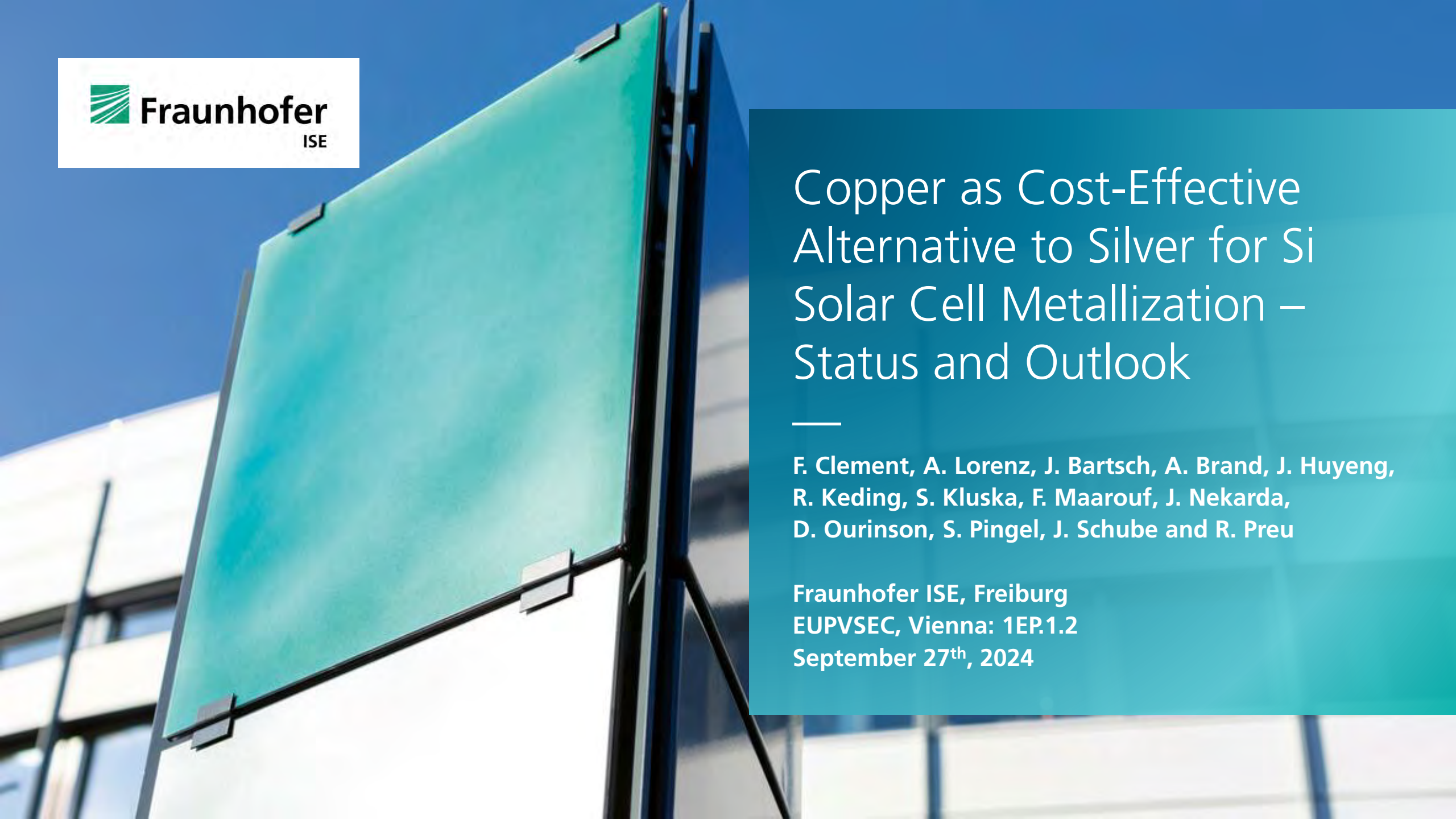


Copper as Cost-Effective Alternative to Silver for Si Solar Cell Metallization – Status and Outlook

F. Clement, A. Lorenz, J. Bartsch, A. Brand, J. Huyeng, R. Keding, S. Kluska, F. Maarouf, J. Nekarda, D. Ourinson, S. Pingel, J. Schube and R. Preu

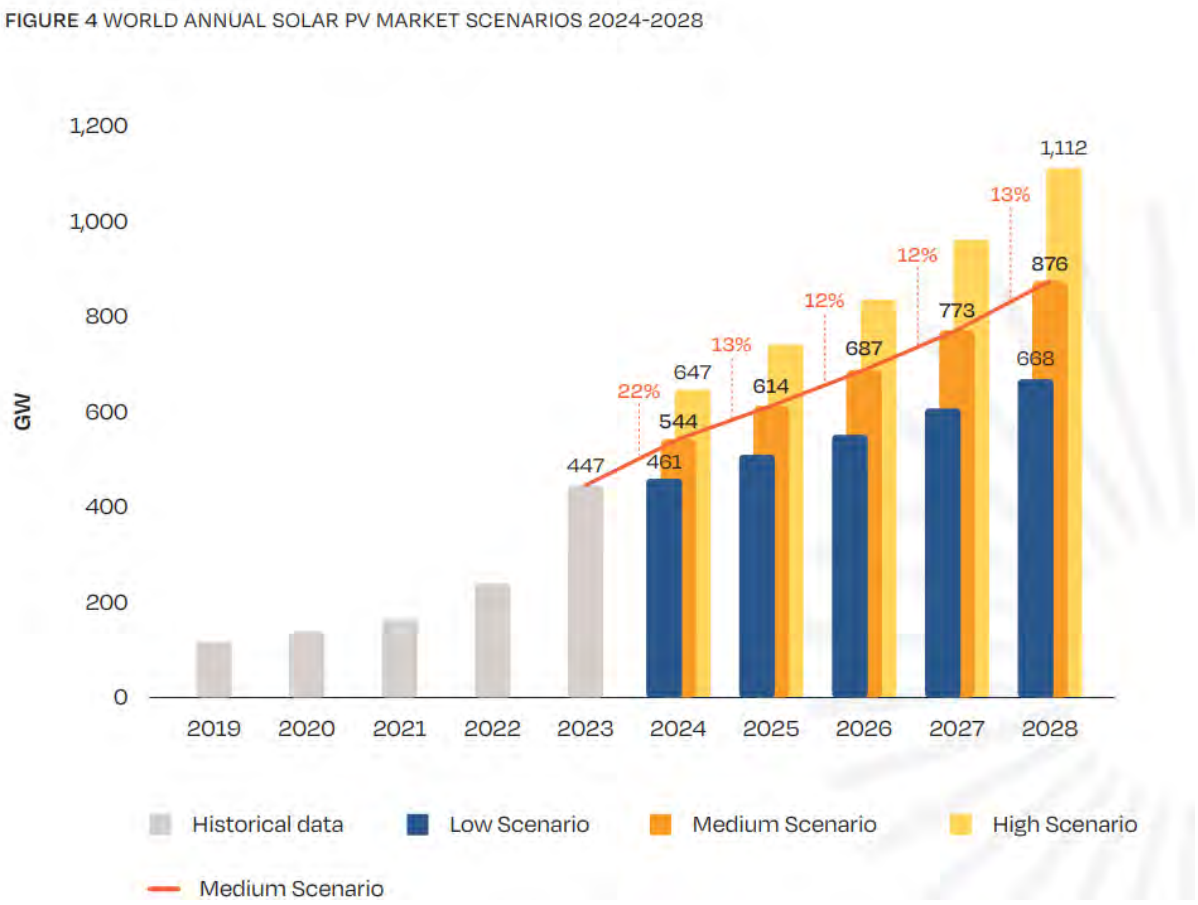
Fraunhofer ISE, Freiburg
EUPVSEC, Vienna: 1EP.1.2
September 27th, 2024

Background and Motivation

Rapid growth of the PV Industry – Risk and Challenges

Rapid growth of PV:

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



Forecast of the globally installed PV capacity until 2028. Source: [2]

[1] Solar Power Europe 2024 .
[2] https://api.solarpowereurope.org/uploads/Global_Market_Outlook_for_Solar_Power_2024_a083b6dcd5.pdf

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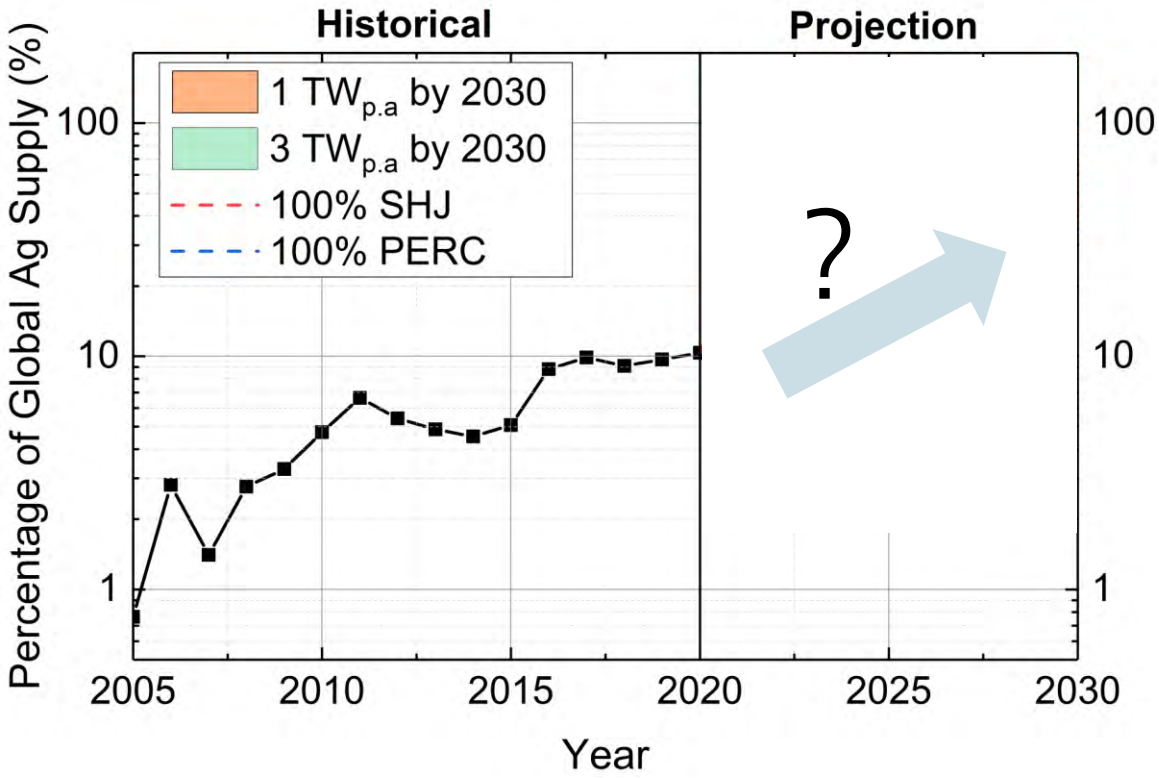

Development of global silver consumption until 2030 with a projected yearly increase of 1 or 3 TW/year. Source: [6]

[1] Solar Power Europe 2024
[3] Verlinden PJ. J Renew Sustain Energy. 2020;12(5) [4] Hallam B et al., Prog Photovolt: Res Appl. 2022;31(6) [5] Chang et al., Prog Photovolt: Res Appl. 2024; 1-12 [6] J. Bartsch et al., PV International 48, 2021

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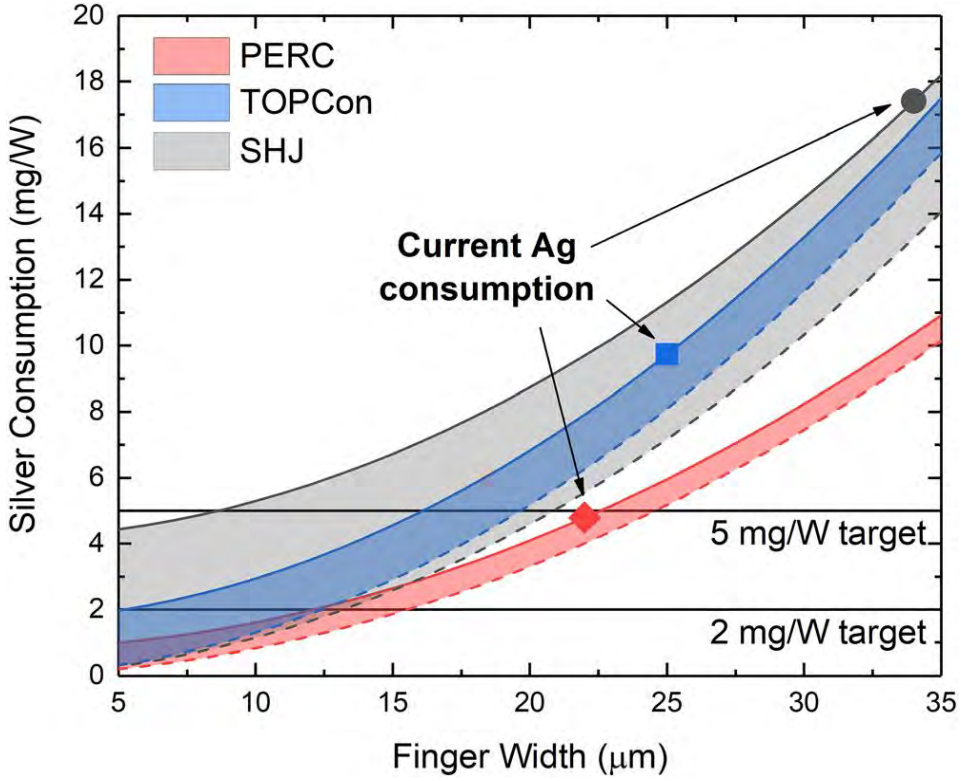

Calculated silver consumption as a function of printed width of ag fingers in industrial screen-printed PERC, TOPCon and SHJ solar cells. Solid lines show the total silver consumption in the finger, busbar and soldering tab regions, and dash lines show finger silver consumption only; Source: [5]

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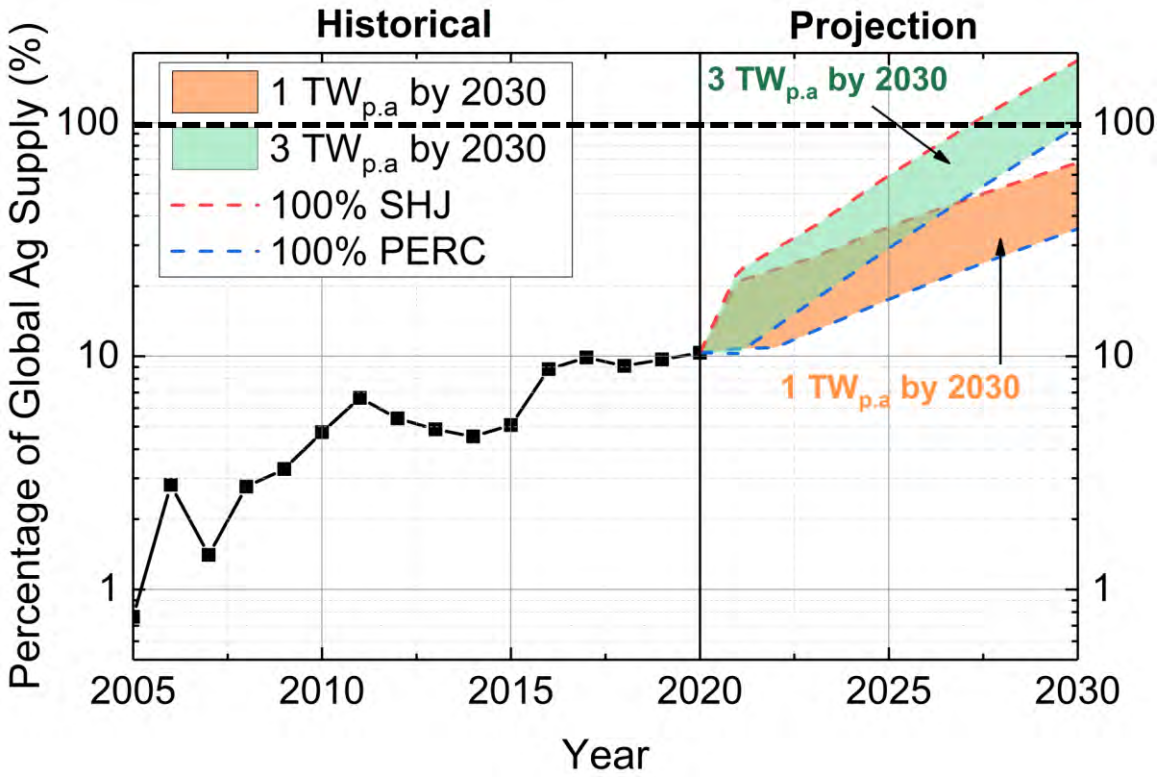

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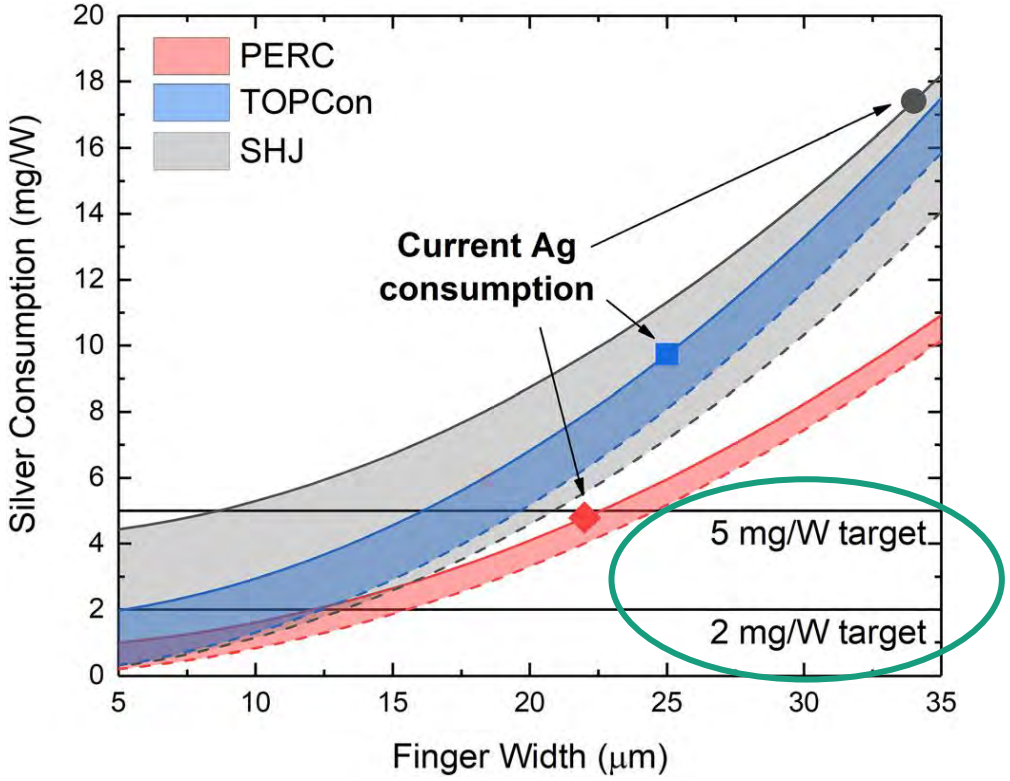
- Most critical resource: Silver usage in metallization
- Today: 5 mg/W (PERC) – 17 mg/W (SHJ) Ag is used
- Sustainable TW production: reducing Ag usage to **5** or even **2 mg/W** [3-5]

➔Silver has to be reduced or replaced!

➔This talk: Copper as alternative



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Technology Roadmap

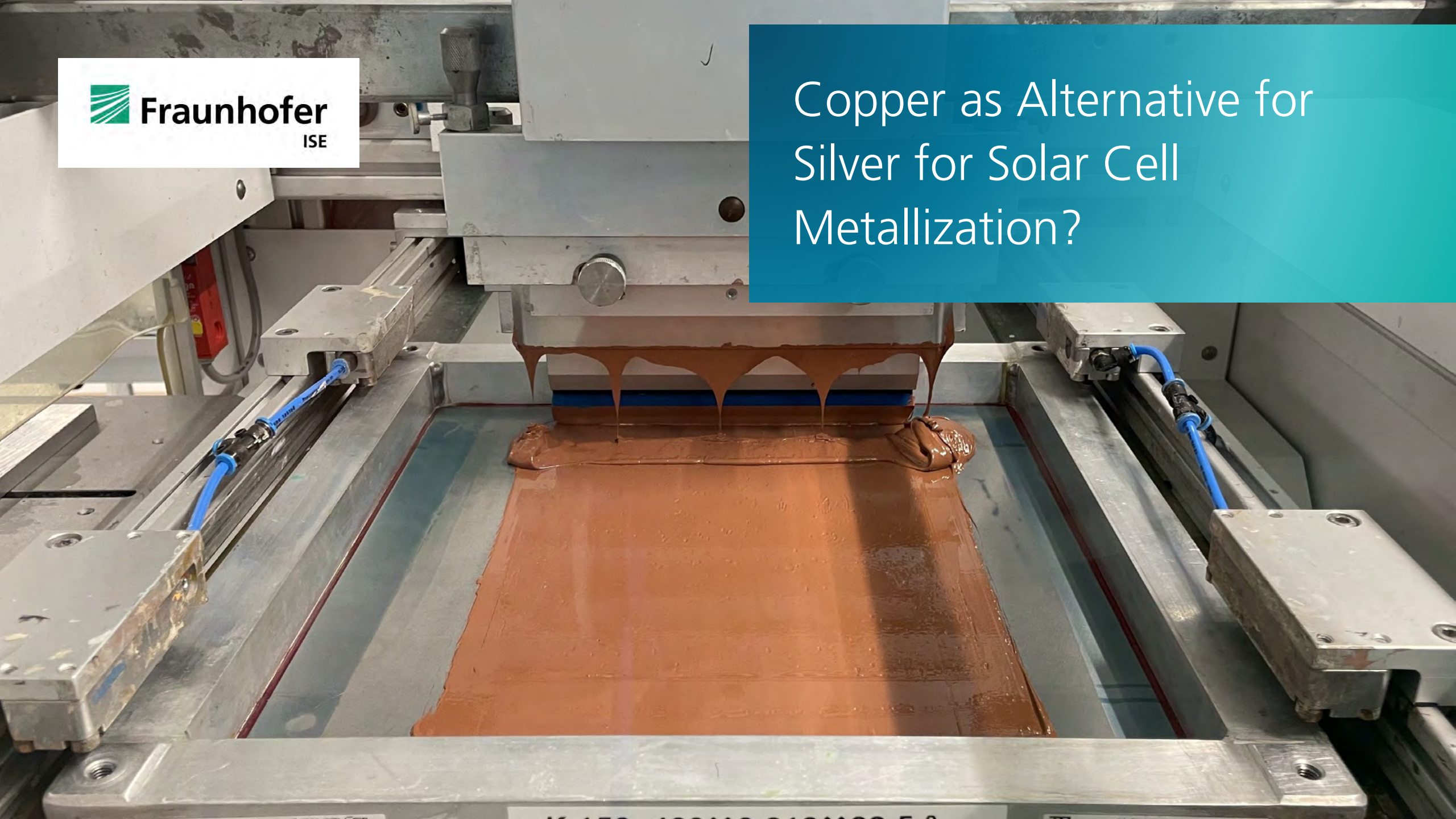
How can we reduce / replace Silver?

foto from www.tradestation.com

?

foto from www.degussa-goldhandel.de

Fraunhofer ISE



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Copper as Alternative for Silver for Solar Cell Metallization?

Perspectives for Solar Cell Metallization with Copper

Advantages and Challenges of Copper Metallization

Benefits:

- Resistivity comparable to Ag
- Substantial cost reduction
- More sustainable production
- Reduction of economic risks and material dependency

	Copper	Silver
Resistivity	0.018 µΩm	0.016 µΩm
Price [$/Kg] [7]	9.03	920.28
Carbon footprint [Kg CO_2 Equivalents per Kg] [8]	1.71	98.1
Abundance in earth's crust [%] [9]	0.0055	7 x 10^{-6}

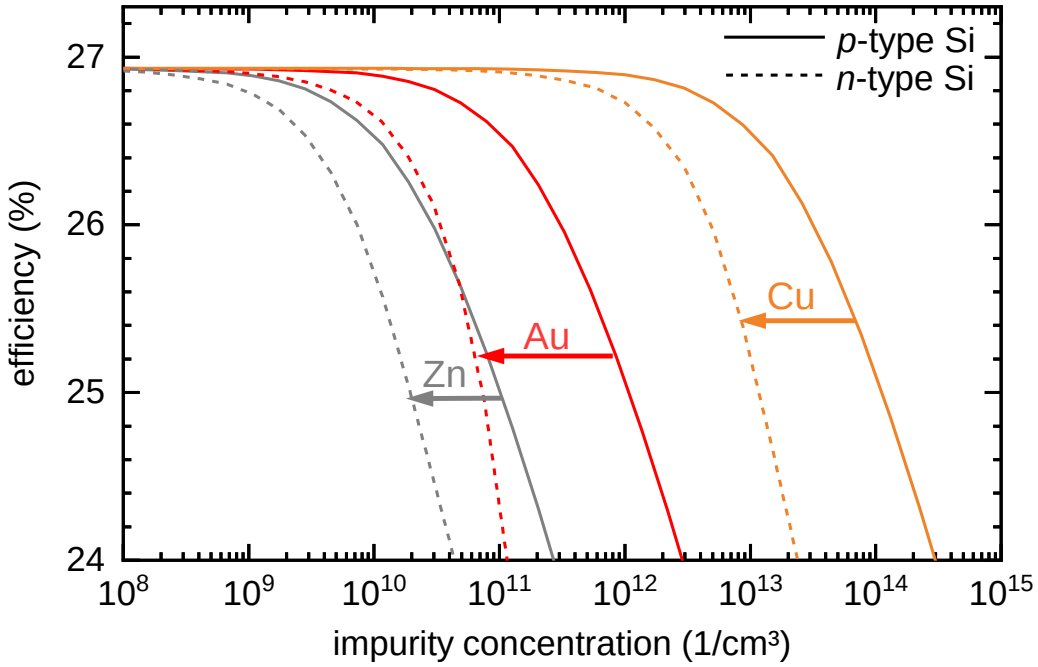
[7] https://www.dailymetalprice.com [Sep 11, 2024]
[8] LCA data MFD & Printers (epa.gov) [accessed June 1st, 2024)
[9] Pandey, B. State-of-the-Art Report on Technology for Producing Rare Metals in India (2012).

Perspectives for Solar Cell Metallization with Copper

Advantages and Challenges of Copper Metallization

Risk and Challenge:

- Cu particularly critical for high-temperature n-type solar cell concepts (e.g.TOPCon)
  - Diffusion of Cu into Silicon, i.e. n-type Si, and formation of recombination-active precipitates (deep-level traps)



Simulated cell eff. depending on Impurities that are more detrimental for n-type Si [10]

[10] A. Richter et al. MRS Meeting 2022.

Perspectives for Solar Cell Metallization with Copper

Advantages and Challenges of Copper Metallization

Risk and Challenge:

- Cu particularly critical for high-temperature n-type solar cell concepts (e.g.TOPCon)
  - Diffusion of Cu into Silicon and formation of recombination-active precipitates (deep-level traps)
  - Oxidation of contacts (loss of conductivity)
- Long-term stability of copper contacts
  ➔ effects on module reliability

Natural corrosion: patina and verdigris due to reactions with air or vinegar.

Bild: https://www.11880-gebaeudereinigung.com/

Perspectives for Solar Cell Metallization with Copper

Advantages and Challenges of Copper Metallization

Risk and Challenge:

- Cu particularly critical for high-temperature n-type solar cell concepts (e.g.TOPCon)
  - Diffusion of Cu into Silicon and formation of recombination-active precipitates (deep-level traps) [1]
  - Oxidation of contacts (loss of conductivity)
- Long-term stability of copper contacts
  ➔ effects on module reliability

➢**How can we replace silver with copper without performance losses?**

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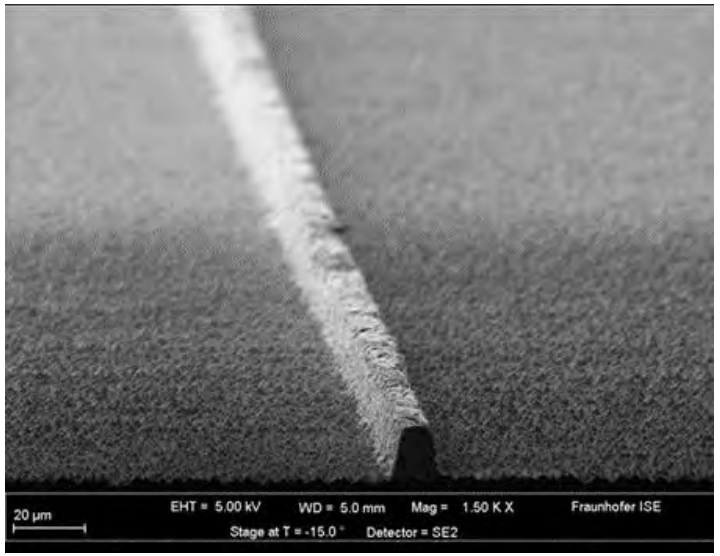
Technology Roadmap

How can we reduce / replace Silver?

foto from www.tradestation.com

Ag reduction / replacement …..

- **Fine line printing**
- Screen printing
  - Ag(/Cu) pastes
  - 100% Cu pastes
- Cu plating



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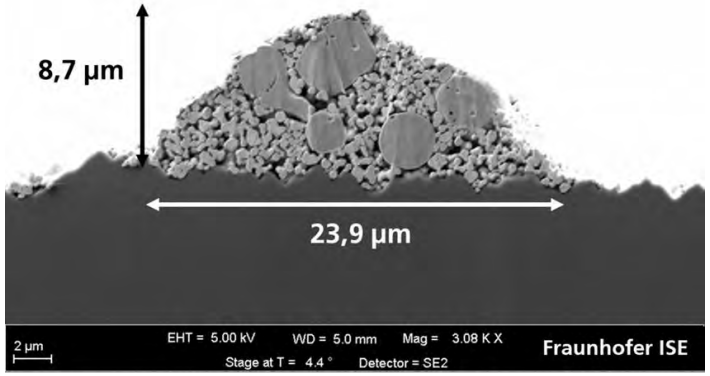

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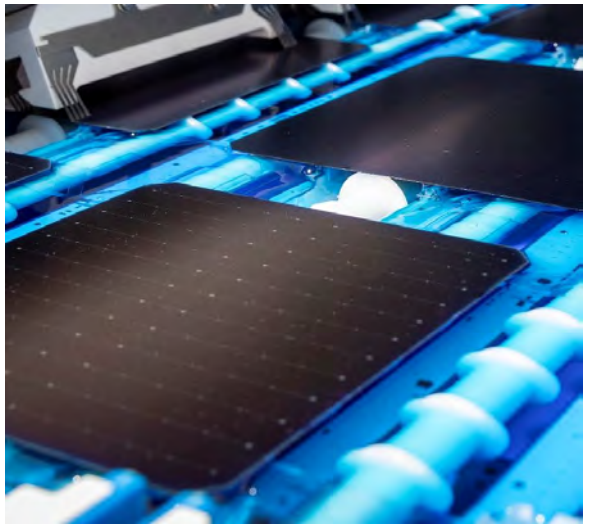

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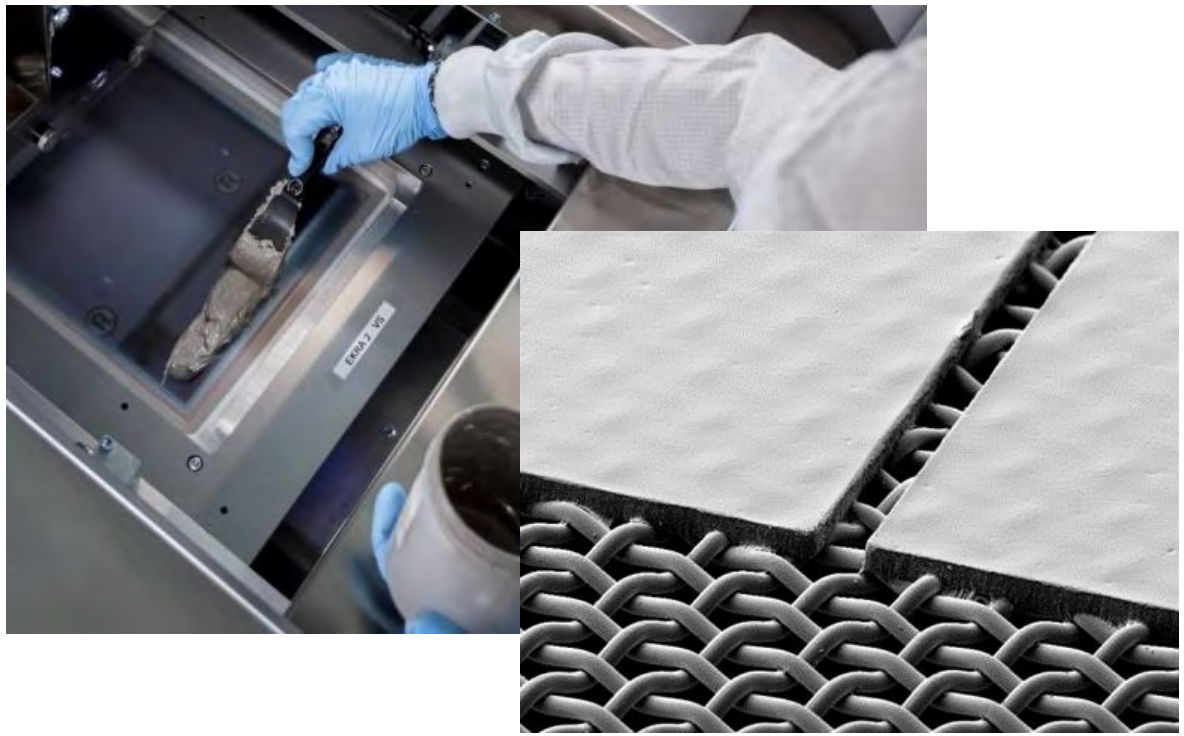
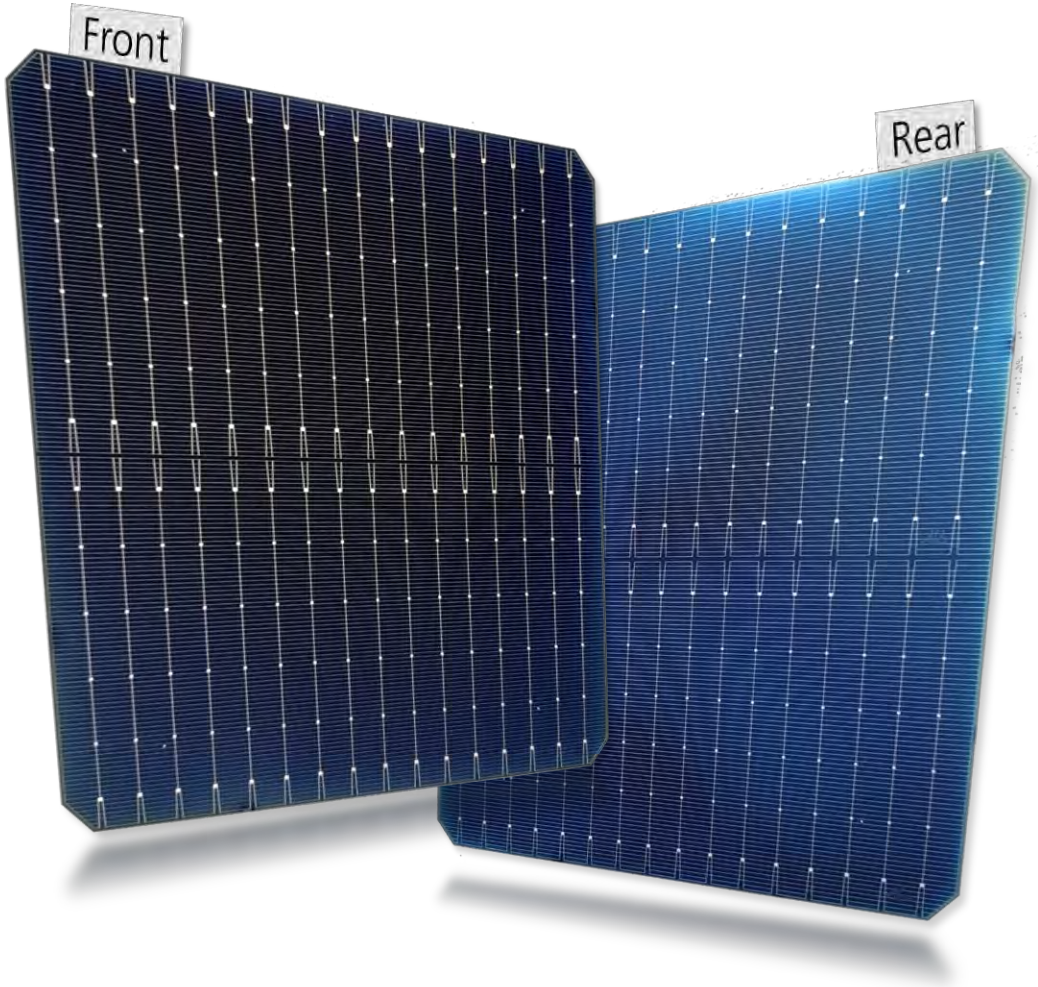
The „Old Bull“: Silver Based Screen Printing – Status and Outlook

Screen Printed Metallization for Si Solar Cells

Towards Minimizing Silver Dependence

- State-of-the-art: flatbed screen printing





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Screen Printed Metallization for Si Solar Cells

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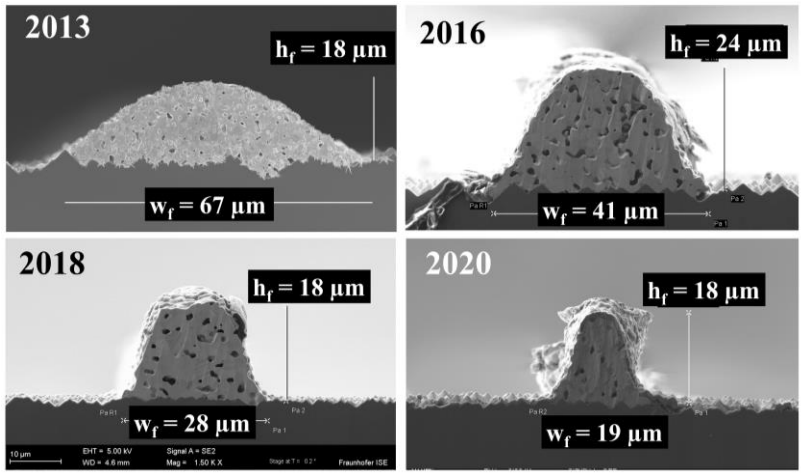
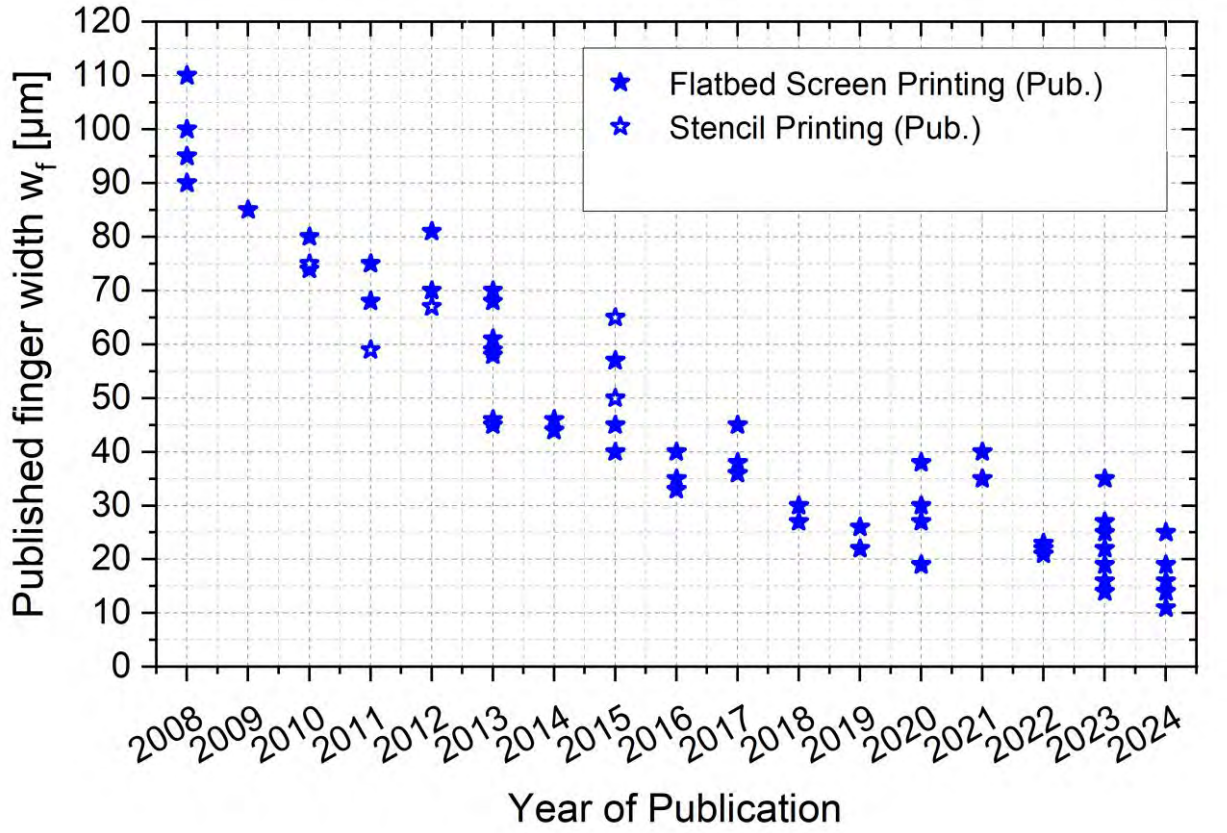
- State-of-the-art: flatbed screen printing
- Finger width reduction by factor 8 since 2010 [11]



Evolution of screen-printed finger width illustrated by selected SEM images of screen printed contacts. Source: Fraunhofer ISE



Evolution of screen-printed finger width based on published results from 2008 to 2004. Updated version, based on [11]

[11] Tepner S. & Lorenz, A.. Progress in Photovoltaics: Research and Applications 31 (2023) 557–590.

Fraunhofer ISE

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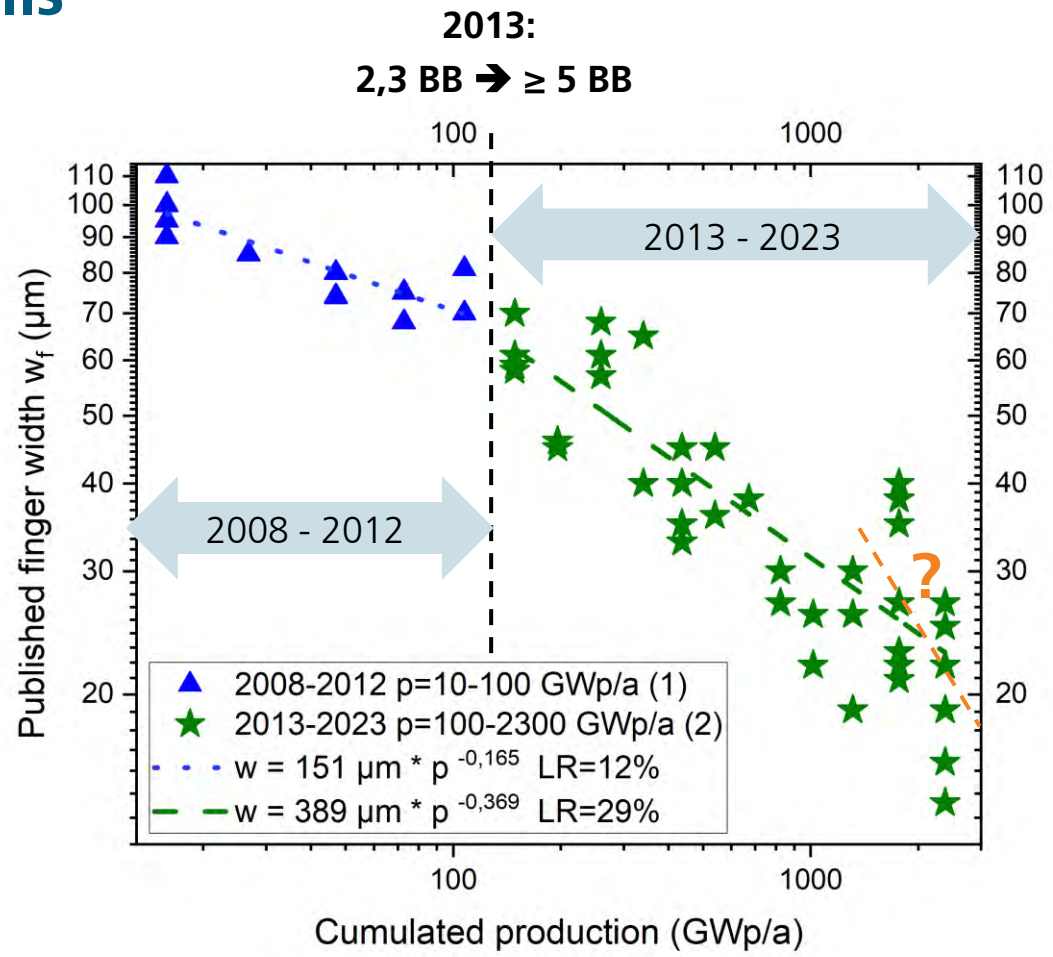

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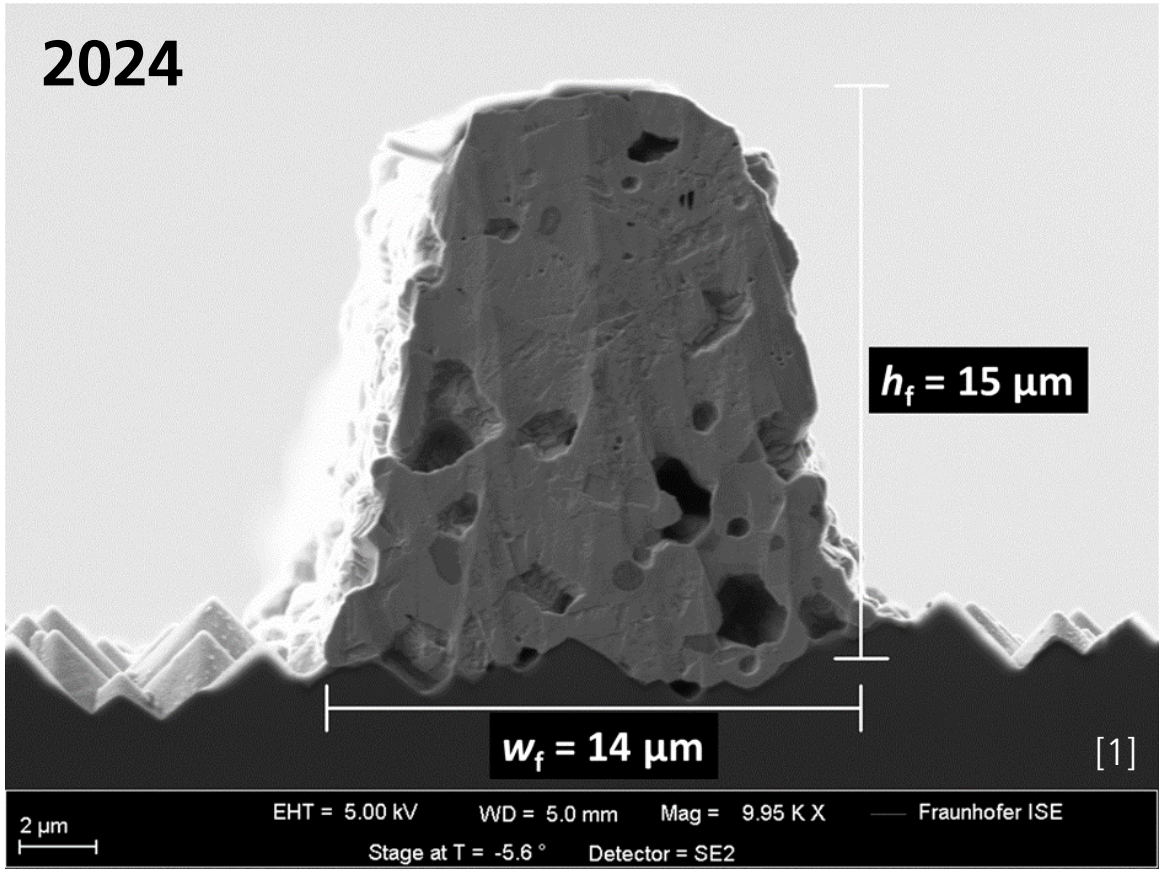
- Recent result:
  - PERC front side metallization **w_f = 14 µm** [12,13]



[12] Source: Fraunhofer ISE, Lohmüller et al. [submitted for publication on EUPVSEC 2024]
[13] https://www.pv-magazine.com/2024/05/01/fraunhofer-ise-develops-23-4-efficient-perc-solar-cells-with-limited-silver-amount/

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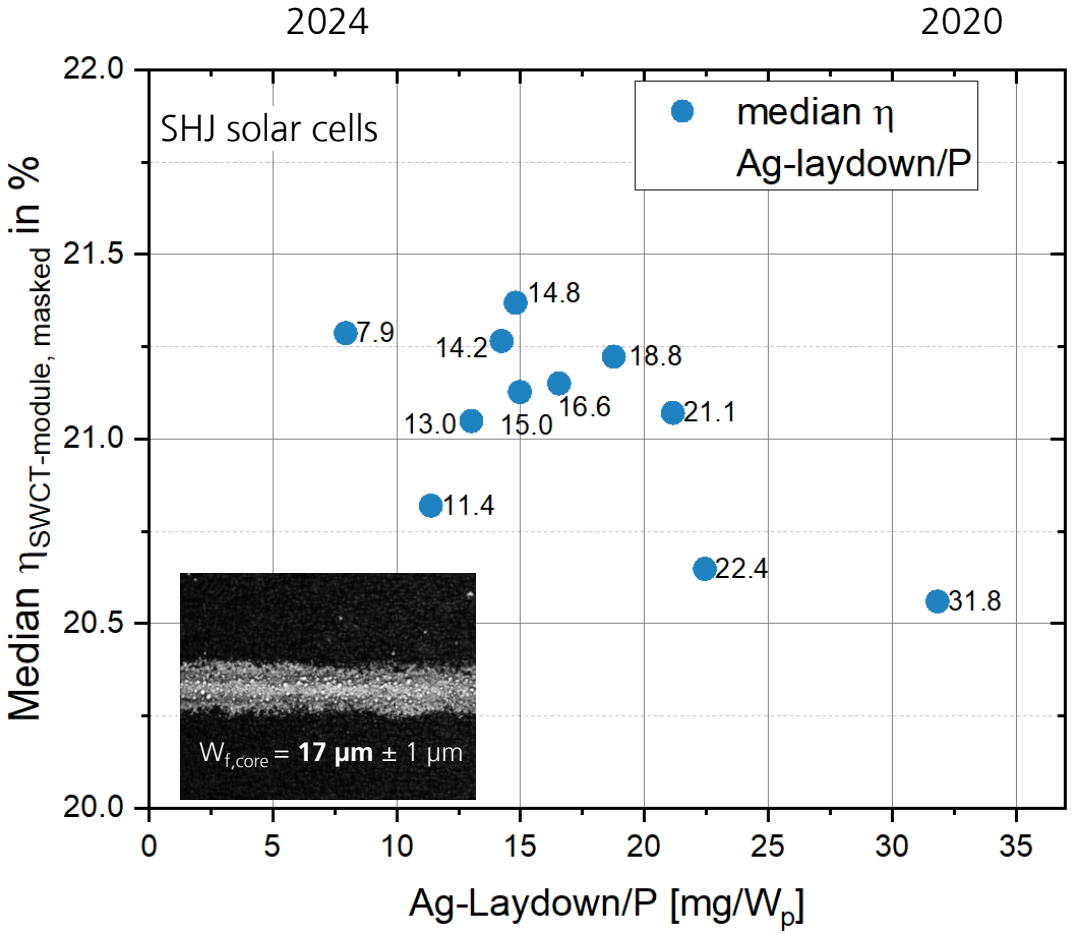
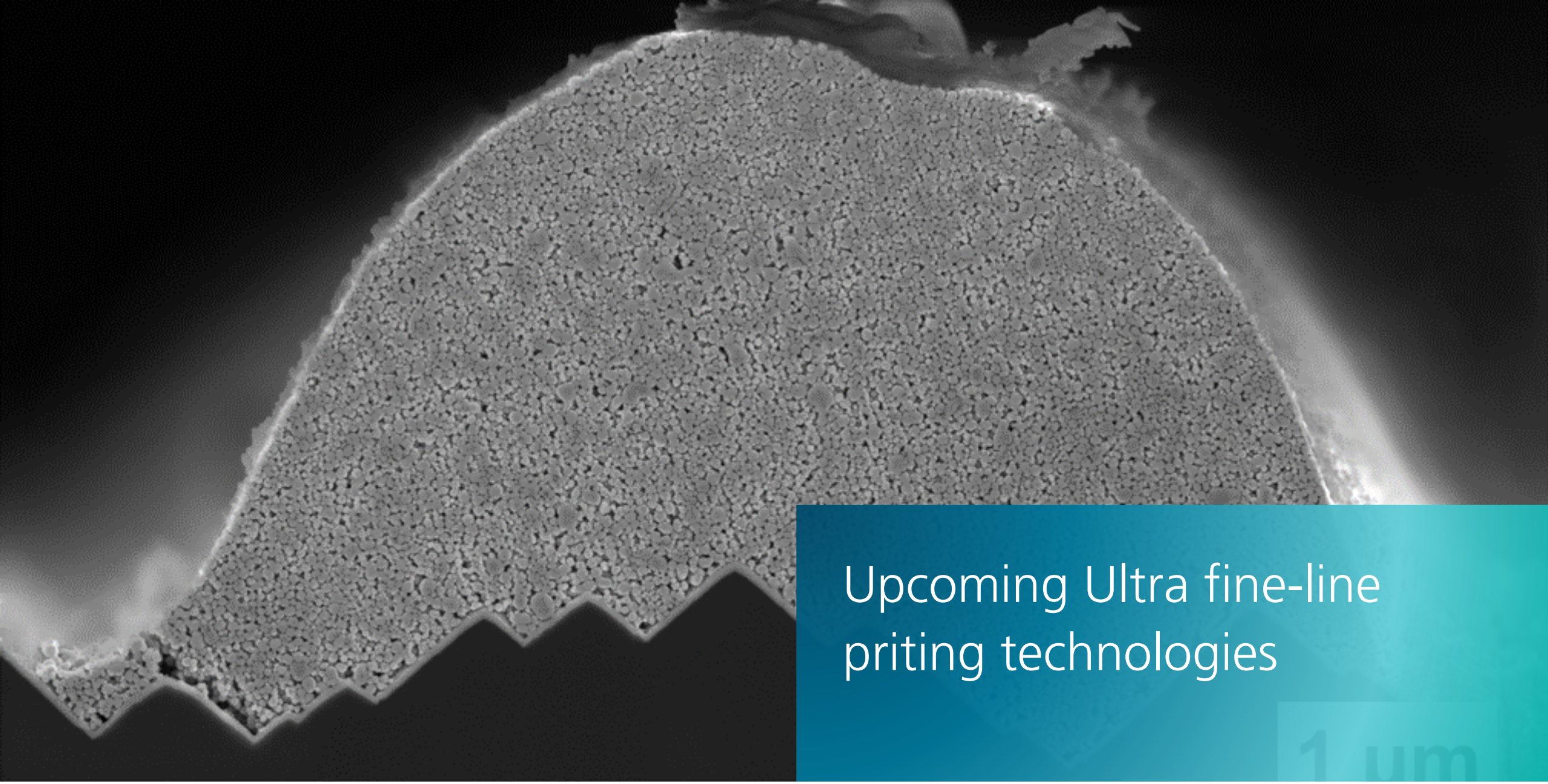


Reduction of silver consumption @Fraunhofer ISE of SHJ solar cells without busbars / pads for smart wire (SWCT) module integration

[14] S. Pingel et al., Metallization Workshop 2024 (to be published)



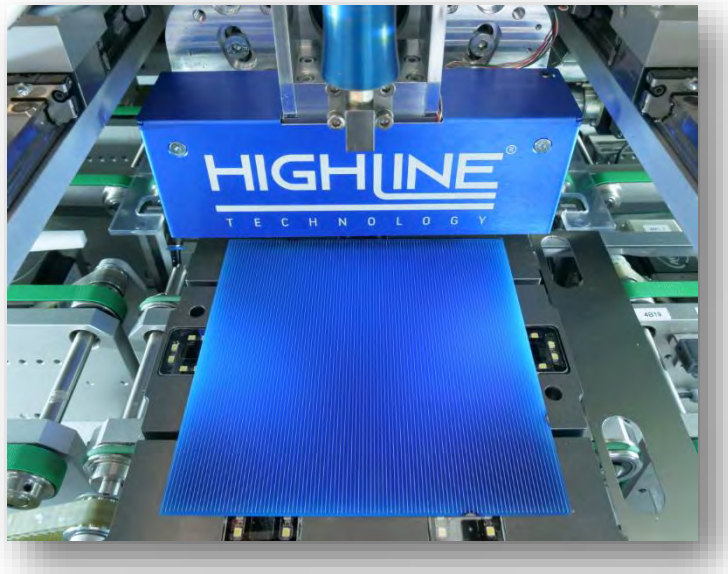
Upcoming Ultra fine-line priting technologies

Fraunhofer ISE

Ultra Fine-Line Printing

Upcoming Technologies

- **Parallel Dispensing Technology**
  - allows more homogenous finger geometry
    ➔ about 20% less silver consumption demonstrated
  - Industrial printheads available
    ➔ HighLine Technology (Fraunhofer ISE Spin-off)



In-line Intermitted Parallel Dispensing printhead [16]

SEM image of a dispensed contact finger [15]

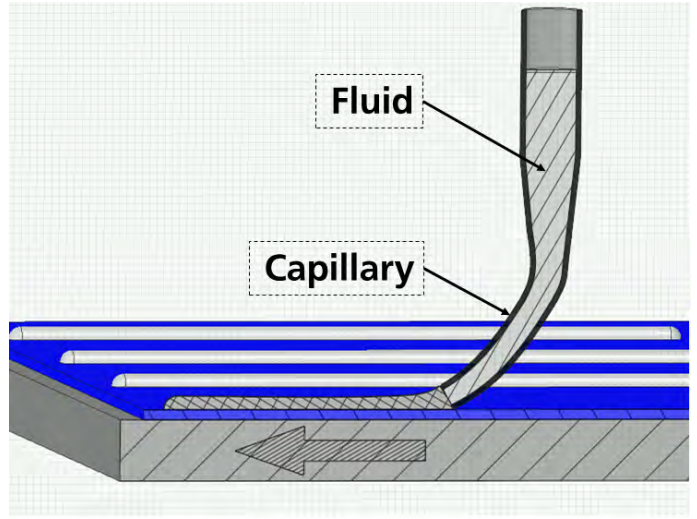
[15] Pospischil et al. (Met WS 2019)
[16] www.highline-technology.de

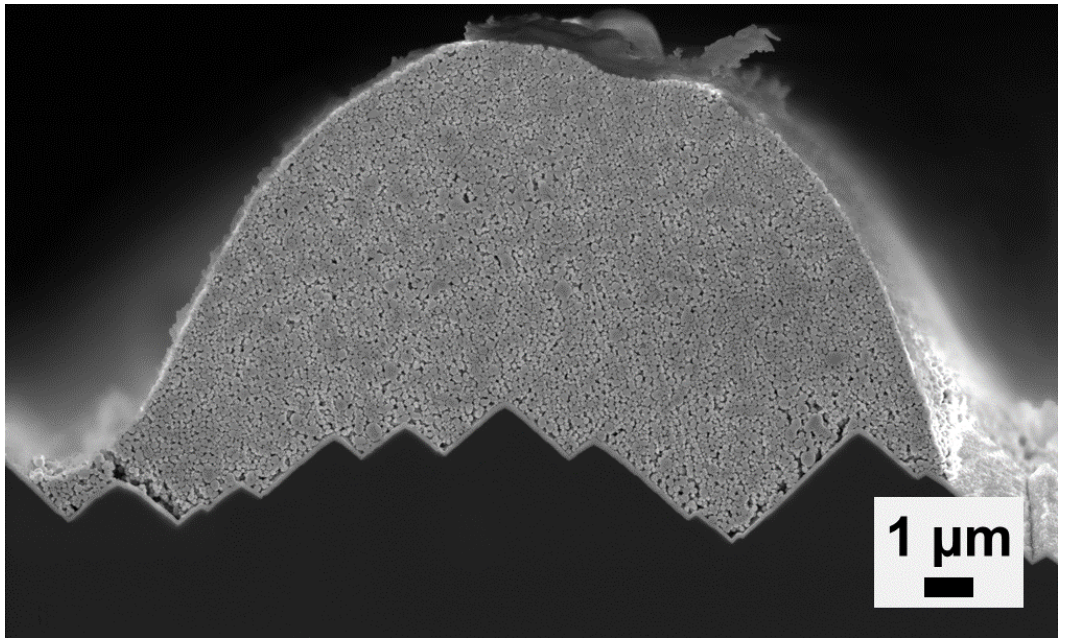
Ultra Fine-Line Printing

Upcoming Technologies

- Parallel Dispensing Technology

- **Flextrail Printing Technology**[17,18]
  - finger width down to 10µm
  - Significant silver saving potential
  - technology upscaling is ongoing





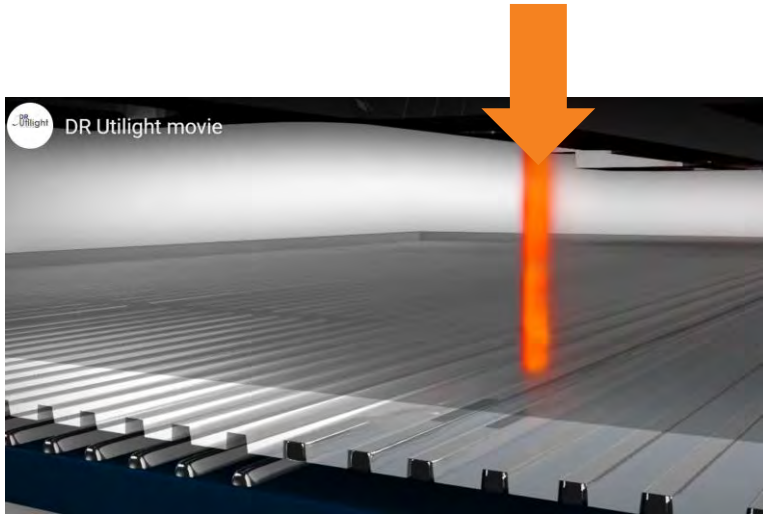
[17] J. Schube et al., Energy Technology (2022

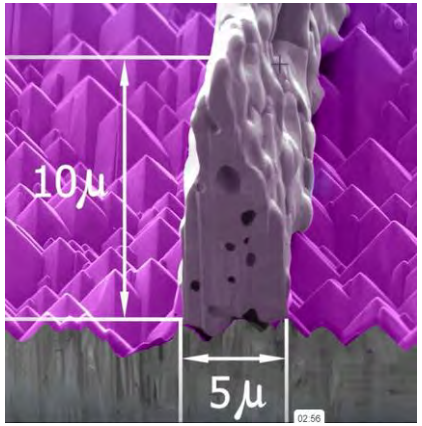
[18] M. Jahn, EP 3 736 050 (2022)..

Ultra Fine-Line Printing

Upcoming Technologies

- Parallel dispensing technology
- Flextrail printing technology
- Further high potential ultra fine-line printing technologies:
  - Glass stencil printing [19]
  - Pattern transfer printing (PTP) [21]
  - „Lumet Metallization Technology“ [20]
  - ….





[19] T. Schweigstill this conference (1BO.3.6) [20] https://www.lumet.com/..

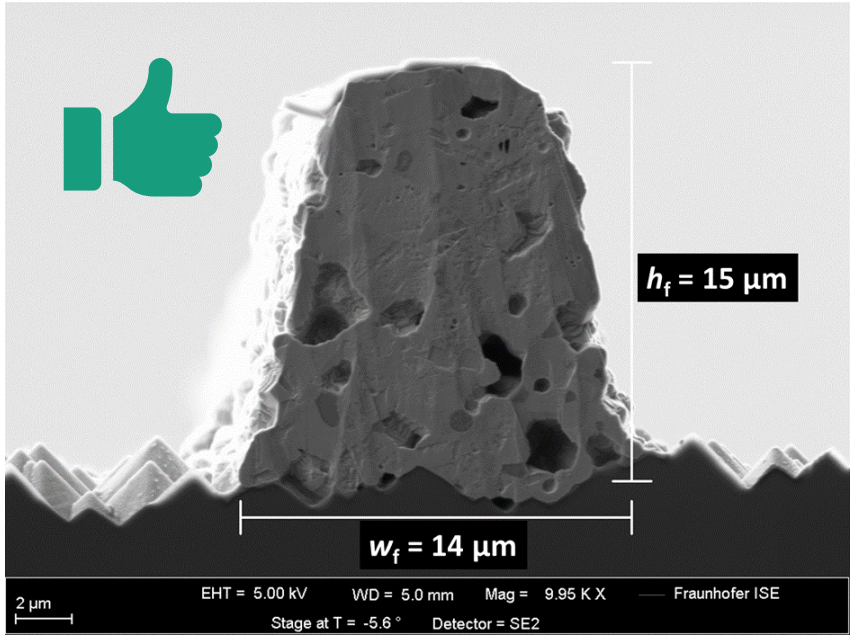
[21] https://www.utilight.com/

Technology Roadmap

How can we reduce / replace Silver?

foto from www.tradestation.com

Ag reduction / replacement (First step):
Fine line printing allows ultra-fine finger geometries (below 15 µm)



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Ag reduction / replacement (second step):

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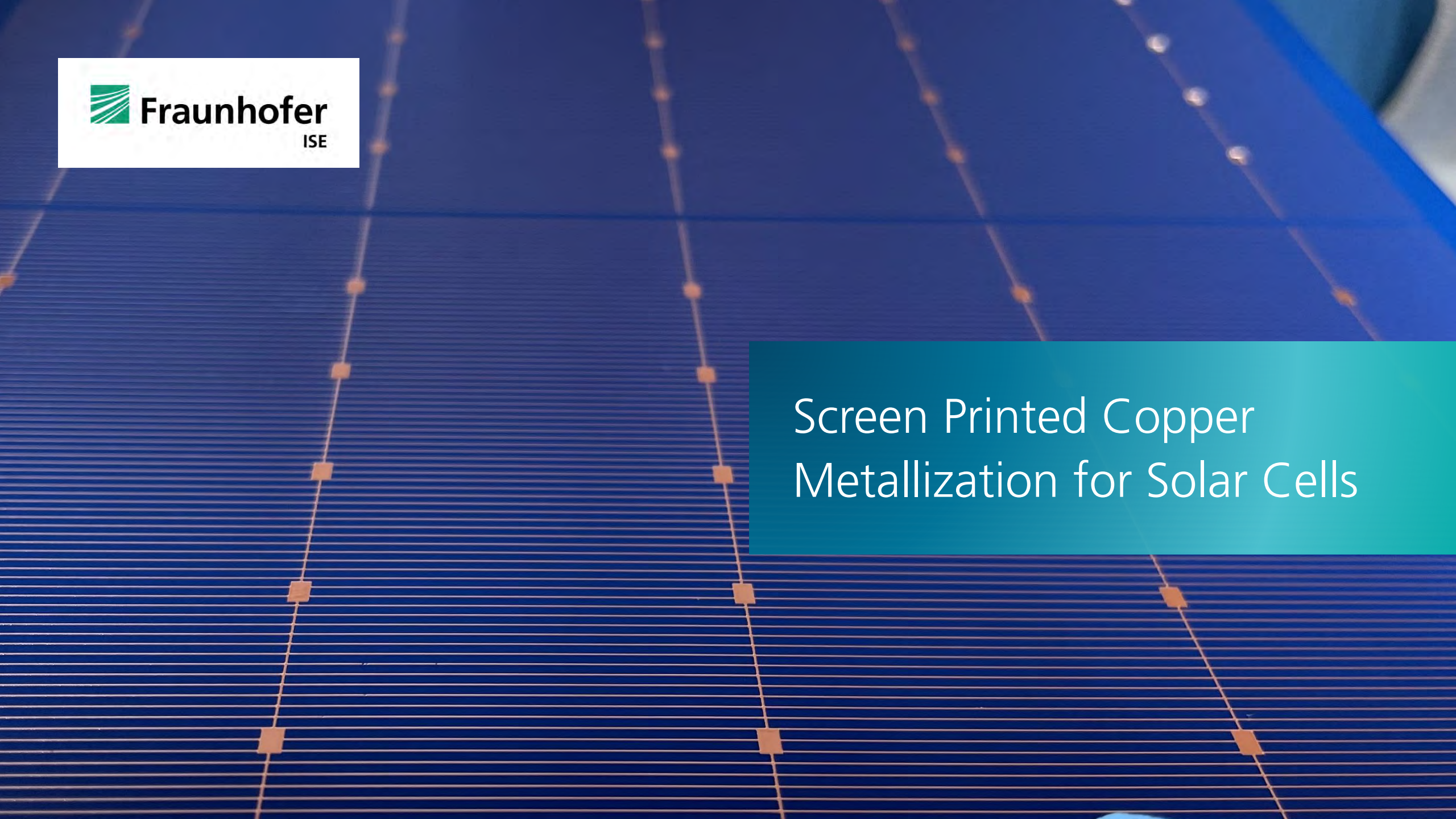
- Cu plating

?

Fraunhofer ISE



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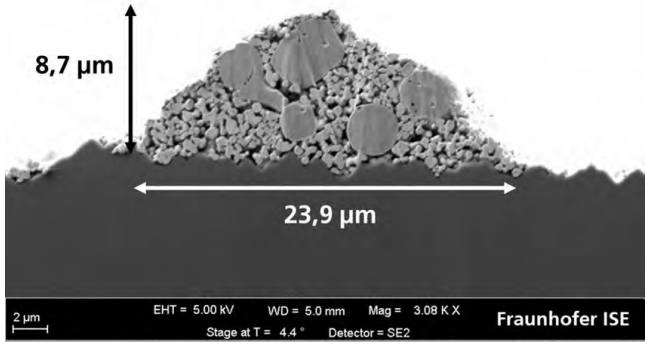
Screen Printed Copper Metallization for Solar Cells

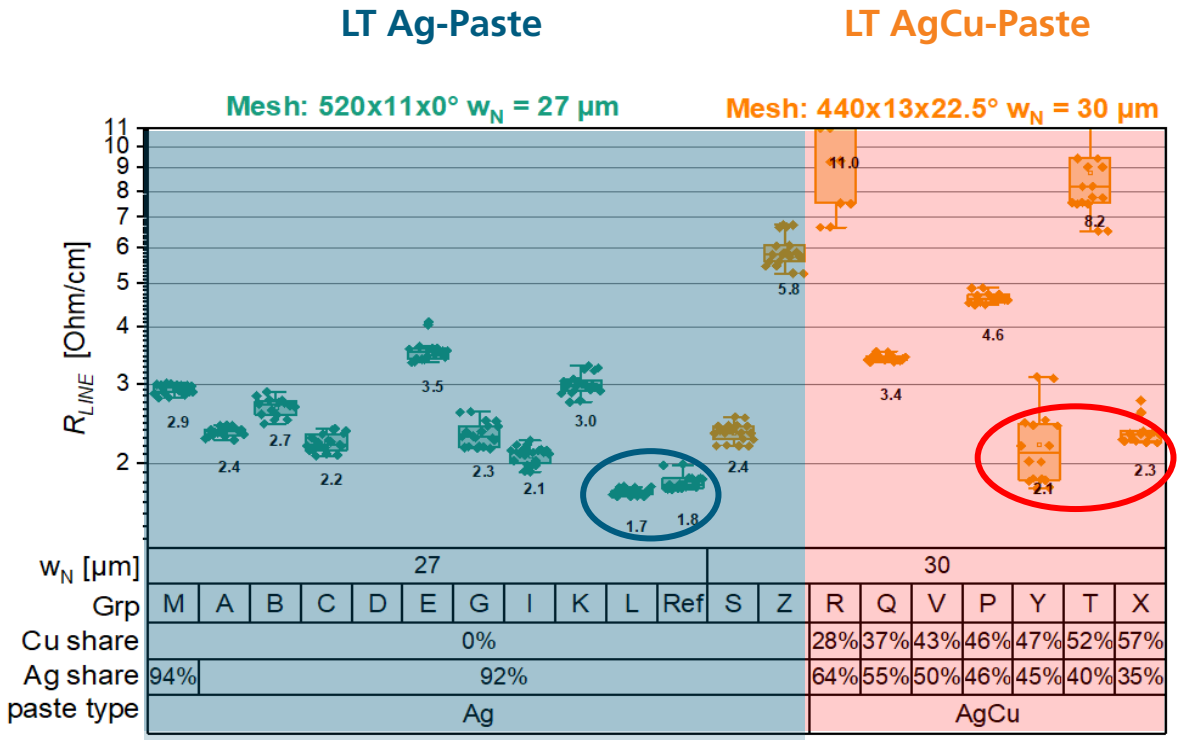
Screen Printing of Copper Contacts

SHJ solar cells with screen printed silver-copper (AgCu) metallization

- Low temperature approach with silver-copper pastes
- Latest versions of AgCu pastes can compete with the best Ag pastes

➢ **AgCu fingers allow to reduce Ag consumption by at least 50% for SHJ cell**





R_{LINE} data for Ag and AgCu pastes printed with varied w_N (27 µm and 30 µm are shown).

Screen Printing of Copper Contacts

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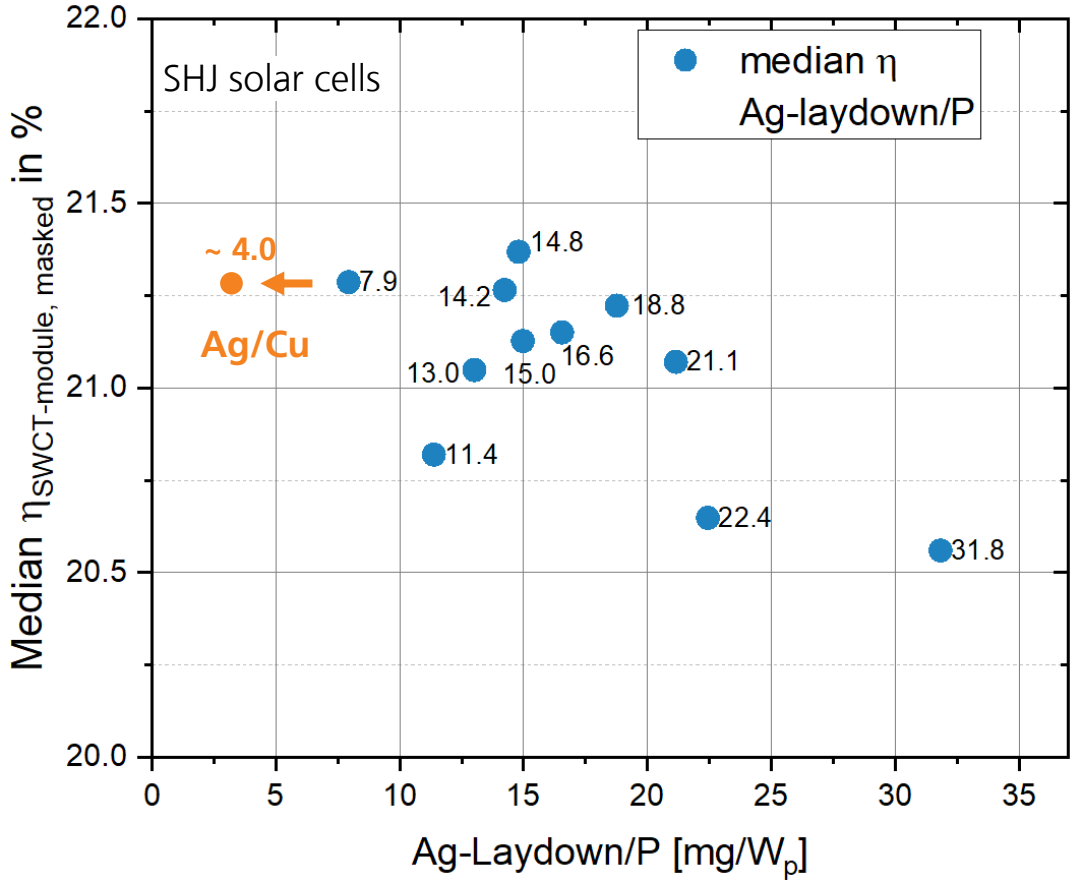
➢ Ag consumption below 5 mg/W achievable

➢ Significant step towards the 2 mg/W long-term goal for sustainable SHJ production



Reduction of silver consumption @Fraunhofer ISE of SHJ solar cells without busbars / pads for smart wire (SWCT) module integration

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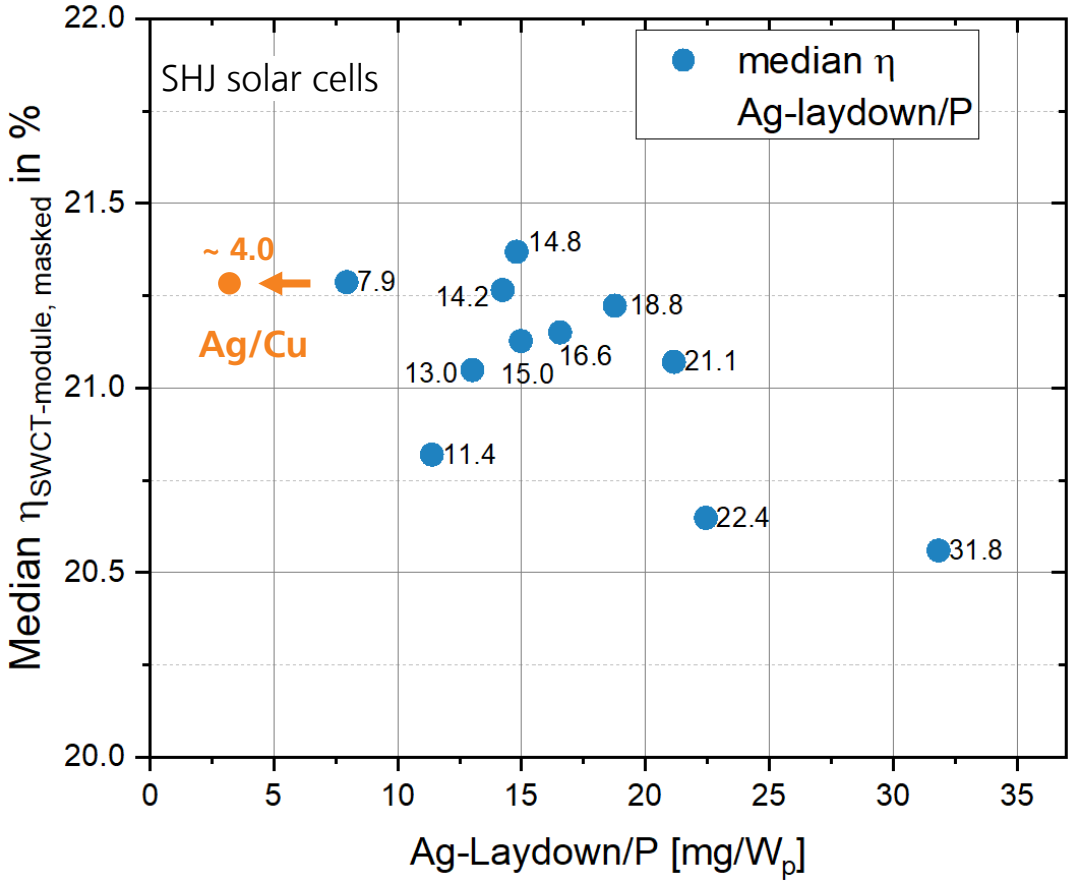
➢ **Will 100% Cu pastes be the next step?**

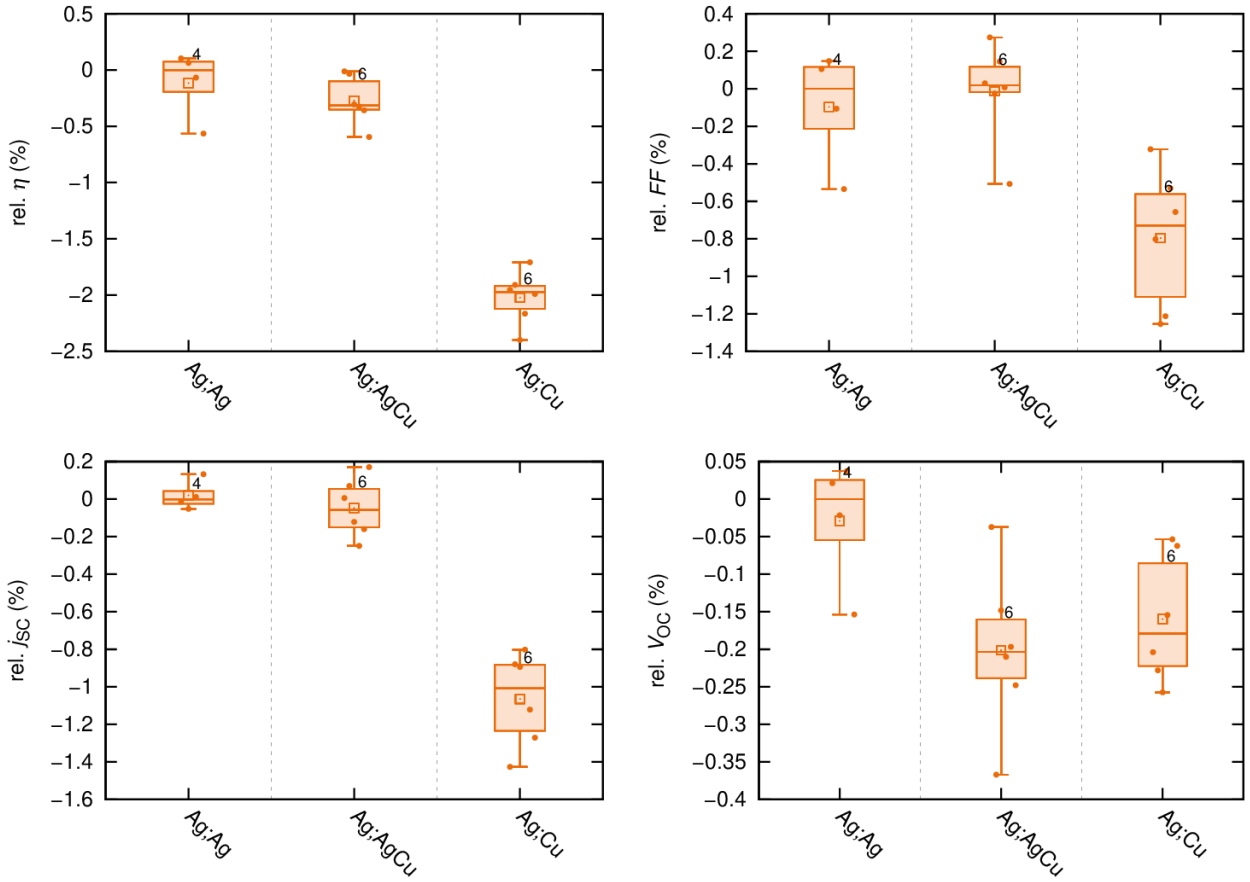


Reduction of silver consumption @Fraunhofer ISE of SHJ solar cells without busbars / pads for smart wire (SWCT) module integration

Screen Printing of Copper Contacts

SHJ solar cells with screen printed copper metallization

- SHJ solar cells with Ag front side and different rear side metallization
  - Reference: standard Ag paste
  - Silver Copper paste with around 50% Cu
  - Pure Copper paste 100% Cu
- Solar cell results show….
  - Ag/cu pastes allow same efficiency level
  - Cu pastes show promising results, but still need some improvement (printing geometry and line resistance)



IV results for AHJ cells: relative values in comparison to both side Ag reference. The rear side metallization is varied (Ag, Ag/Cu, Cu)

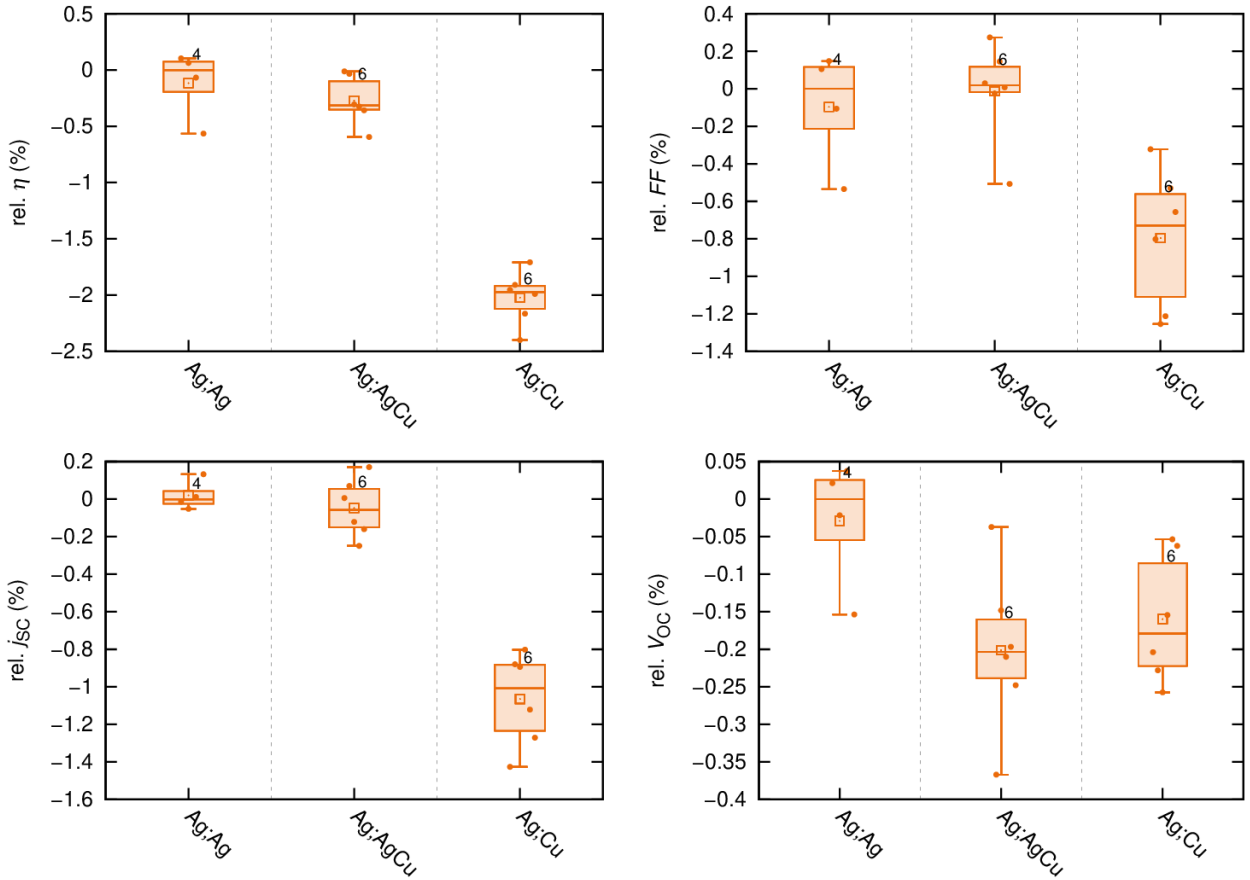
Screen Printing of Copper Contacts

SHJ solar cells with screen printed copper metallization

- SHJ solar cells with Ag front side and different rear side metallization
  - Reference: standard Ag paste
  - Silver Copper paste with around 50% Cu
  - Pure Copper paste 100% Cu
- Solar cell results show….
  - Ag/cu pastes allow same efficiency level
  - Cu pastes show promising results, but still need some improvement (printing geometry and line resistance)

➢ **Ag/Cu pastes "ready for production"***

➢ **Cu pastes not "far away"***



IV results for AHJ cells: relative values in comparison to both side Ag reference. The rear side metallization is varied (Ag, Ag/Cu, Cu)

* See also talks by CEA INES and TNO this conference

Screen Printing of Copper Contacts

TOPCon solar cells with screen printed low temperature copper metallization

Previous Work:

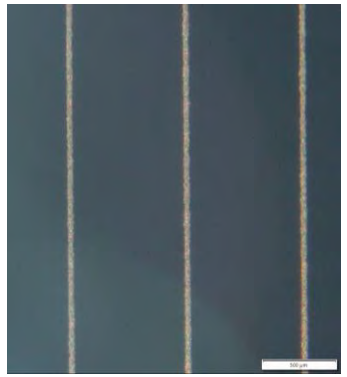
- Cu metallization successfully demonstrated on IBC solar cells [22]

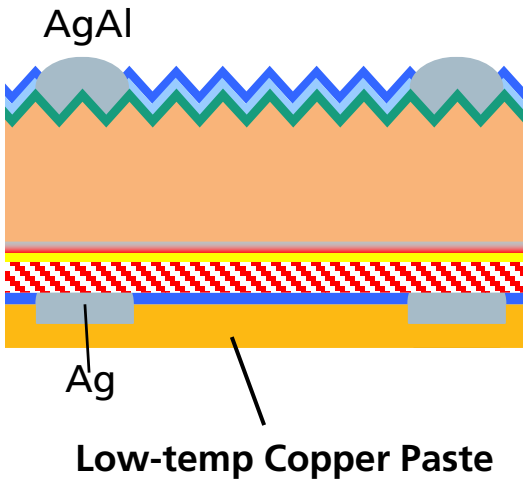
Previous Study at ISE:

- TOPCon solar cells with rear side **Ag contacts + full area low-temp copper** conduction layer
- Similar conversion efficiency as reference group
- 75 % silver reduction on the rear side
- No detectable Cu oxidation (r_S) or Cu diffusion into Si (V_{OC})
- Results published by D. Ourinson [23]

Reduced Ag by special screen

Conventional rear Ag fingers



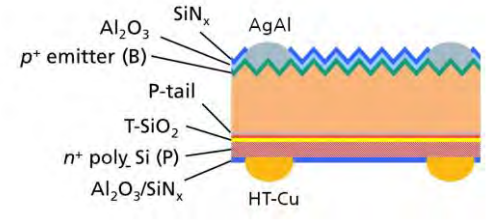


Best cell	η (%)	V_{OC} (mV)	j_{SC} (mA/cm²)	*FF* (%)	r_S (Ωcm²)
„LT-Cu“	**23.0**	701	40.8	80.2	0.6
Ag-Ref	**23.0**	699	40.7	80.7	0.5

[22] Chen et al., Solar RRL 7 (2023) [23] Ourinson et al., SolMat 266 (2024)

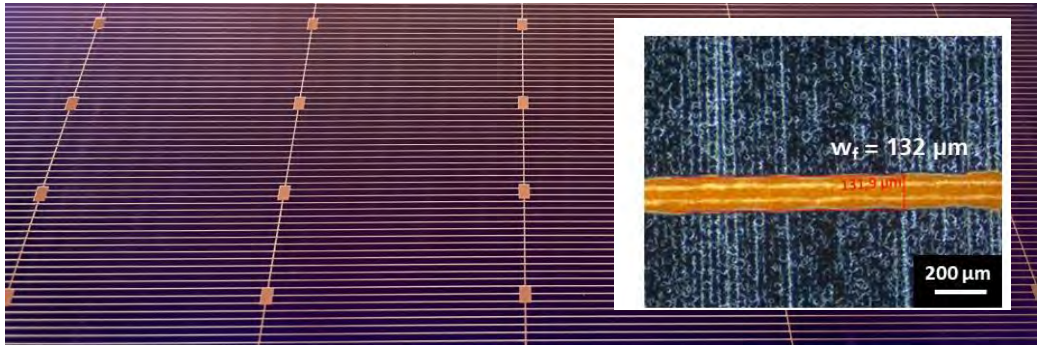
Screen Printing of Copper Contacts

TOPCon solar cells with screen printed copper rear side metallization [24]



- High temperature approach with copper paste
- Fully functional TOPCon solar cells with screen printed & fired copper metallization on the rear
- Screen printed Cu contacts: w_f ~ 130µm
  → Process Optimization for fine line contacts ongoing
- Silver reduction: ~ 60% less silver
  → 2-5 mg/W silver consumption reasonable

➢ **Feasibility confirmed, further optimization of Cu paste and firing process is ongoing**



Group	η (%)	V_{OC} (mV)	j_{SC} (mA/cm²)	*FF* (%)
1 (Cu-RS)	21.6	679	40.2	79.3
2 (Ag-Ref)	23.5	712	40.9	80.5

Group	*Ag Front [mg]*	*Ag Rear [mg]*	Total Ag [mg]
1 (Cu-RS)	39	-	39
2 (Ag-Ref)	39	65	104

[24] Lorenz et al., IEEE PVSC 2024, Seattle (USA)

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Technology Roadmap

Screen Printing: How can we reduce / replace Silver?

foto from www.tradestation.com

Low Temperature Metallization (SHJ)

High Temperature Metallization (TOPCon)

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Technology Roadmap

Screen Printing: How can we reduce / replace Silver?

foto from www.tradestation.com

Low Temperature Metallization (SHJ)

High Temperature Metallization (TOPCon)

- Metallization with Ag/Cu pastes ready for mass production
  ➔ at least 50% less Ag
- Approaches with 100% Cu pastes show high potential

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Technology Roadmap

Screen Printing: How can we reduce / replace Silver?

foto from www.tradestation.com

Low Temperature Metallization (SHJ)

- Metallization with Ag/Cu pastes ready for mass production
  ➔ at least 50% less Ag
- Approaches with 100% Cu pastes show high potential

High Temperature Metallization (TOPCon)

- Print (Ag paste) on Print (Cu pastes) approach promising
- Approaches with 100% Cu pastes still challenging

  ➔ Plating as alternative ?

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Copper Plating of High-Efficiency Solar Cells

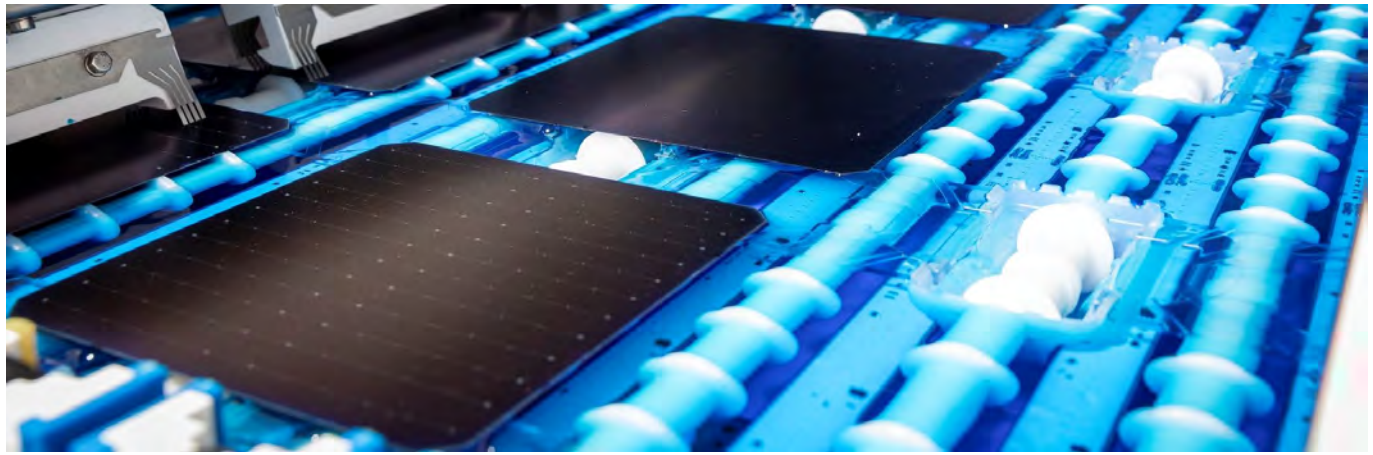
Fraunhofer ISE

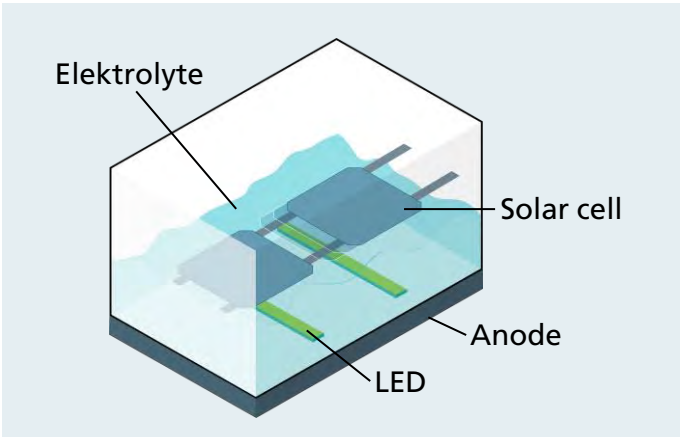
Electroplating of Copper Contacts

TOPCon Solar Cells with Plated Copper Metallization

Objective:

- TOPCon solar cells with plated Ni/Cu metallization
- First pilot fabrication of TOPCon solar cells with format M10 (182 mm x 182 mm) at Fraunhofer ISE



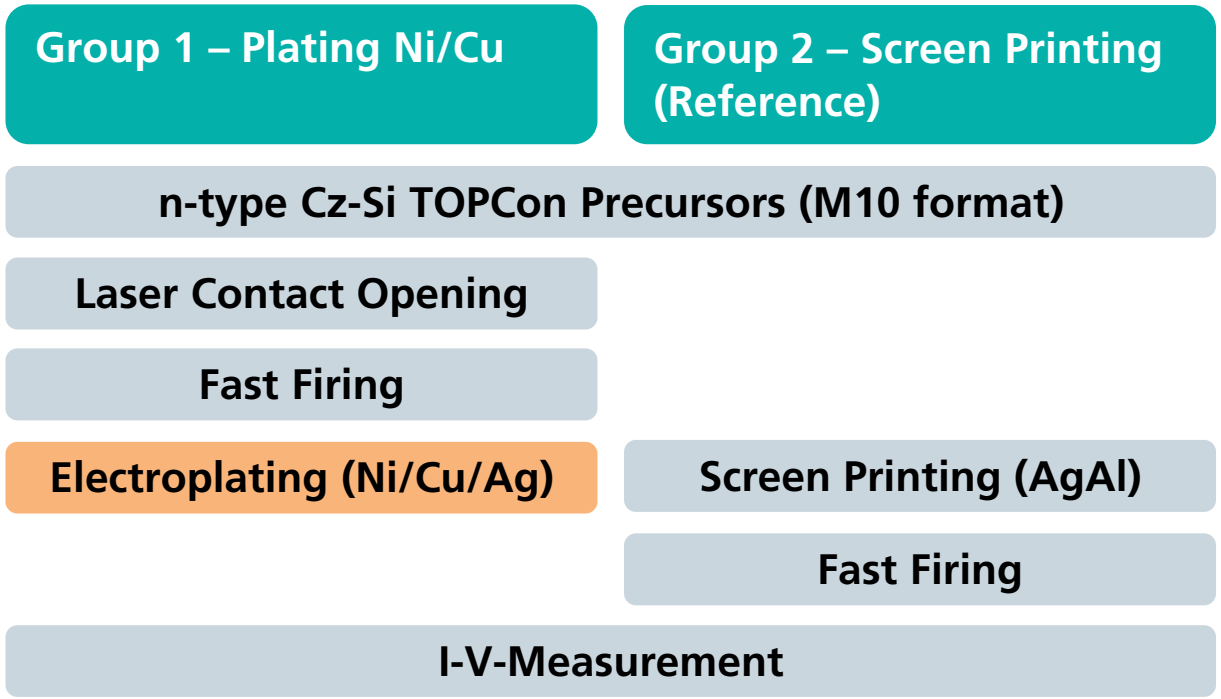


Electroplating of Copper Contacts

TOPCon Solar Cells with Plated Copper Metallization

Experimental:

- TOPCon precursors fabricated at Fraunhofer ISE, format M10 (182 mm x 182 mm)
- Industrial Cz-Si (n-type) Silicon wafers, base resistivity ρ_{Si} = 0.3-2.1 Ωcm
- Two experimental groups:
  - Group 1: Laser contact opening (LCO) + Electroplating (Ni/Cu/Ag) on front and rear side (RENA InCell Plating Device)
  - Group 2 (Reference): Screen printing (commercial AgAl and Ag paste)

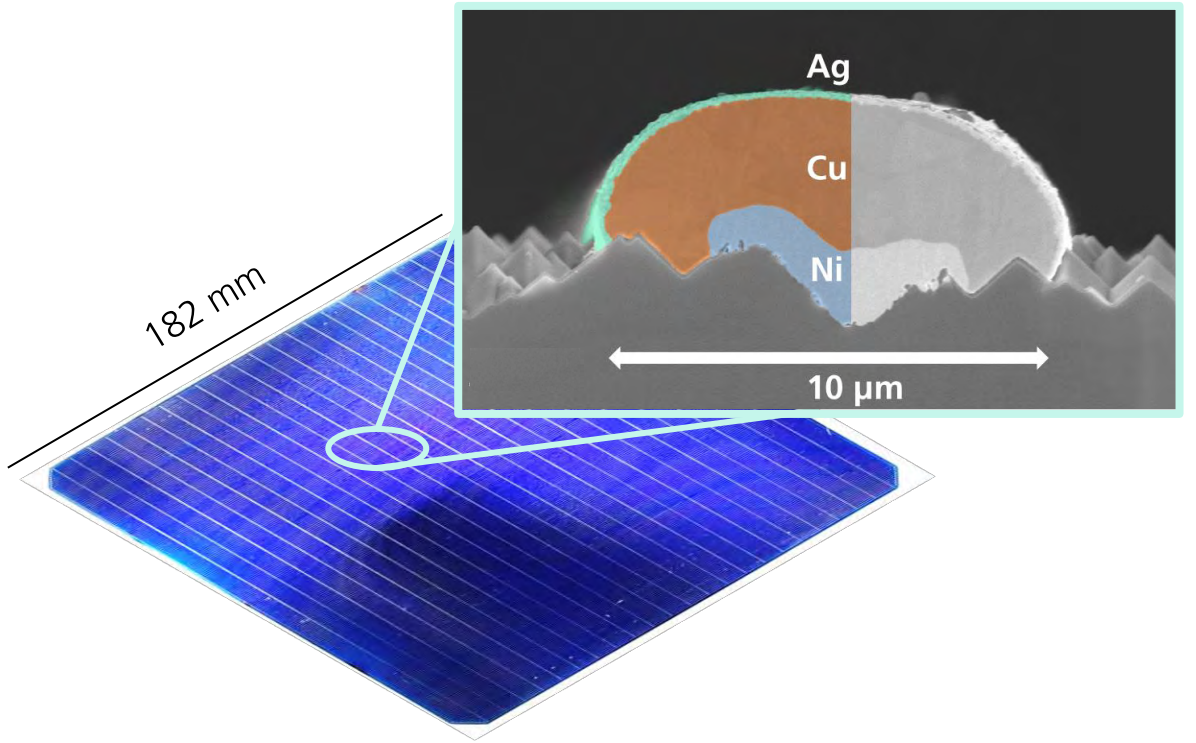


Electroplating of Copper Contacts

TOPCon Solar Cells with Plated Copper Metallization

Results:

- First TOPCon solar cells with format M10 completely fabricated at Fraunhofer ISE [25]
- Champion cell efficiencies:
  - Screen printing: η_{max} **= 24.0 %**
  - Electroplating: η_{max} **= 24.0 %**
- Silver capping: **~ 9 mg / cell (1 mg/W)**
  Ag reduction by **~93 %** to SP reference
- Perspective: Silver can be completely avoided by using Sn as capping layer



Group	η (%)	V_{OC} (mV)	j_{SC} (mA/cm²)	*FF* (%)
1 (PL)	24.0	708	41.0	82.7
2 (SP)	24.0	713	41.0	82.0

[25] https://www.ise.fraunhofer.de/en/press-media/news/2024/fraunhofer-ise-successfully-produces-topcon-solar-cell-with-24-percent-efficiency-in-m10-format.html

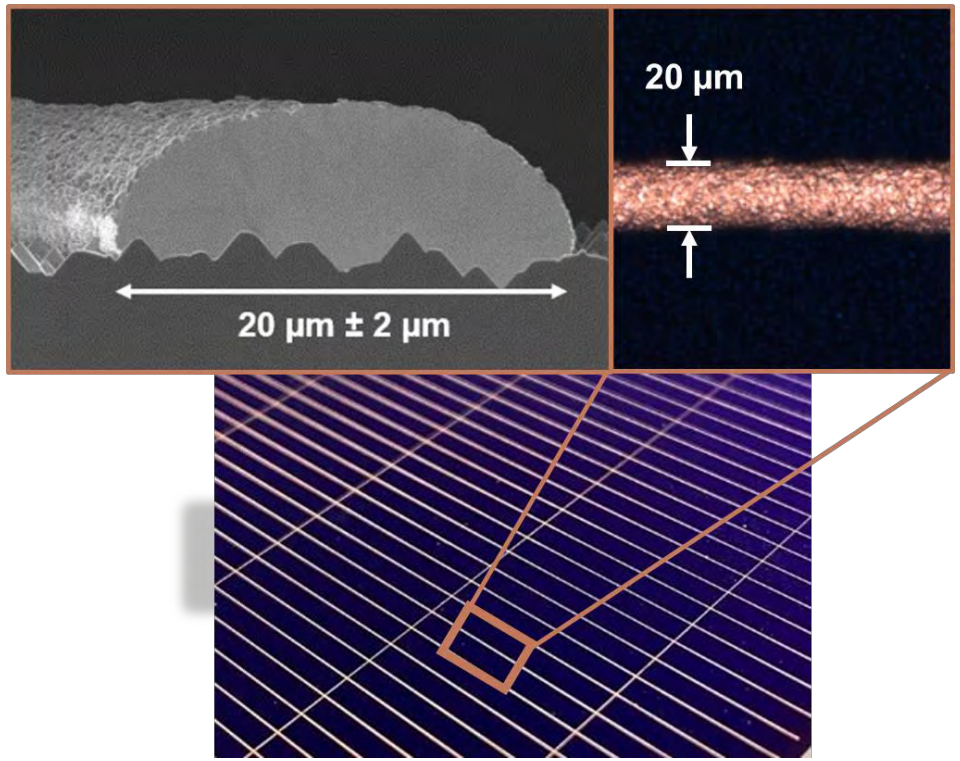
Electroplating of Copper Contacts

SHJ Solar Cells with Plated Copper Metallization

Results:

- Patented process for plated Cu contacts on SHJ
  - PVD metal masking → organic free
  - Laser patterning → narrow width, fast
  - Bifacial plating Cu/Sn → **Silver free**

- Succesfull piloting on industrial SHJ solar cells M2-G12 format
- Cost of ownership benefits compared to screen printing for SHJ
- Market Introduction:
  ➔ Fraunhofer ISE Spin-off: PV^{2+} GmbH



PV^{2+} Fraunhofer ISE

Mask and Plate Copper Contacts

Ultra-Low-Temperature Metallization Approach

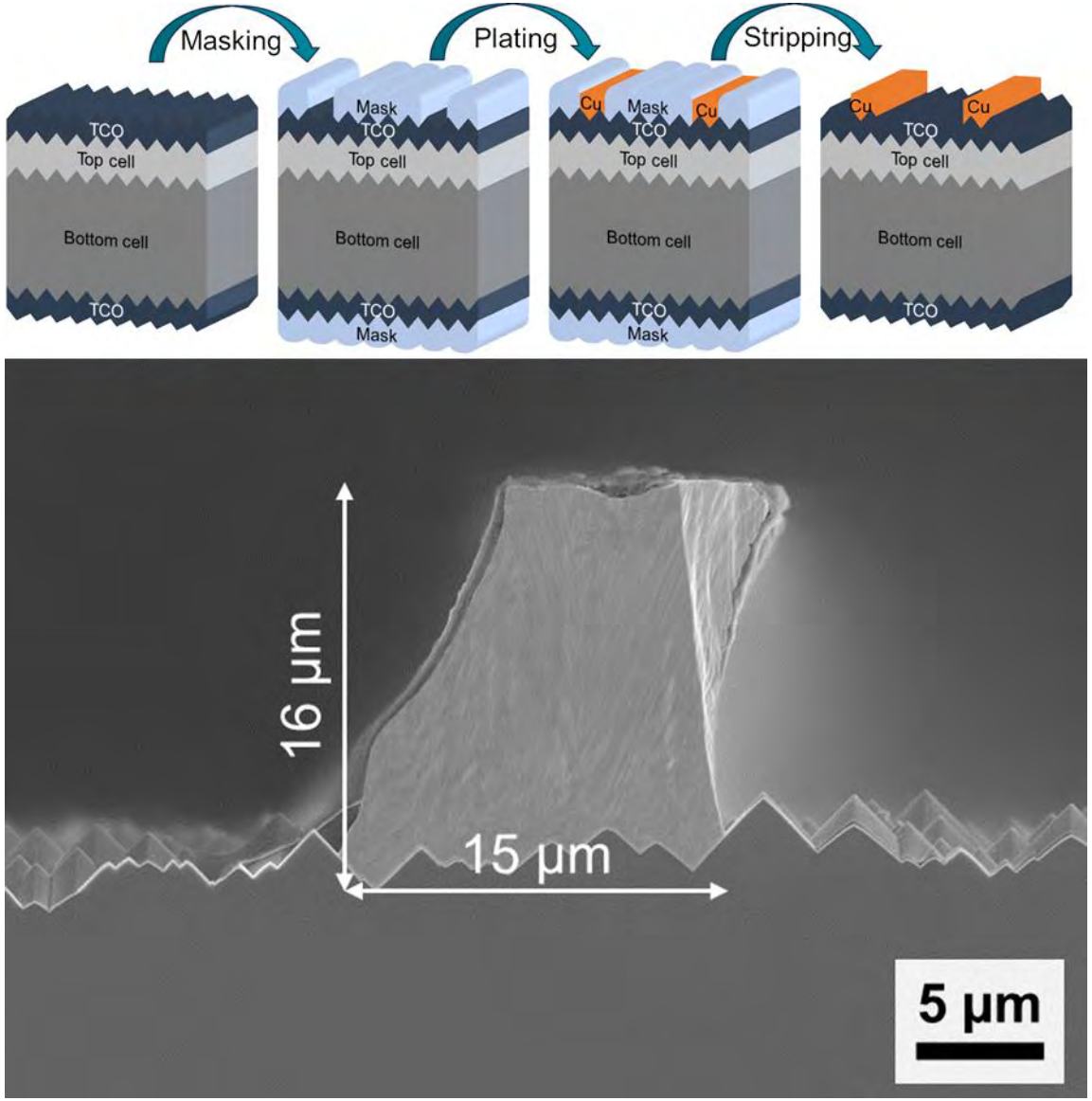
Approach

- Masking using hotmelt inkjet printing [26]
- Cu electroplating directly on ITO (no seed layer)
- Mechanical adhesion improved by pre-treatment
- Process temperature well below 100 °C

Process integration

- III-V//Si tandem solar cells with $\eta = 31.6$ % [27,28]
- Electrical performance on ITO and texture
  - (2.5 ± 0.1) µΩ cm finger resistivity
  - (0.4 ± 0.2) mΩ cm² contact resistivity

➢Transfer to SHJ and Pero-Si tandem (tbp.)



[26] J. Hermans et al. SNEC, 2015
[27] J. Schube et al., *Scientific Reports*, 2023.
[28] R. Keding et al., *EUPVSEC*, 2023.

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Technology Roadmap

Plating: How can we reduce / replace Silver?

foto from www.tradestation.com

Plating (SHJ, TOPCon)

Fraunhofer ISE

Technology Roadmap

Plating: How can we reduce / replace Silver?

foto from www.tradestation.com

Plating (SHJ, TOPCon)

- Ni/Cu(/Ag) Plating for TOPCon:
  - almost Ag free
  - and ready for mass production
- Cu plating for SHJ / Tandem:
  - high potential demonstrated
  - process upscaling is ongoing

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Copper as Cost-Effective Alternative to Silver

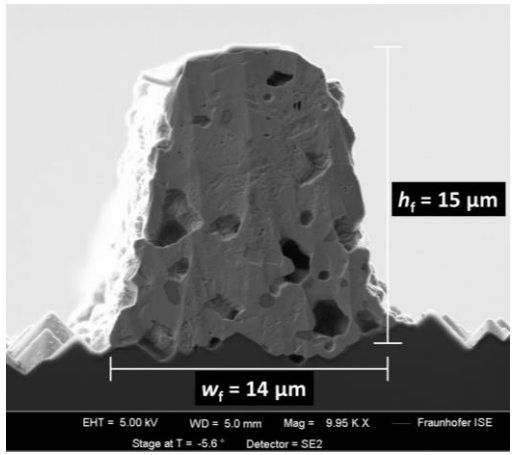
Summary and outlook

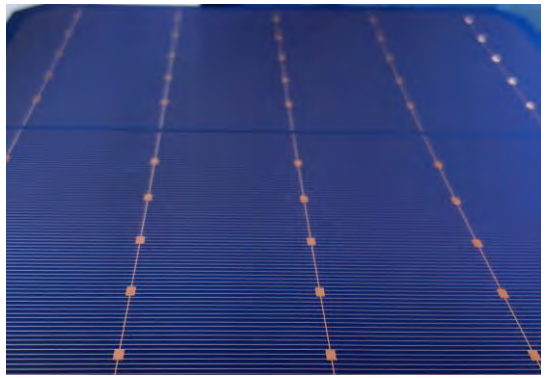
Summary & Outlook:

- There is a strong need to reduce / replace silver
- Different printing technologies allow ultra fine line contacts with less silver consumption
- Ag/Cu pastes replace Ag pastes for low temperature metallization step by step
- Cu pastes are a promising alternative to Ag pastes for low and high temperature metallization
- Cu plating is ready for production especially for TOPCon solar cells

➢ **Cu will replace Ag step by step in the future**

➢ **Other metals (e.g Al) will also play a role**





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Supported by:

Federal Ministry for Economic Affairs and Climate Action

on the basis of a decision by the German Bundestag

Thank you for your attention!

Dr. Florian Clement
Fraunhofer ISE
Phone: +49 761 4588 2229
florian.clement@ise.fraunhofer.de

Many thanks to:

all co-workers, R&D and industry partners, funding agencies, …

Further information:

link to Fraunhofer ISE contributions of the 41st EU PVSEC