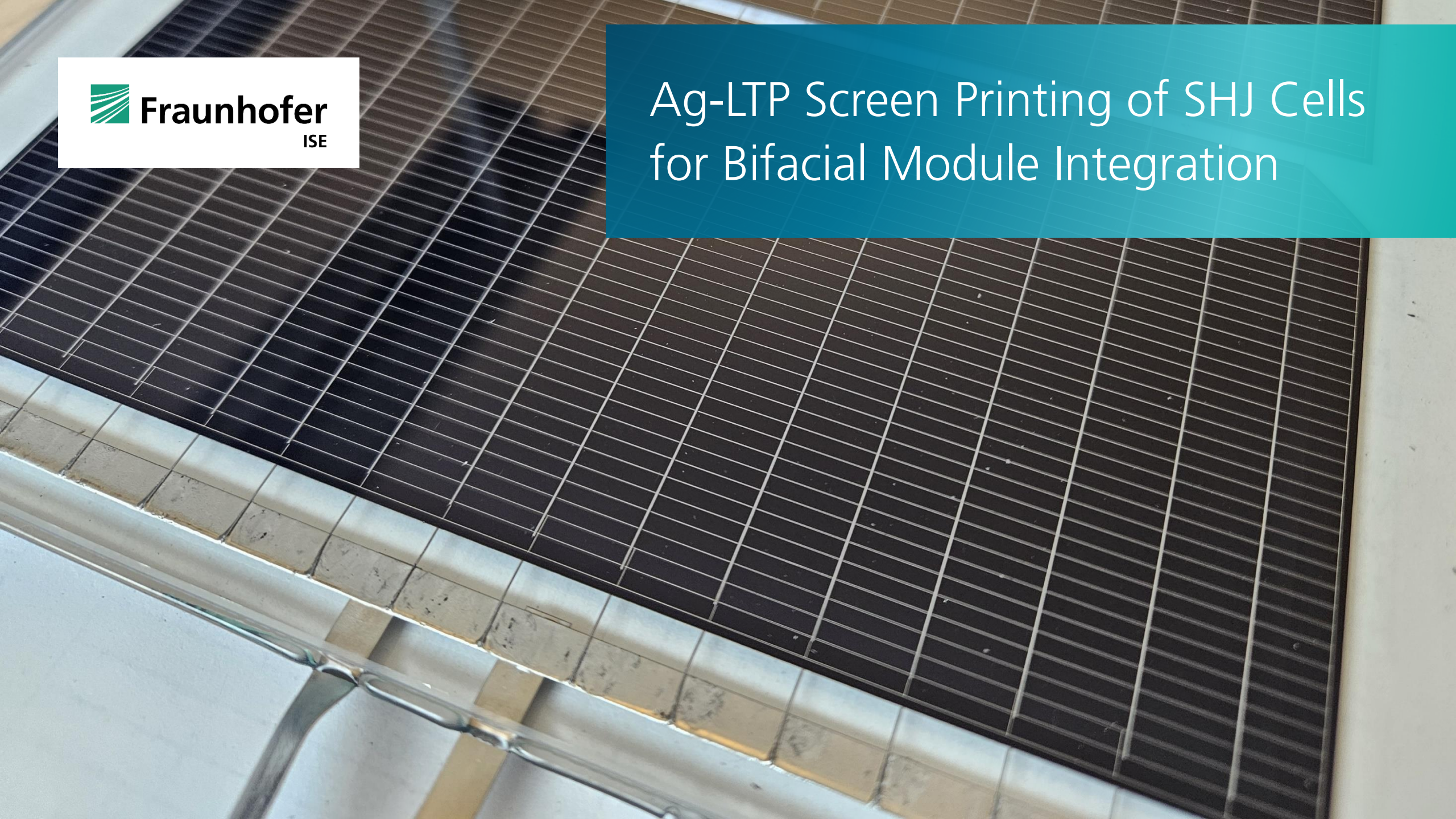
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Cu paste on the RS enables < 5 mg_{Ag}/W
 R_{LINE} stable after 24 days storage in air

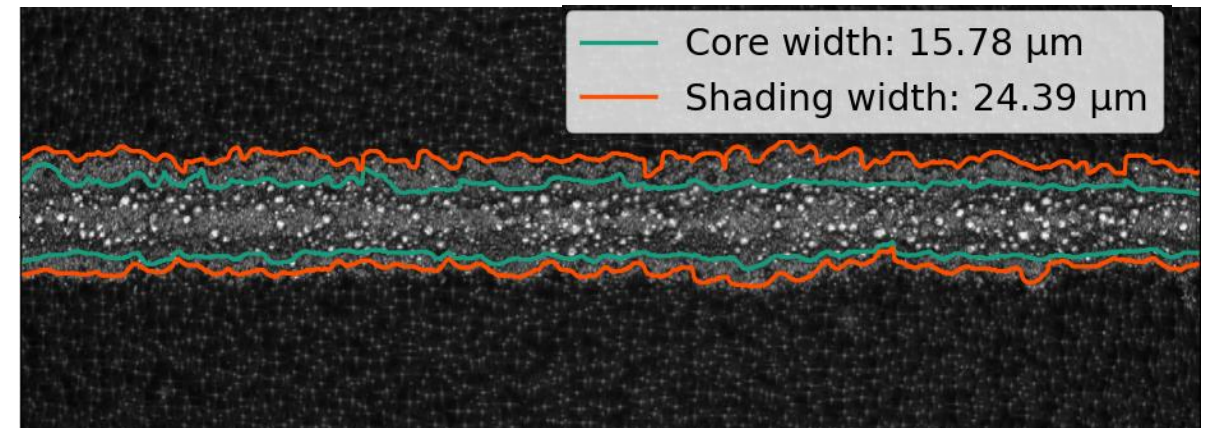


Ag-LTP Screen Printing of SHJ Cells for Bifacial Module Integration



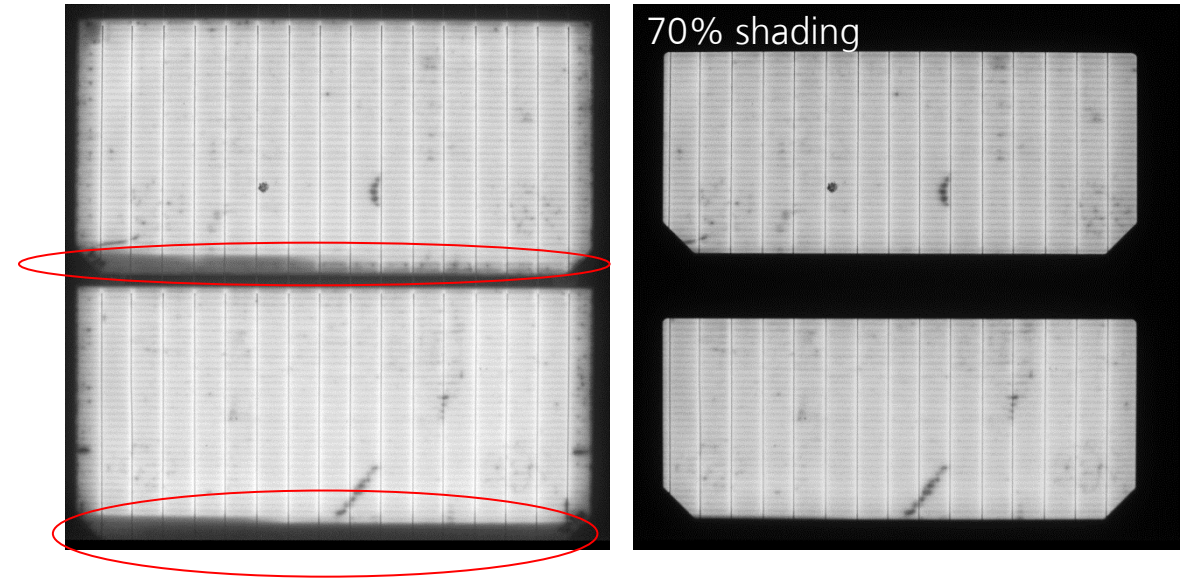
Ag-LTP Screen Printing of SHJ Cells for Bifacial Module Integration

- Cell production based on industrial M6 SHJ precursors
- LTP Ag paste, metallization varied
 - $p_F = 0.6$ to 2 mm
 - $w_N = 14$ to 30 μm
 - Mesh type: 380x14x22.5 and 520x11x0
- Achieved: LTP finger $w_C = 16\text{-}17 \mu\text{m}$



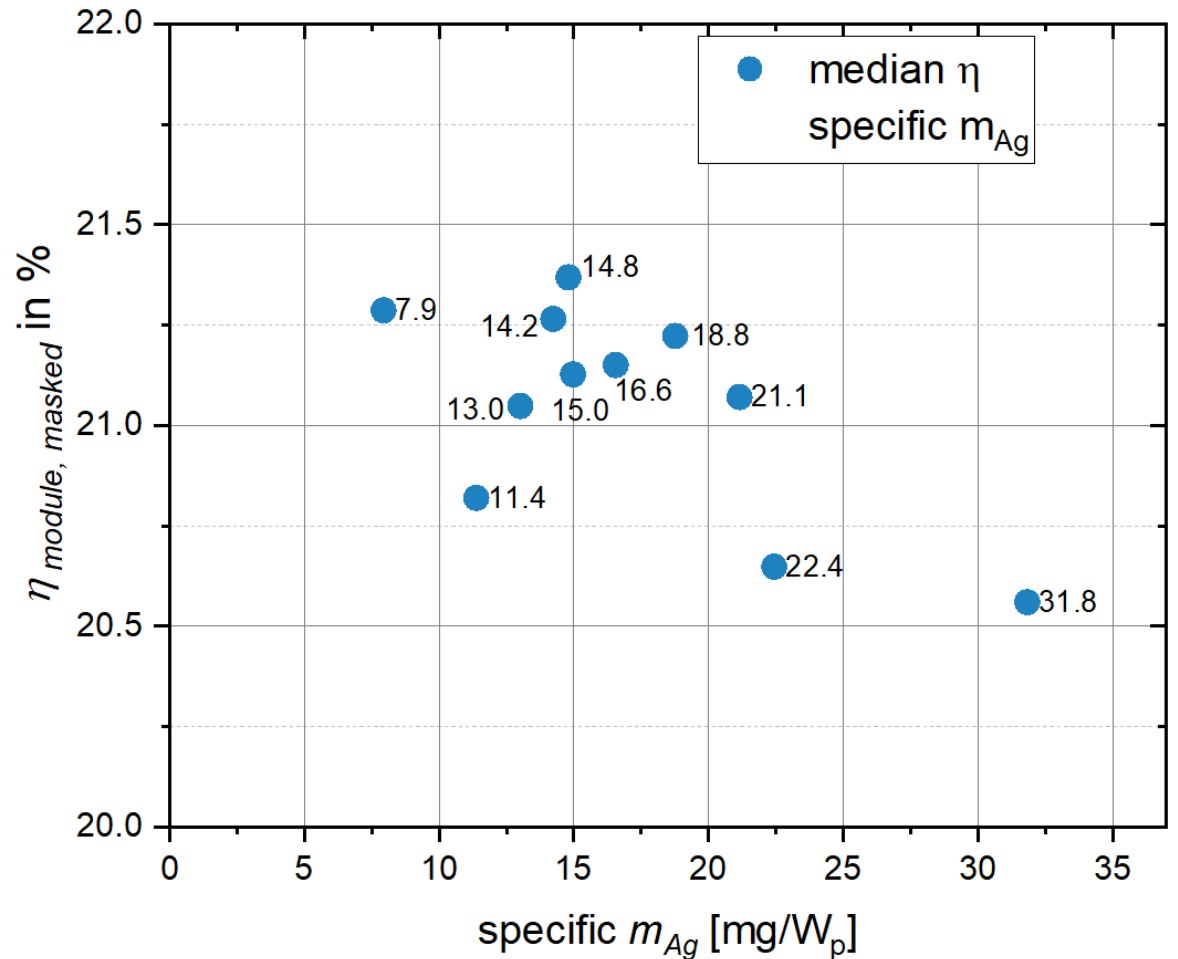
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- Cell separation by LSMC
- Bifacial (non-AR) glass-glass modules with 16 wires
- Module wire / grid finger contact issue in cell perimeter area \rightarrow masked IV ($\eta +0.2\%$ to 1.3%)



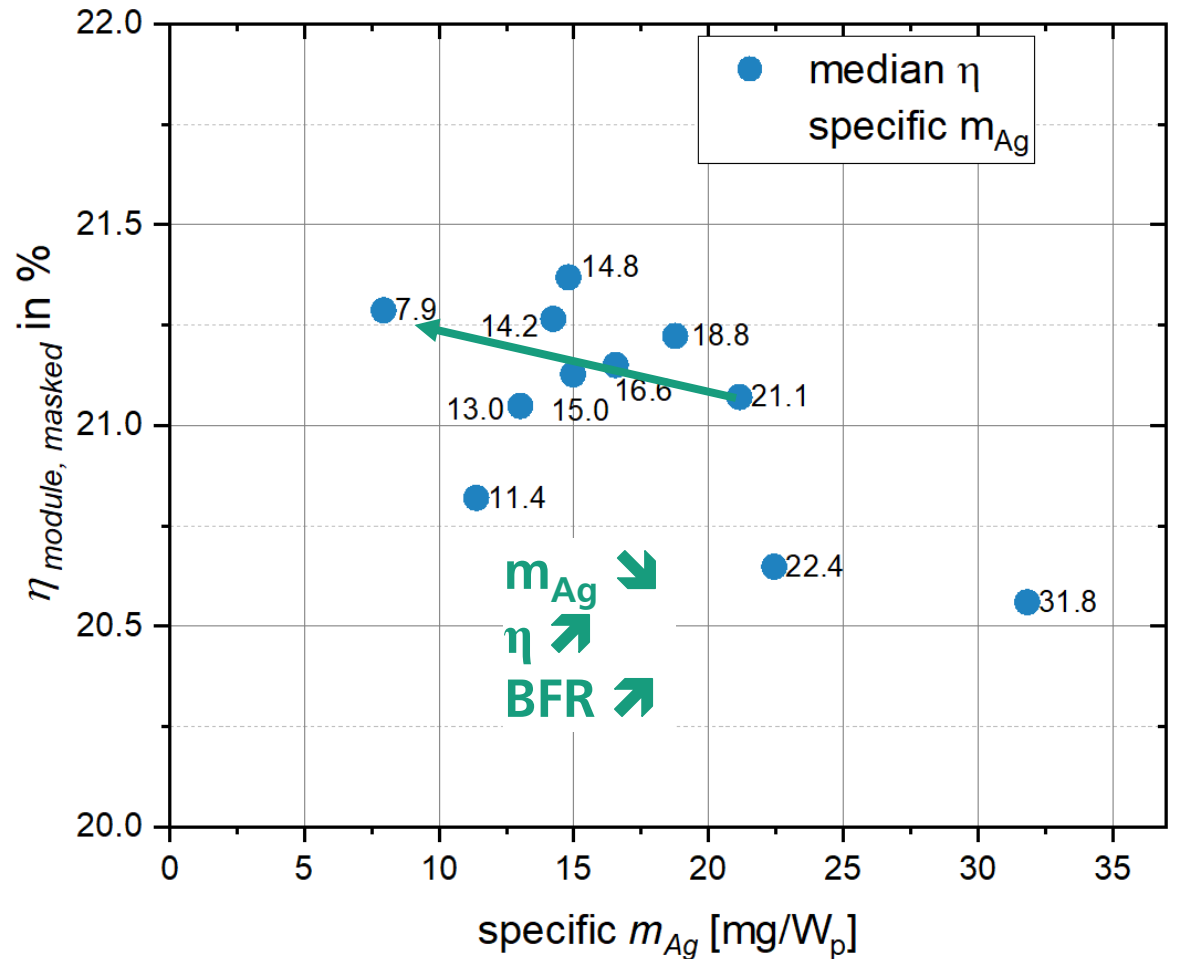
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- Bifacial (non-AR) glass-glass modules with 16 wires
- Module wire / grid finger contact issue in cell perimeter area \rightarrow masked IV ($\eta +0.2\%$ to 1.3%)
- Fineline result: $< 10 \text{ mg}_{\text{Ag, cell}}/\text{W}$**
Module integrations adds $< 1 \text{ mg}/\text{W}^*$



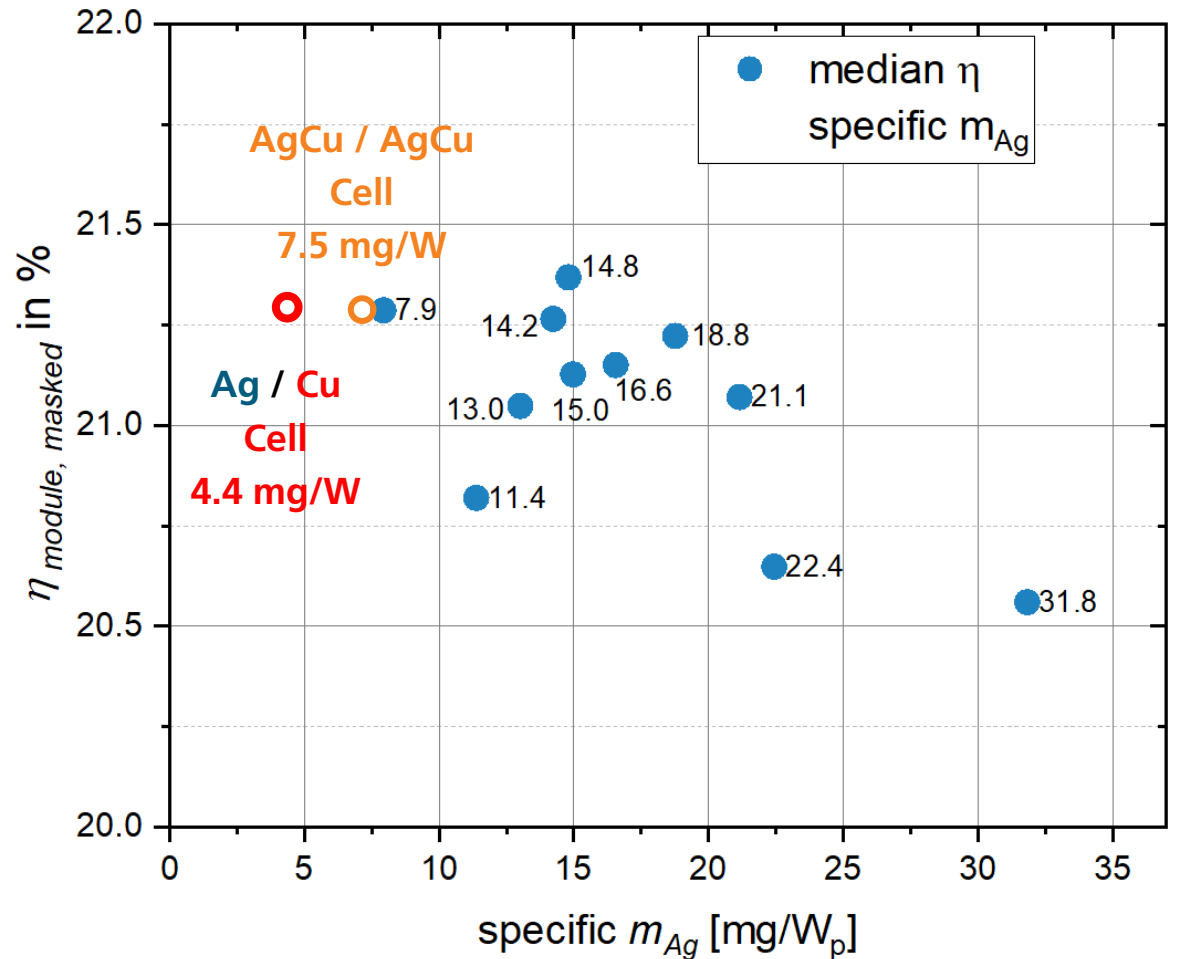
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- Cell production based on industrial M6 SHJ precursors
- LTP Ag paste, metallization varied
 - $p_F = 0.6$ to 2 mm
 - $w_N = 14$ to 30 μm
 - Mesh type: 380x14x22.5 and 520x11x0
- Achieved: LTP finger $w_C = 16\text{-}17 \mu\text{m}$
- Cell separation by LSMC
- Bifacial (non-AR) glass-glass modules with 16 wires
- Module wire / grid finger contact issue in cell perimeter area \rightarrow masked IV ($\eta +0.2\%$ to 1.3%)
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Module integrations adds $< 1 \text{ mg}/\text{W}^*$



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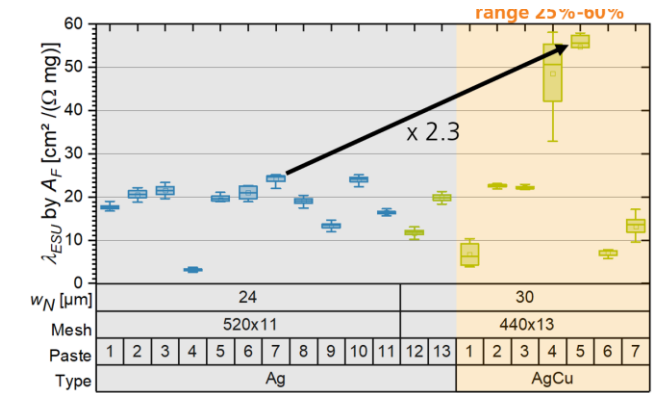
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Summary

Paste Screening Ag & AgCu:

- AgCu: Ag reduction by 25-60%_{weight} → improved Ag utilization: **high $\lambda_{ESU,Ag}$**
- Best **Ag and AgCu paste** are (or need to be) **fine-line compatible**
- Challenge AgCu: small A_F with low R_{LINE} and ρ_C



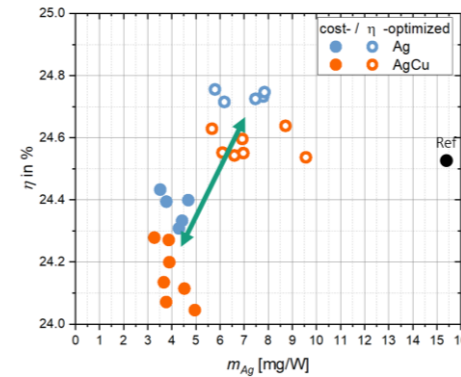
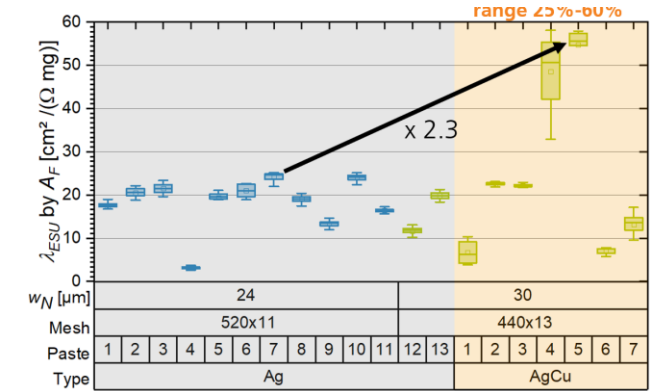
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- Specific m_{Ag} in mg/W: Best Ag and AgCu pastes are equivalent
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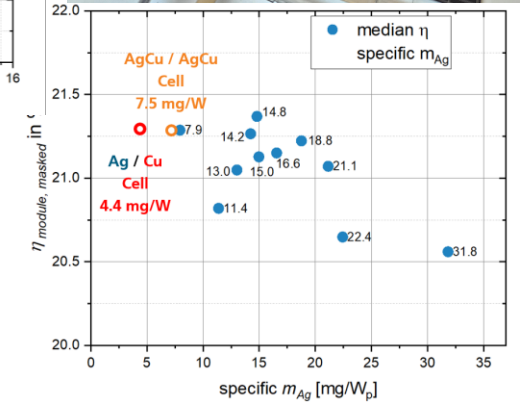
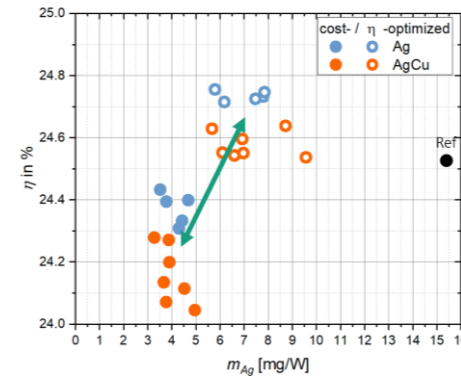
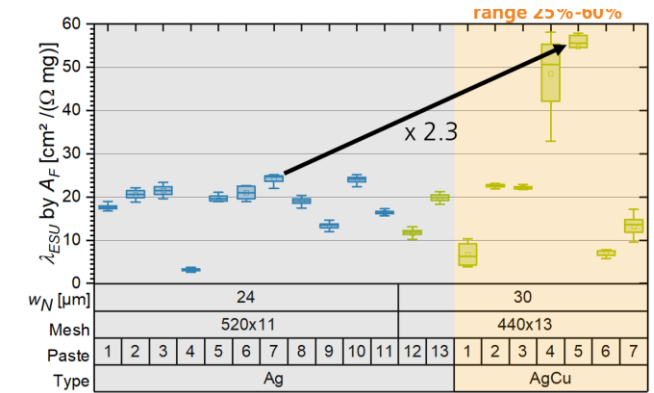
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Cell and Module results:

- AgCu / AgCu** cells: **~ 7.5 mg/W**, Ag on the FS competitive
- Ag / Cu** cells achieves **< 5 mg/W**
- < 10 mg/W Ag cells** in module, $\sim 1/3 m_{Ag}$ Ref, $\eta \nearrow$, BFR \nearrow
- Cu: finer lines, higher AR, improved ρ_C



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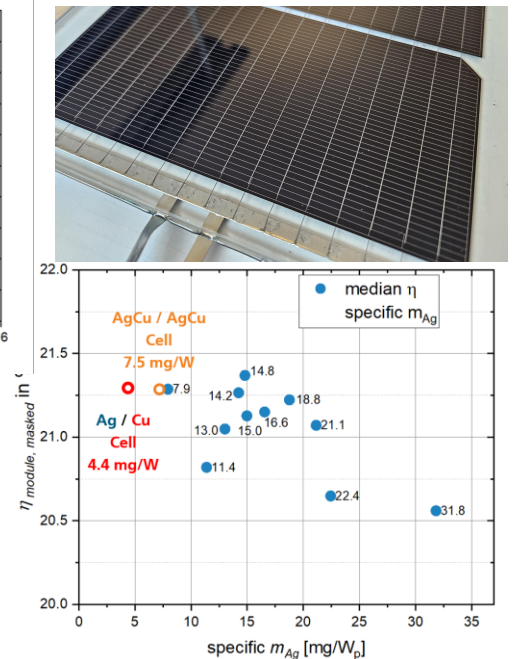
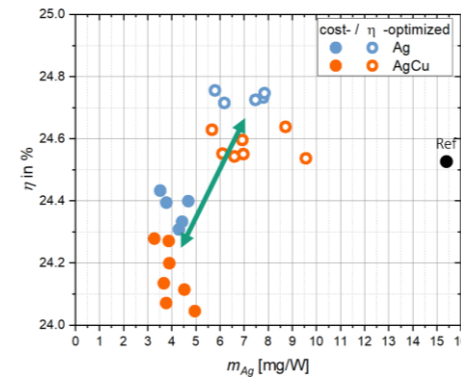
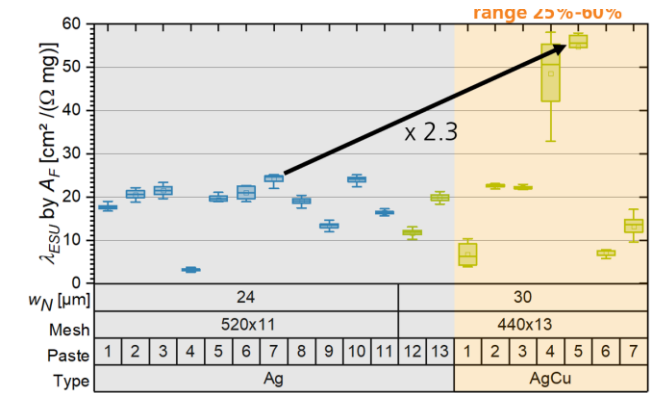
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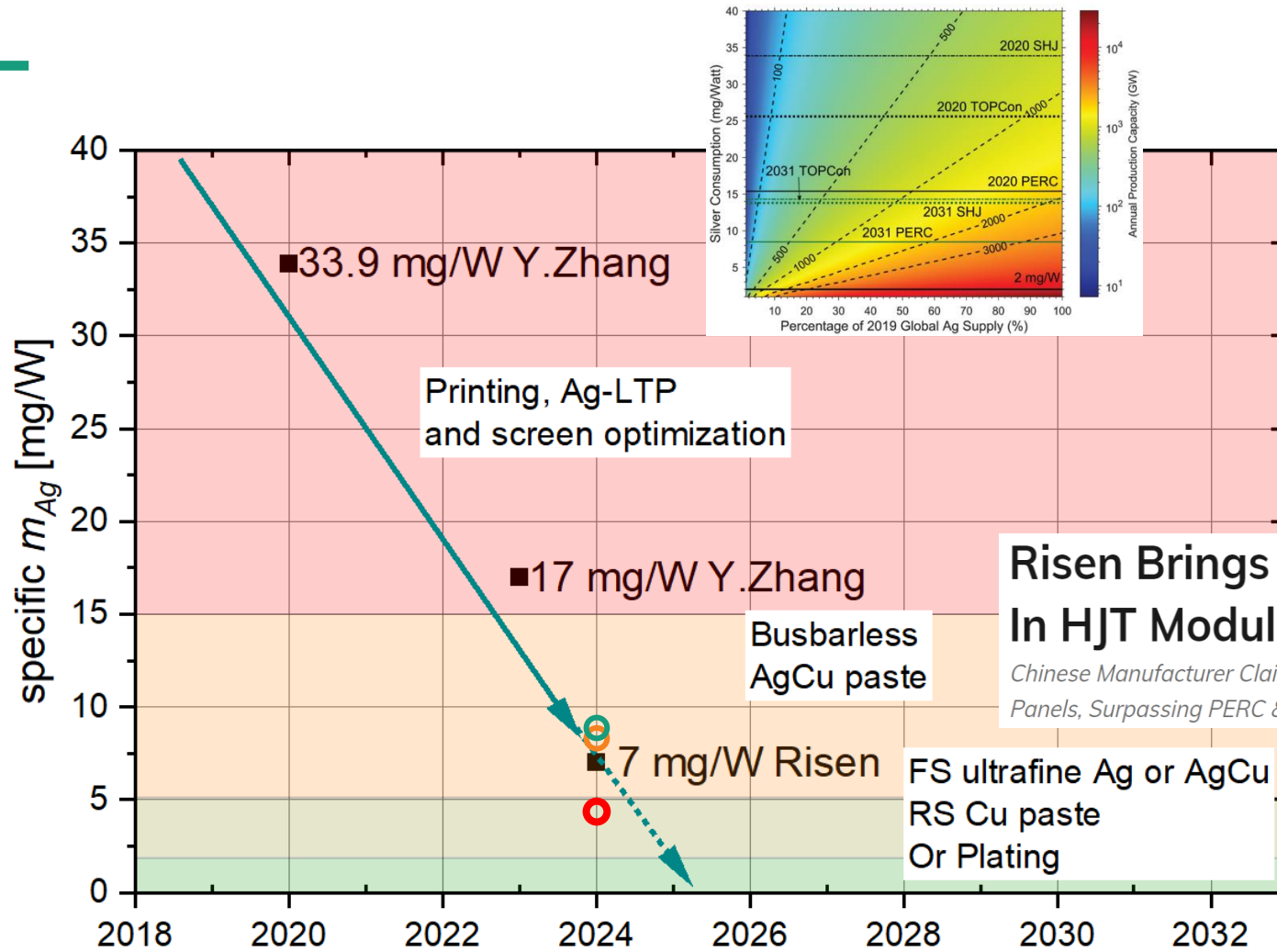
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Outlook:

- Module integration of Cu pastes (low temperature soldering, ...), reliability testing
- Combined simulation: interconnection & cell metallization → cost and Ag content \searrow



Rapid Evolution of the Ag Consumption in SHJ Cells and Modules



Risen Brings Down Silver Consumption In HJT Modules

Chinese Manufacturer Claims Less Than 7 mg/W Silver Use In Hyper-ion Solar Panels, Surpassing PERC & TOPCon

Anu Bhambhani

Published on: Jan 29, 2024, 2:08 pm

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Thank you for your
attention!

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Many thanks to:

all co-workers, paste suppliers (i.e. Namics, ...) and other industry partners.

This work has been funded by the Federal Ministry for Economic Affairs and Climate Action within the projects "Utility4Indium" (contract no. 03EE1127D) and "HIT" (contract no. 03EE1197B).

Supported by:



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**on the basis of a decision
by the German Bundestag**