Bifacial TBC polyZEBRA Solar Cell Meets PV2+'s Copper Plating Metallization

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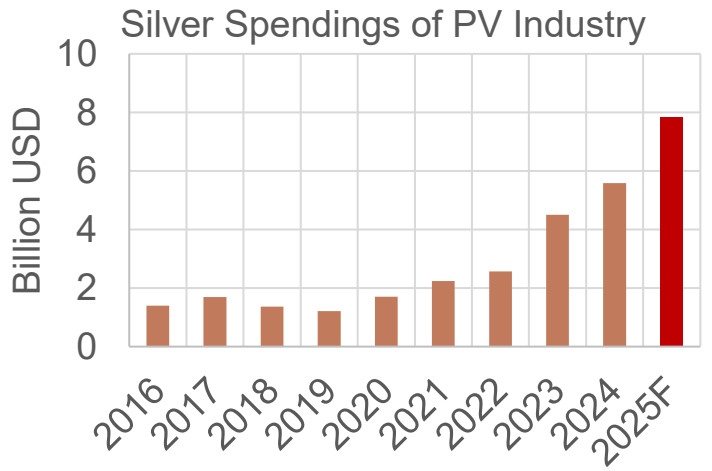
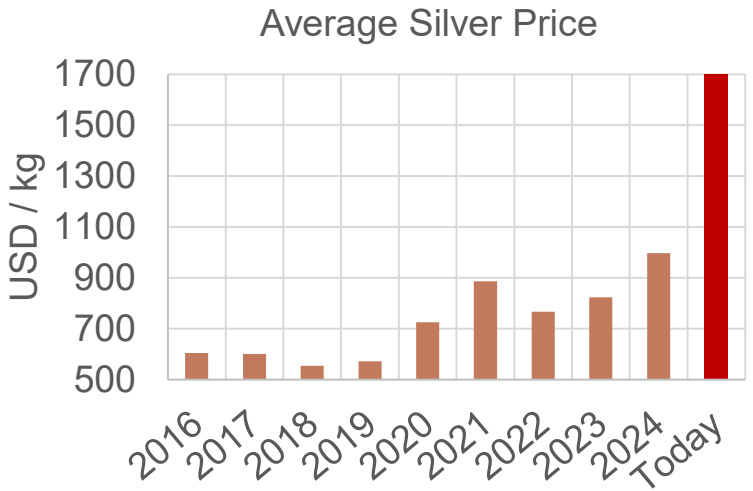
[1] PV2+ GmbH, [2] ISC Konstanz, [3] Fraunhofer ISE

13th Metallization & Interconnection Workshop
Berlin, Oct. 20, 2025

Why Cu ?

- Silver problematic
  - PV industry's spendings for silver are increasing rapidly
  - PV industry's share of total silver demand increasing
  - Deficit of silver supply over demand for 4th consecutive year
  - High silver price is expected to rise further (60% in one year)
  - Substituting silver offers greatest leverage for cost reduction in PV manufacturing





Data from World Silver Survey 2025
CPIA 2024

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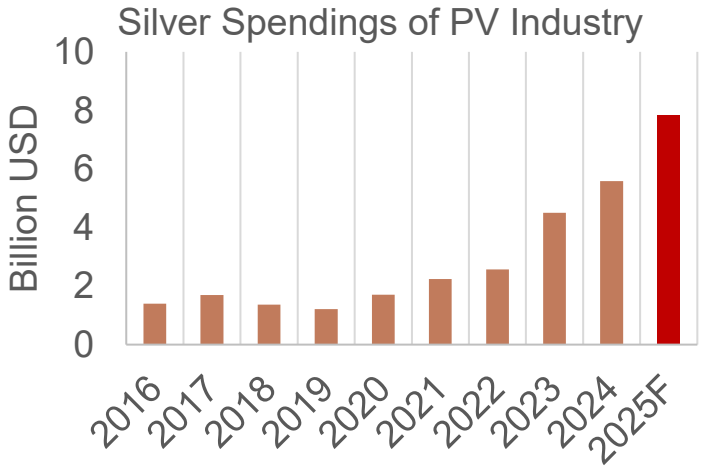
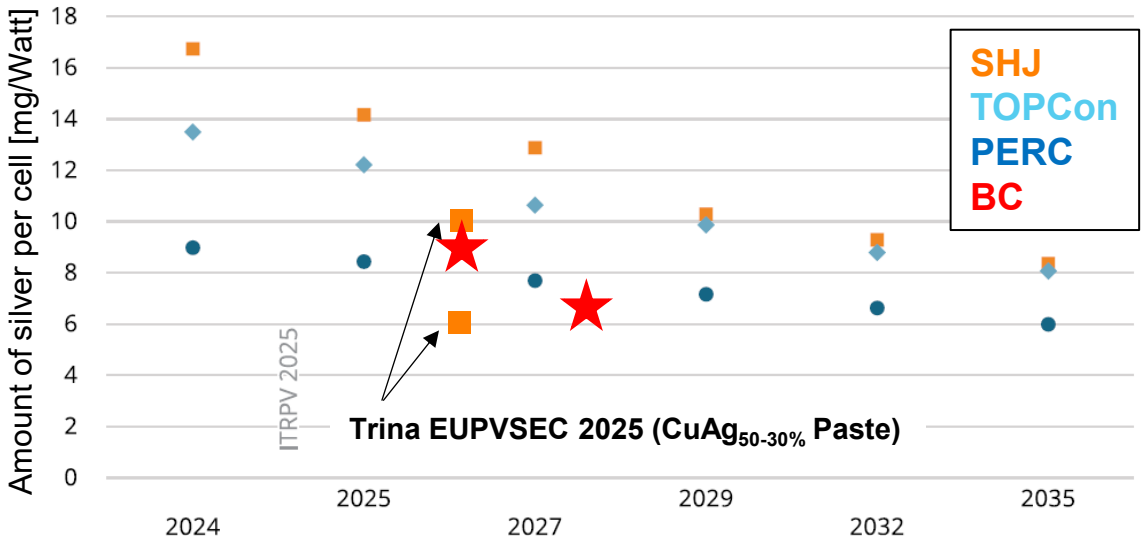


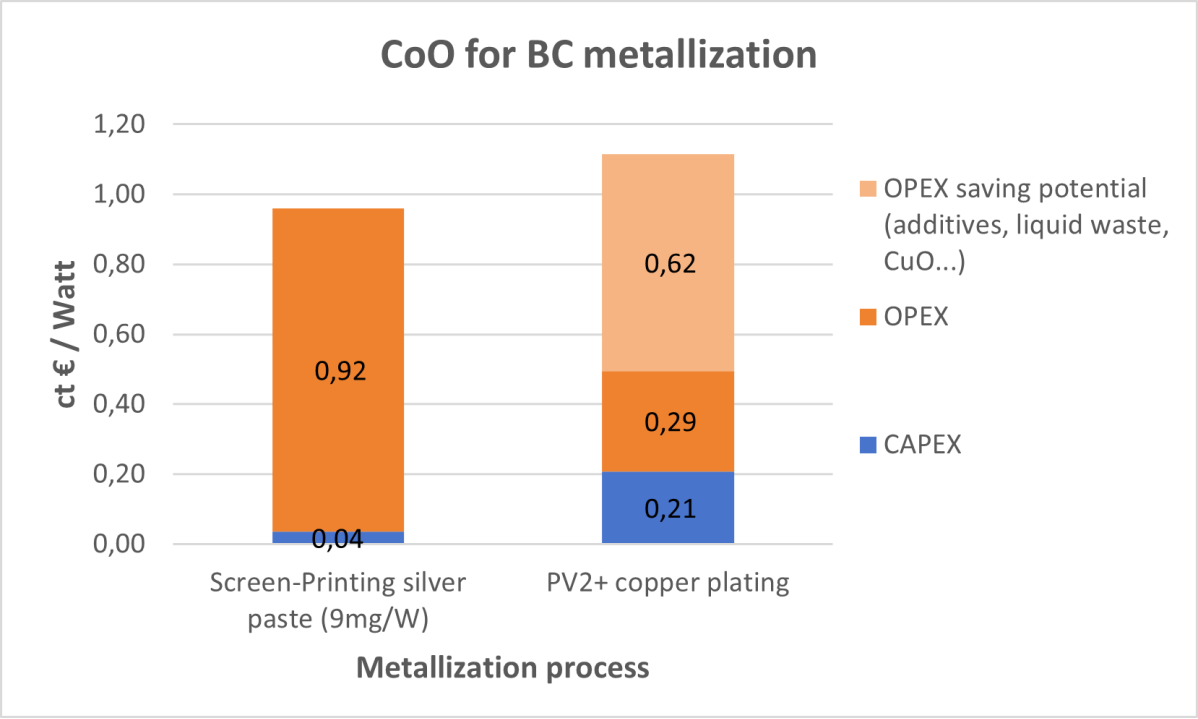
- In 2025: Silver & cell structure
  - TOPCon ≈ 7-10 mg/W
  - SHJ ≈ 6.4 mg/W (-0.1% in efficiency)
  - **BC ≈ 9 mg/W**
    - → Direct plating (electroless Ni + electroplated Cu) [1]
    - → Electroplating into organic resist mask (industrial scale)
    - → PV2+'s electroplating with dielectric mask



[1] *K. Gensowski et al., MIW (2019)*

Cost of Ownership for BC

- Silver price today >1500 USD/kg
  - 9mg/W Ag screen-printing metallization = 0.96 ct€/Wp
  - “Best guess” for PV2+ plating process 1.12 ct€/Wp



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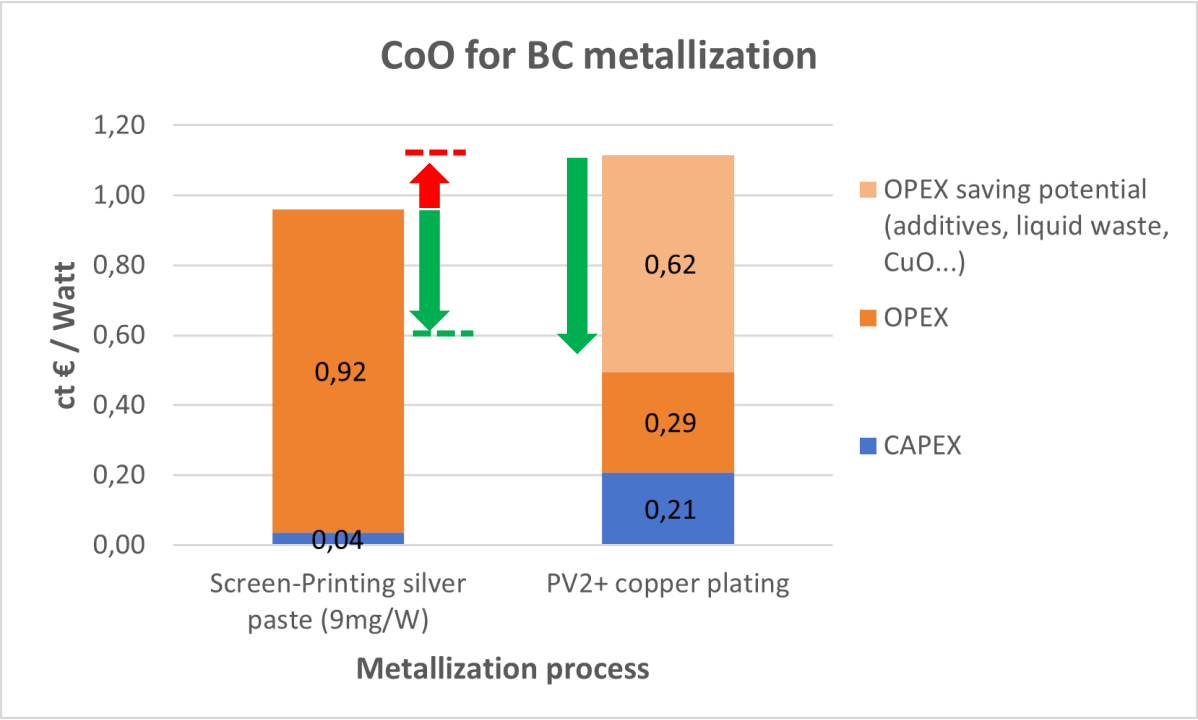
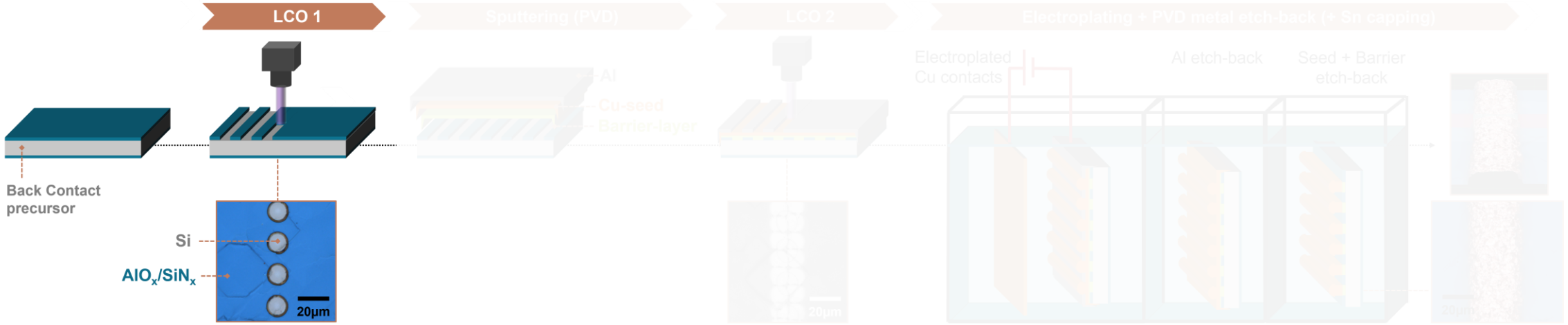
  - 9mg/W Ag screen-printing metallization = 0.96 ct€/Wp
  - “Current guess” for PV2+ plating process 1.12 ct€/Wp

- CoO simulation
  - Ag = 1800 USD/kg
  - Ag = 2250 USD/kg with reduction to 7mg/W
  - Ag ≤ 1400 USD/kg with reduction to 7mg/W

  - PV2+ plating optimization < 0.6 ct€/Wp

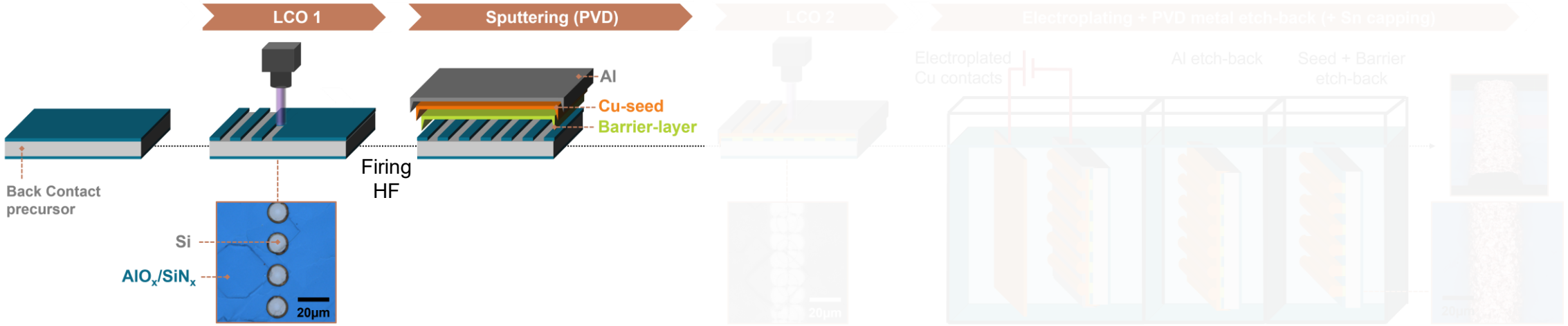


Process Sequence for BC



- Layout easy to adapt
- Passivation damage-free

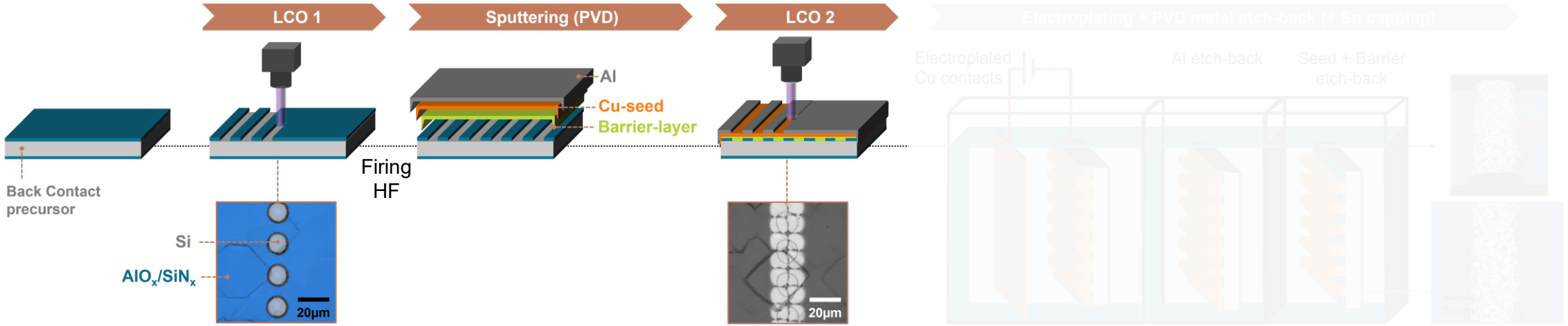
Process Sequence for BC



- Layout easy to adapt
- Passivation damage-free

- One sputtering equipment
- Thin metal layers
  - Al mask ≤ 50 nm
  - Seed/barrier ≤ 100 nm
- Edge protected by Al

Process Sequence for BC



- Layout easy to adapt
- Passivation damage-free

- One sputtering equipment
- Thin metal layers
  - Al mask ≤ 50 nm
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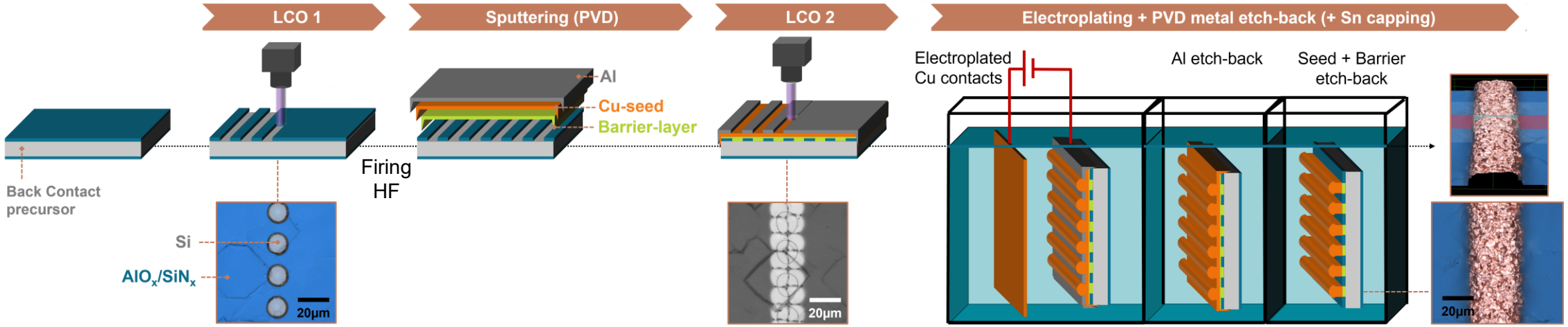
- 1 step (layout easy to modify)
- Passivation damage-free

Process Sequence for BC



- Layout easy to adapt
- Passivation damage-free

- One sputtering equipment
- Thin metal layers
  - Al mask ≤ 50 nm
  - Seed/barrier ≤ 100 nm
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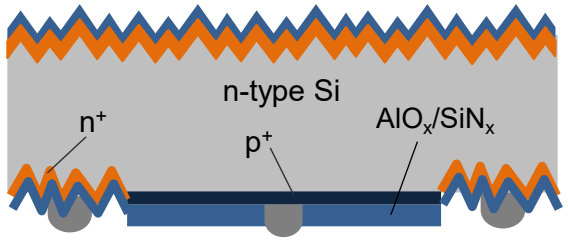
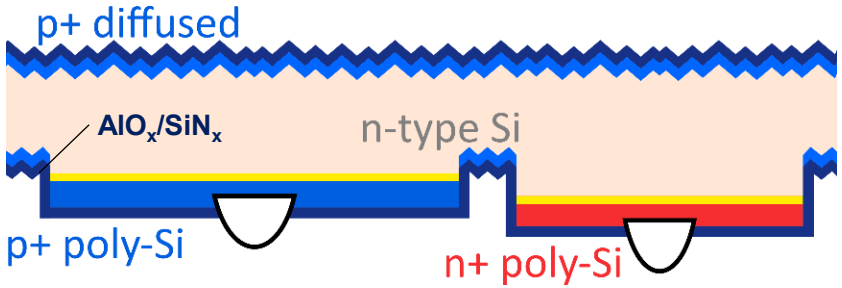
- Masking due to native AlO_x
- Homogeneous growth on p+/n+
- Metals recycled after wet etching
- No organic pollution of waste water

BC Solar Cells

- ZEBRA
  - Large-area IBC cells with diffused junctions [2]
  - Doping and depth optimized for screen-printing



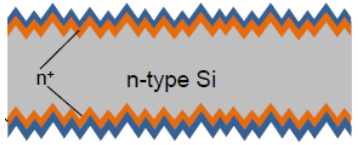
- polyZEBRA
  - Large-area IBC cells with polysilicon junctions [3]
  - Doping and depth optimized for screen-printing

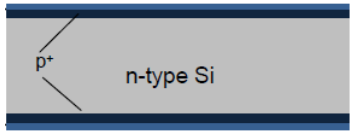


[2] *R. Kopecek et al., IEEE PVSC (2020)*
[3] *J. Linke et al., EUPVSEC (2024)*

Si/PVD Metal Stack

- Wide variety of barrier layer studied in literature
  - Al alloy, Ni, TiW, Mo, W…
    - → Barrier layer against Cu diffusion
    - → Enhanced back-side light reflection





- TLM study to define PVD stack
  - Symmetric lifetime samples with diffused p+/n+ (Zebra-like)
  - 2+2 different barrier/seed-layers

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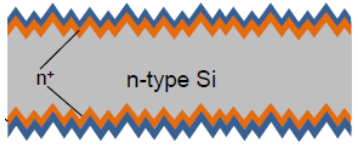

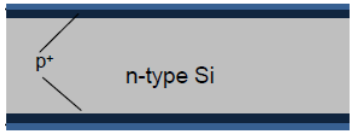

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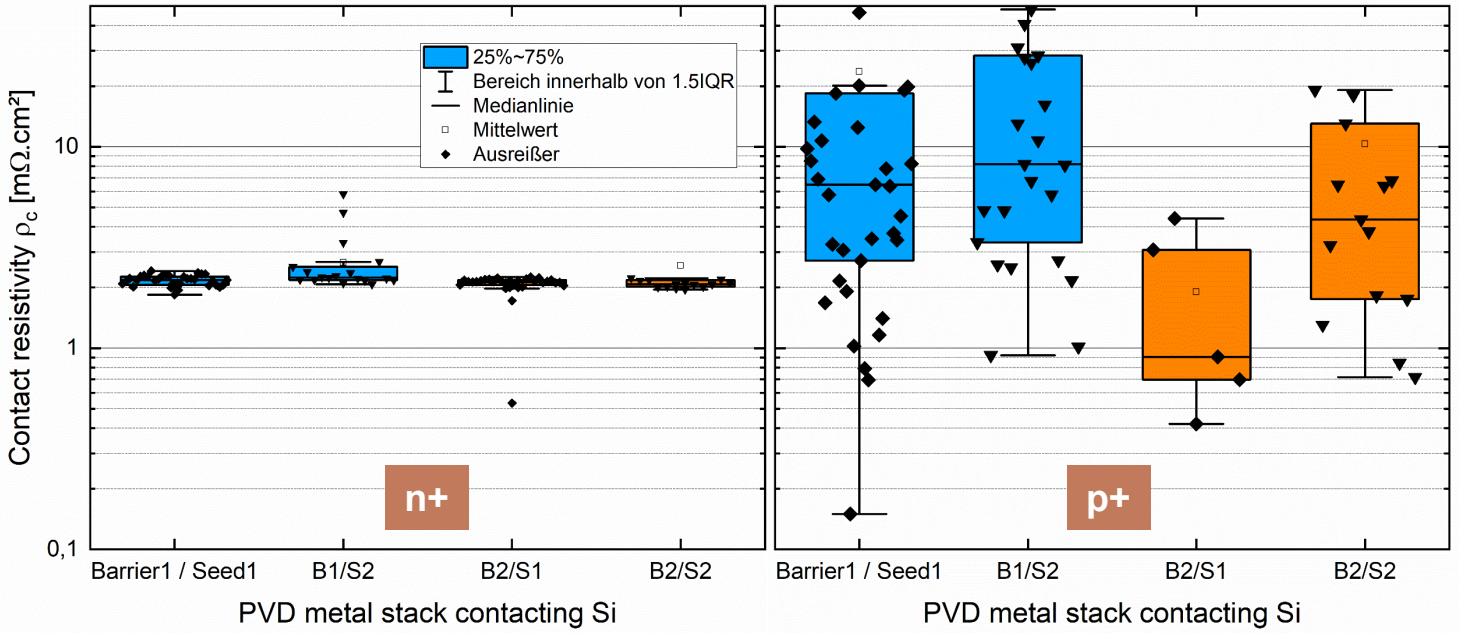
  - 2+2 different barrier/seed-layers

  - → Textured n+: $\rho_c \approx$ 2-3 mΩ.cm²
  - → Flat p+: $\rho_c \approx$ 1-4 mΩ.cm² (barrier 2)



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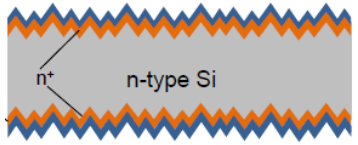
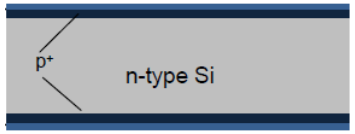
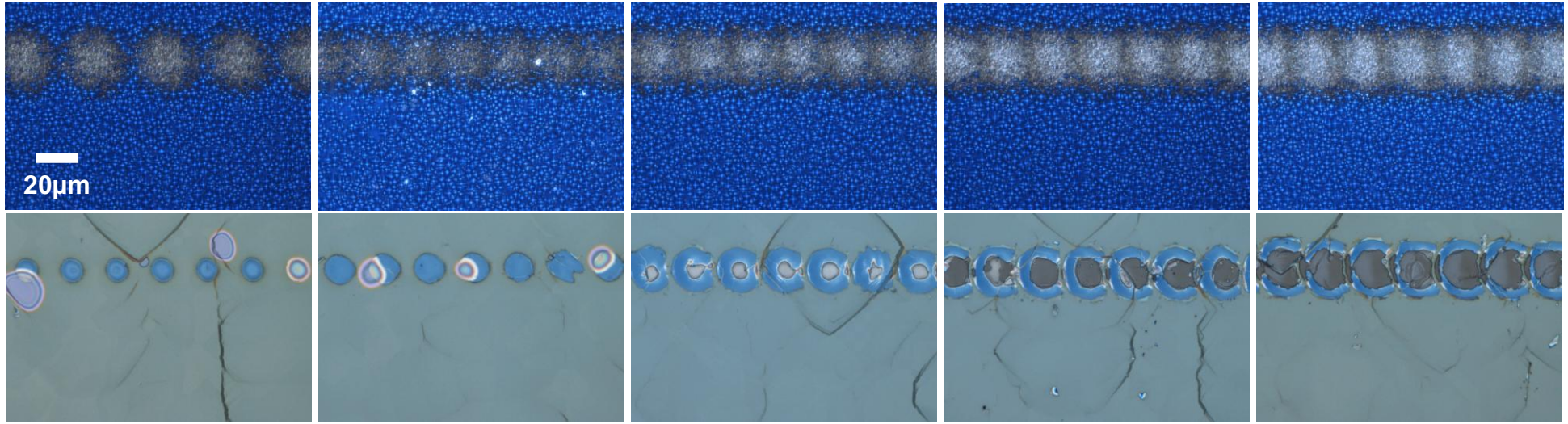




- TLM study to define PVD stack
  - Symmetric lifetime samples with diffused p+/n+ (Zebra-like)
  - LCO1 variation



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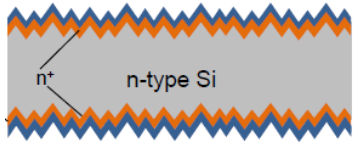
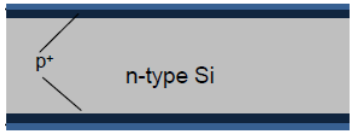
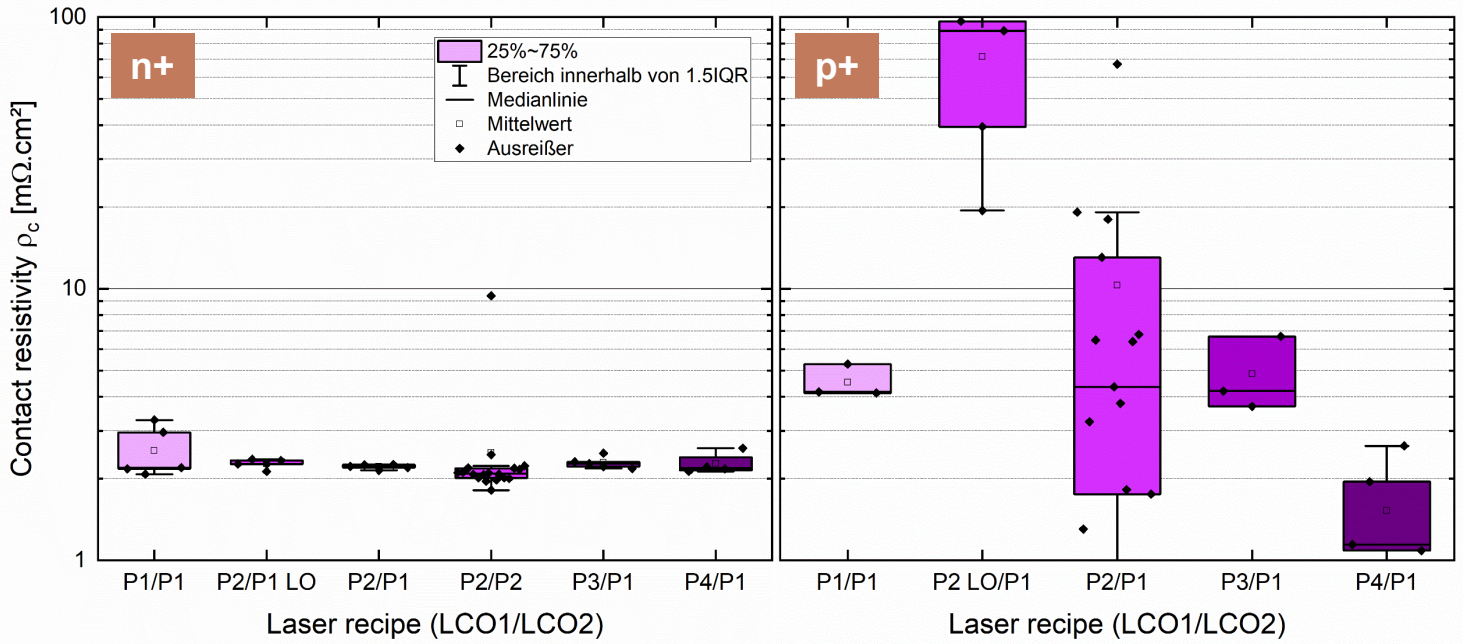




- TLM study to define PVD stack
  - Symmetric lifetime samples with diffused p+/n+ (Zebra-like)
  - **Barrier2+Seed2 (cheaper)**
  - **LCO1/LCO2 variation (power, overlap)**

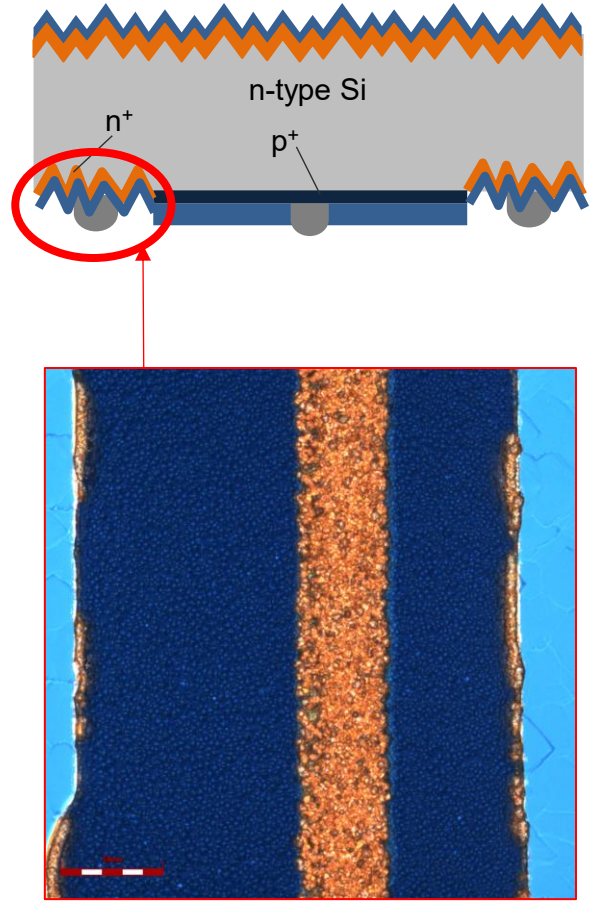
  - → Textured n+: small impact on ρ_c
  - → Flat p+: $\rho_c \approx 1$ mΩ.cm² for strong LCO1

  - After contact annealing (≈ 350°C)
  - → ρ_c down to 0.2 mΩ.cm² for p+



Plating Mask

- Sputtered Al masking quality on textured/flat surface already demonstrated [4]
  - → SiN_x not well covering steep wall between p+/n+ regions
- Standard sputtered mask & electroplating
  - → Parasitic Cu deposition



[4] *T. Hatt et al., Sol.RRL (2023)*

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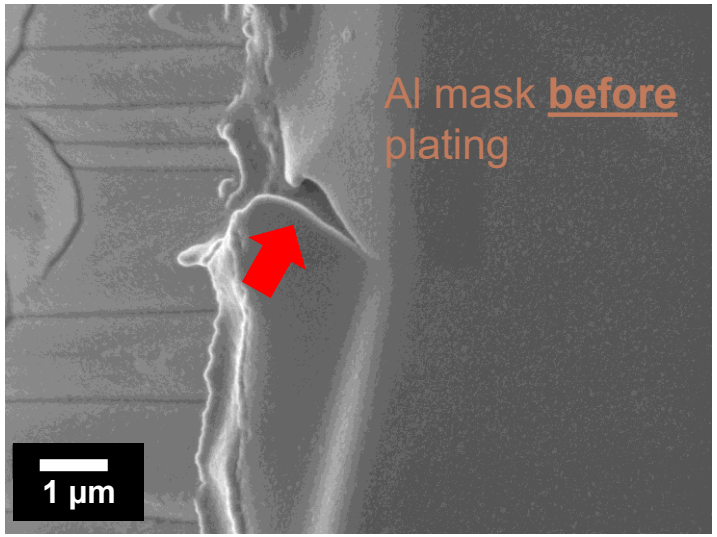
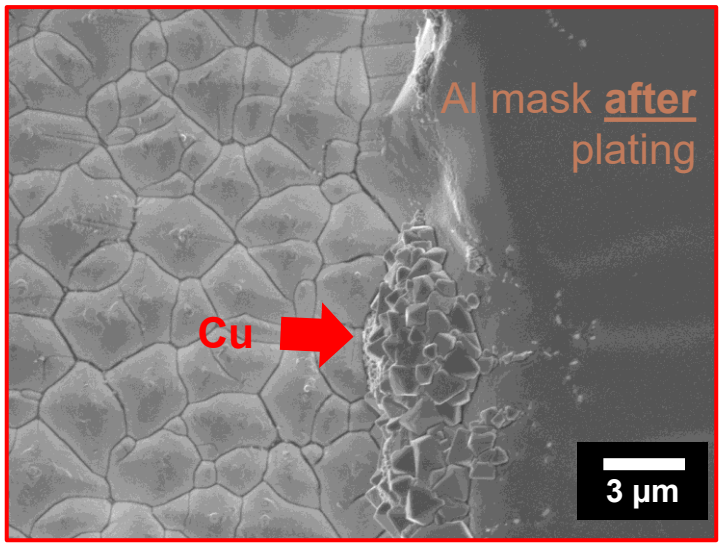
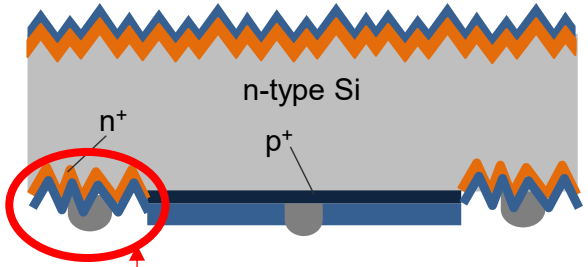
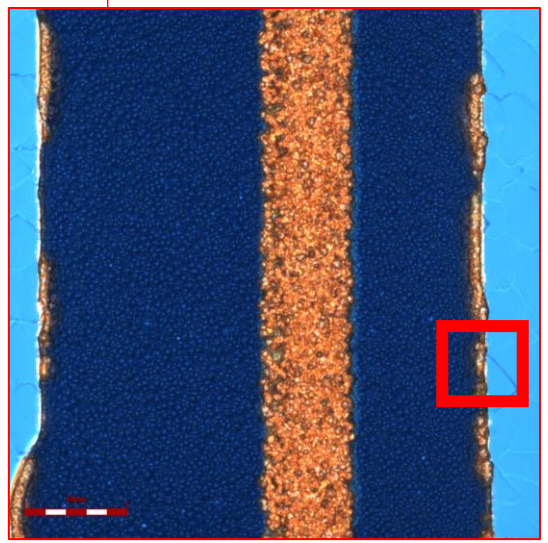
- Standard sputtered mask & electroplating
  - → Parasitic Cu deposition
  - → Si and/or PVD-seed exposed?









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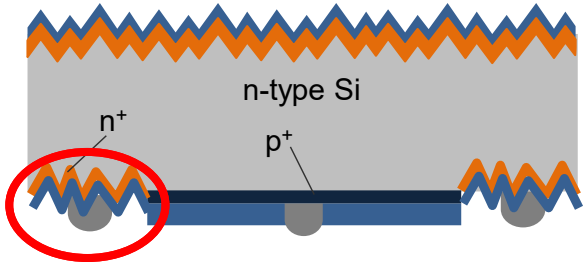
Plating Mask

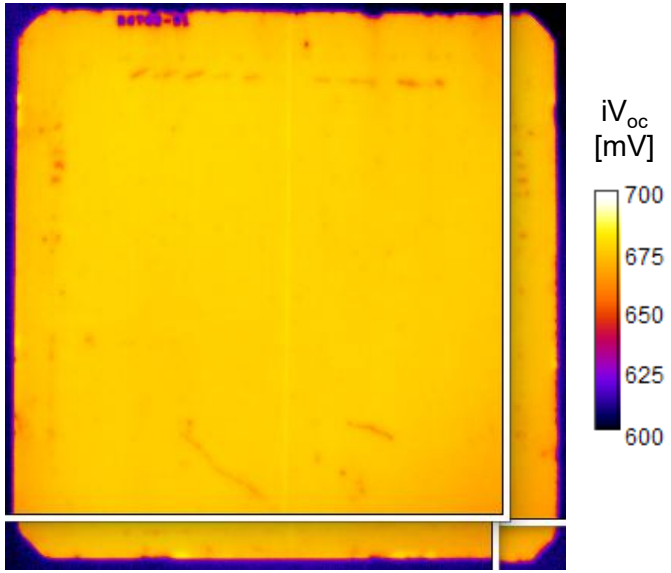
- Optimization of mask and electroplating settings
  - Ultrathin ALD coating
  - PVD sputtering
  - Electroplating settings (pulses, current density…)

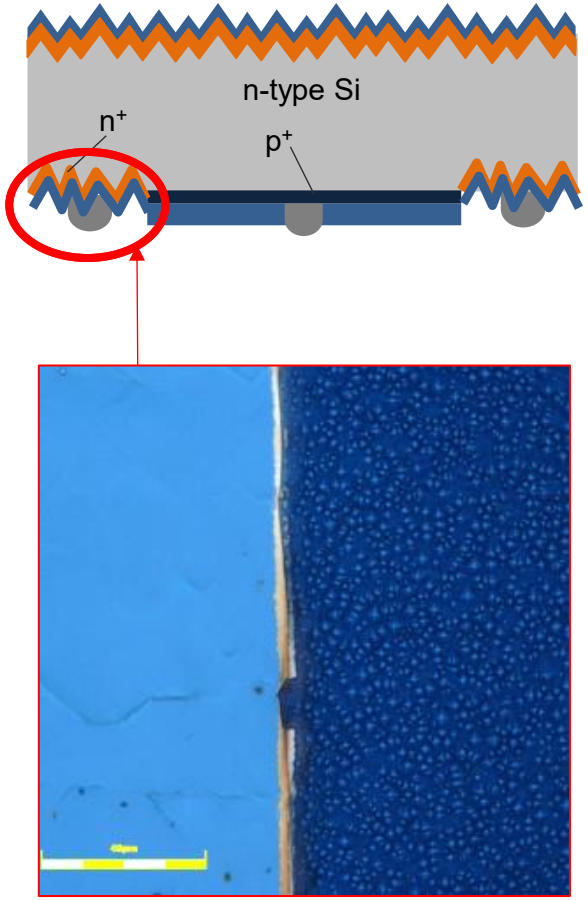


Plating Mask

- Optimization of mask and electroplating settings
  - Ultrathin ALD coating
  - PVD sputtering
  - Electroplating settings (pulses, current density…)
    - → **Large process window identified**

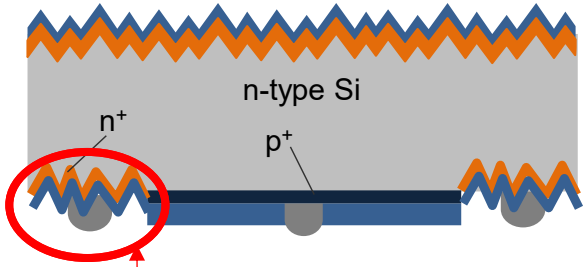
PL after metallization

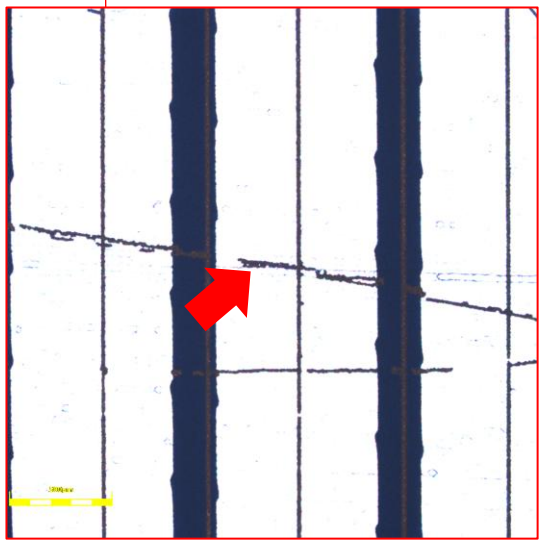




Plating Mask

- R&D Labs → additionnal challenges for plating
  - ISC Firing → PV2+ PVD (→ ISC LCO2 →) PV2+ Etch-back → ISC IV
  - All handling, scratching, particles etc., impact the electrodeposition…



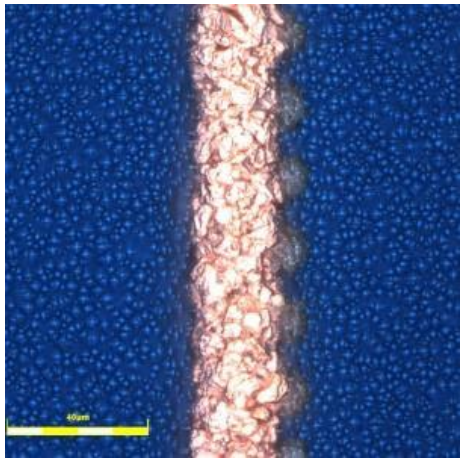


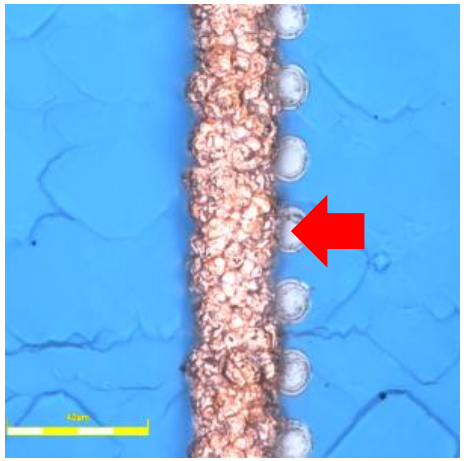
Performance on Cells

- R&D Labs → additionnal challenges for plating

- ZEBRA solar cell
  - Plated Cu contacts: $w_f \approx 25\mu m$ $h_f \approx 9\mu m$
  - Line resistance ≈ 0.8 Ω/cm
  - Performance mostly limited by pFF and FF (LCO1/LCO2 alignement difficulties in the lab)

Cell	Eta [%]	V_{oc} [mV]	j_{sc} [mA/cm²]	FF [%]	pFF [%]
B1-059	9.9	653.0	34.3	44.2	73.4





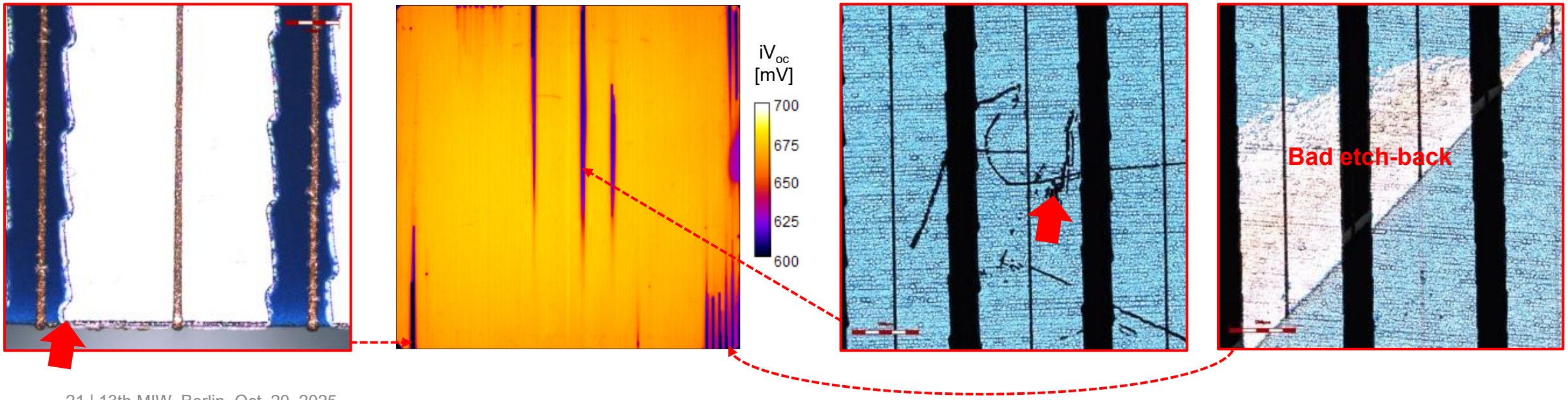
LCO1/LCO2 alignement issues

Performance on Cells

- R&D Labs → additionnal challenges for plating

- ZEBRA solar cell
  - Plated Cu contacts: $w_f \approx 25\mu m$ $h_f \approx 9\mu m$
  - Line resistance ≈ 0.8 Ω/cm
  - Performance mostly limited by shunts

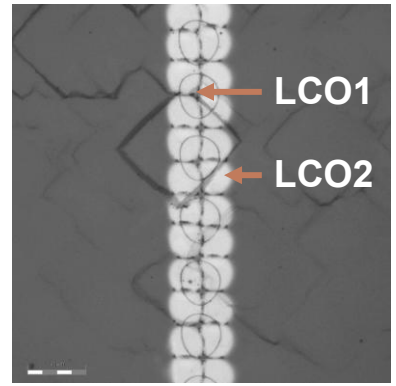
Cell	Eta [%]	V_{oc} [mV]	j_{sc} [mA/cm²]	FF [%]	pFF [%]
B1-059	9.9	653.0	34.3	44.2	73.4
B1-059 cut	16.6	662.0	41.0	60.9	77.9

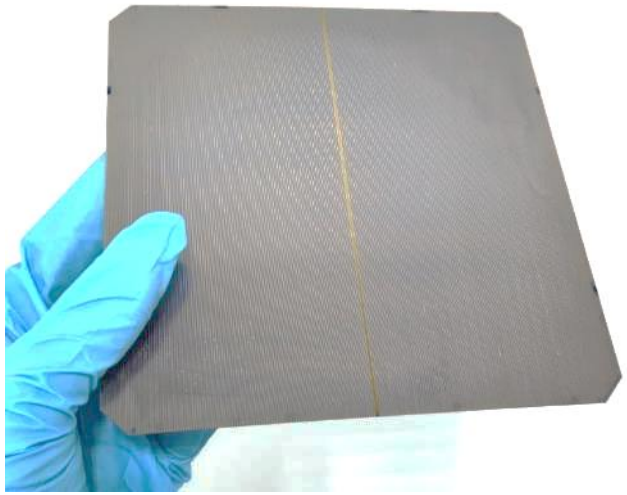


Copper for TBC

- Further developments on mainstream polySi contacts

- polyZEBRA solar cell
  - Designed for screen-printing contacts (doping, thickness…)
  - LCO1/LCO2 alignement improvement & wider contacts
  - Deposition of the masking layer further tuned





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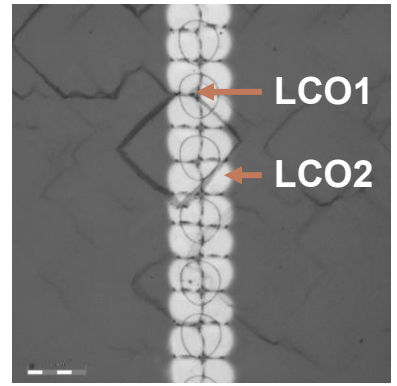
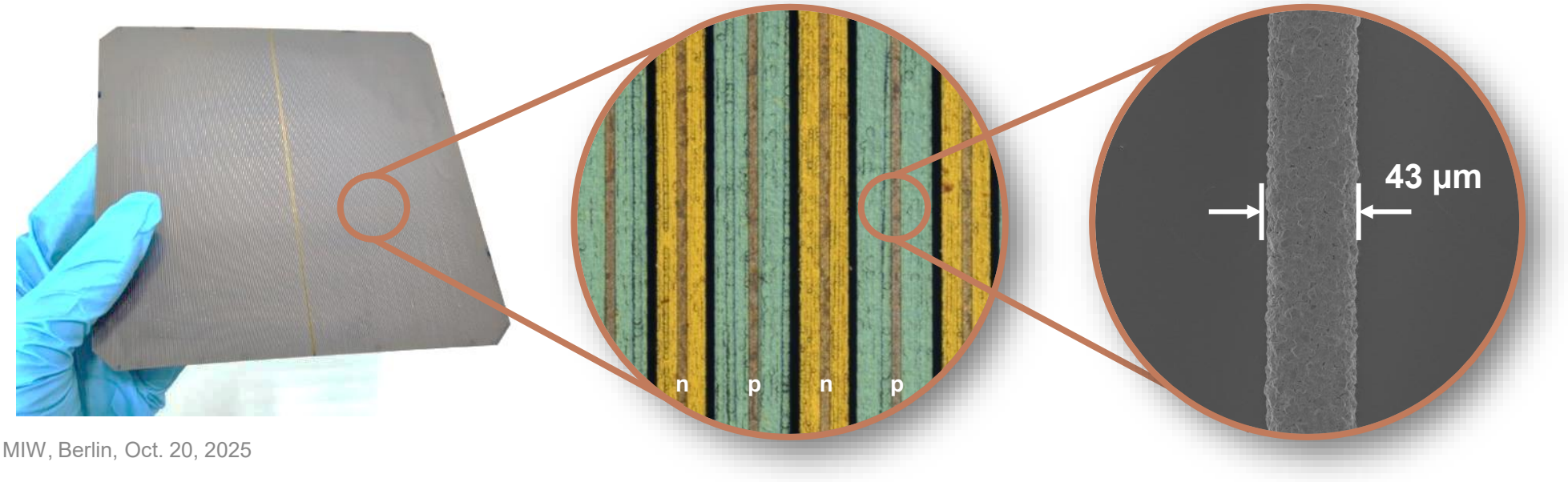


- polyZEBRA solar cell
  - Designed for screen-printing contacts (doping, thickness…)
  - LCO1/LCO2 alignement improvement & wider contacts
  - Deposition of the masking layer further tuned
  - Plated Cu contacts: $w_f \approx$ 45-55µm $h_f \approx$ 8-10µm
  - Line resistance ≈ 0.3 Ω/cm



Performance on Cells

- polyZEBRA solar cell
  - Designed for screen-printing contacts
  - Reasonable efficiency as proof of concept

Cell	Eta [%]	V_{oc} [mV]	j_{sc} [mA/cm²]	FF [%]	pFF [%]
SP Ref. (Ag)	23.7	705.1	41.2	81.7	82.9
Cell1	21.9	710.0	40.8	75.7	78.4

Performance on Cells

- polyZEBRA solar cell
  - Designed for screen-printing contacts
  - Reasonable efficiency as proof of concept
    - → still limited by shunts (scratches)
    - → Not a problem on industial pilot line

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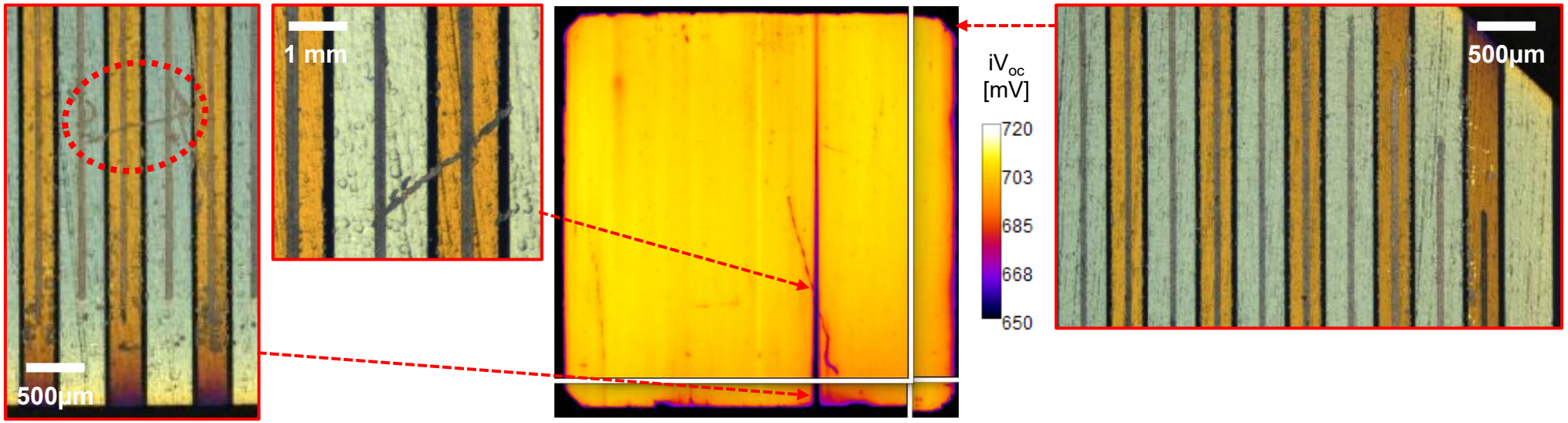
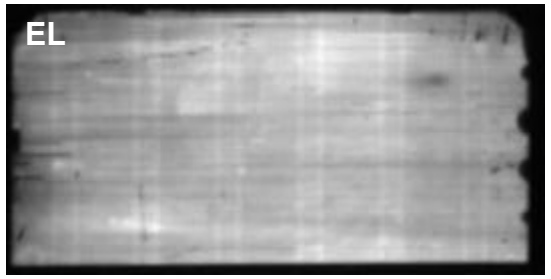
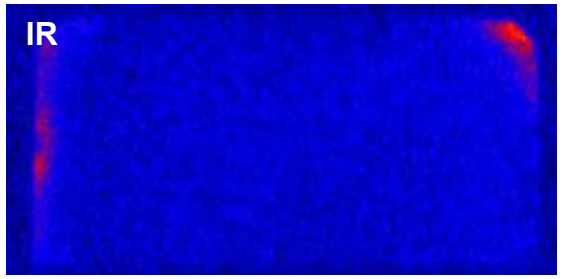


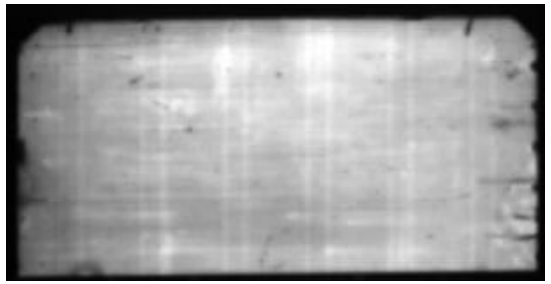
Performance on Cells

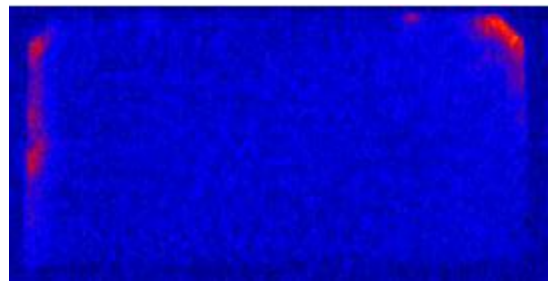
- polyZEBRA solar cell
  - Designed for screen-printing contacts
  - Reasonable efficiency as proof of concept
    - → Further improved on half-cells after removing main shunted area
  - Remaining limitations
    - → Still some shunts
    - → LCO layout to improve further
    - → Optimization of the cell structure for plating

Cell	Eta [%]	V_{oc} [mV]	j_{sc} [mA/cm²]	FF [%]	pFF [%]
SP Ref. (Ag)	23.7	705.1	41.2	81.7	82.9
Cell1	21.9	710.0	40.8	75.7	78.4
Cell1 half	**22.6**	**711.7**	**40.4**	**78.6**	**81.1**
Cell2 half	**22.7**	**711.8**	**40.3**	**79.1**	**81.0**



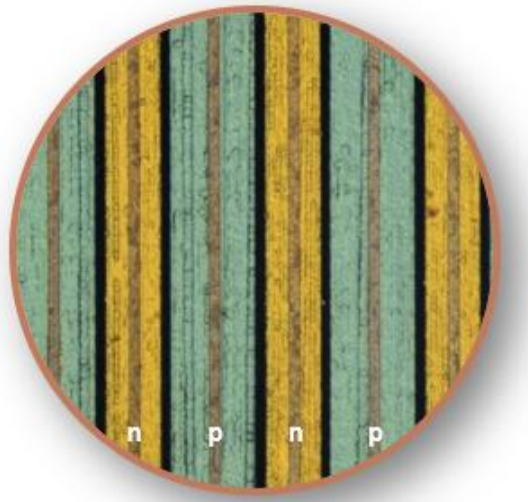




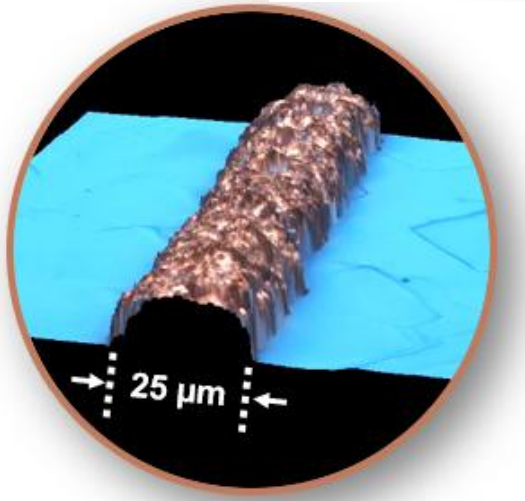


Conclusion

- Proof of concept of PV2+‘s Cu plating metallization on polyZEBRA solar cells
  - High cost savings potential to reach metallization < 0.6 ct€/Wp
  - ρ_c < 1mΩ.cm² and good adhesion with PVD metal seed-layer
  - Homogeneous electroplating current distribution on p+/n+ polarity
  - No use of expensive organic resist causing costly wastewater treatment
  - Promising performance demonstrated for highly bifacial TBC

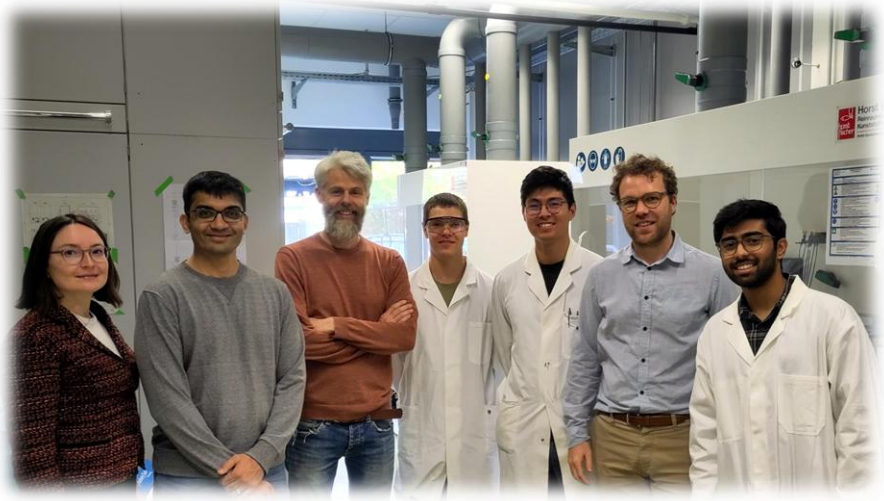


- Pleasant PV collaboration in Baden-Würtemberg
  - InvestBW funding within the project „LOGIC“ (contract no. BW1_4206/01)

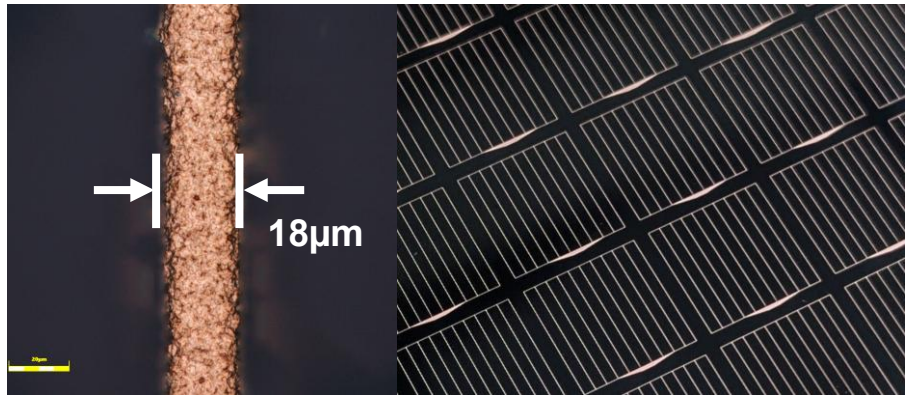


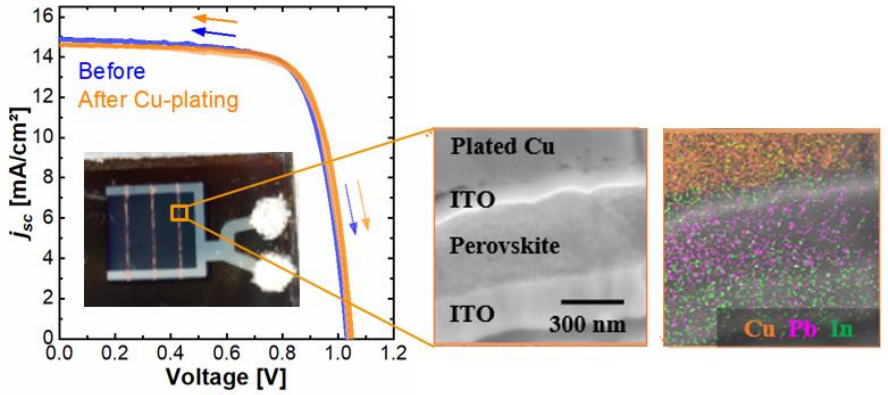
Outlook

- PV2+ team advancing to transfer its metallization approach to solar cell manufacturers (BC, HJT…)
  - HJT → efficiency comparable to Ag screen-printed reference reached
  - HJT modules → passed IEC DH & TC



- Further developments for next generation solar cells ongoing
  - 28.0% efficiency reached on dual-junction III/V solar cell





Abundant Copper for Solar Power in Abundance

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