Challenges and Perspectives for the TCO and Metal Electrodes in Perovskite-Silicon Tandem Solar Cells: Performance and Scalability

40 YEARS
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#CreatingTheEnergyFuture

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10th Metallization and Interconnection Workshop 2021

16th November 2021

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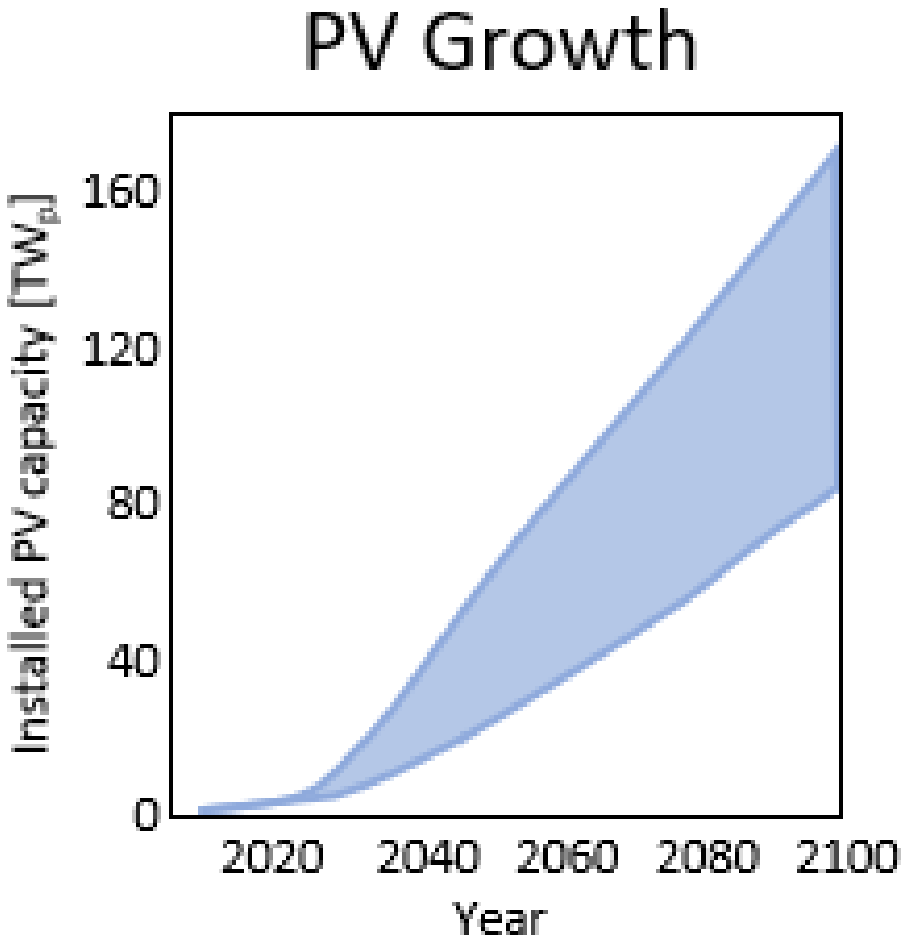
Motivation: PV Will/Must Reach Terrawatt Scale in ~10 Years

Production Landscape Has to Adapt to Allow Massive Grows

- Predicted PV grows[1]
  - 2030: ~1 - 2 TW_p per year
  - 2100: ~3 - 9 TW_p per year



[1]J.C. Goldschmidt et.al. (2021), DOI: 10.1039/d1ee02497c

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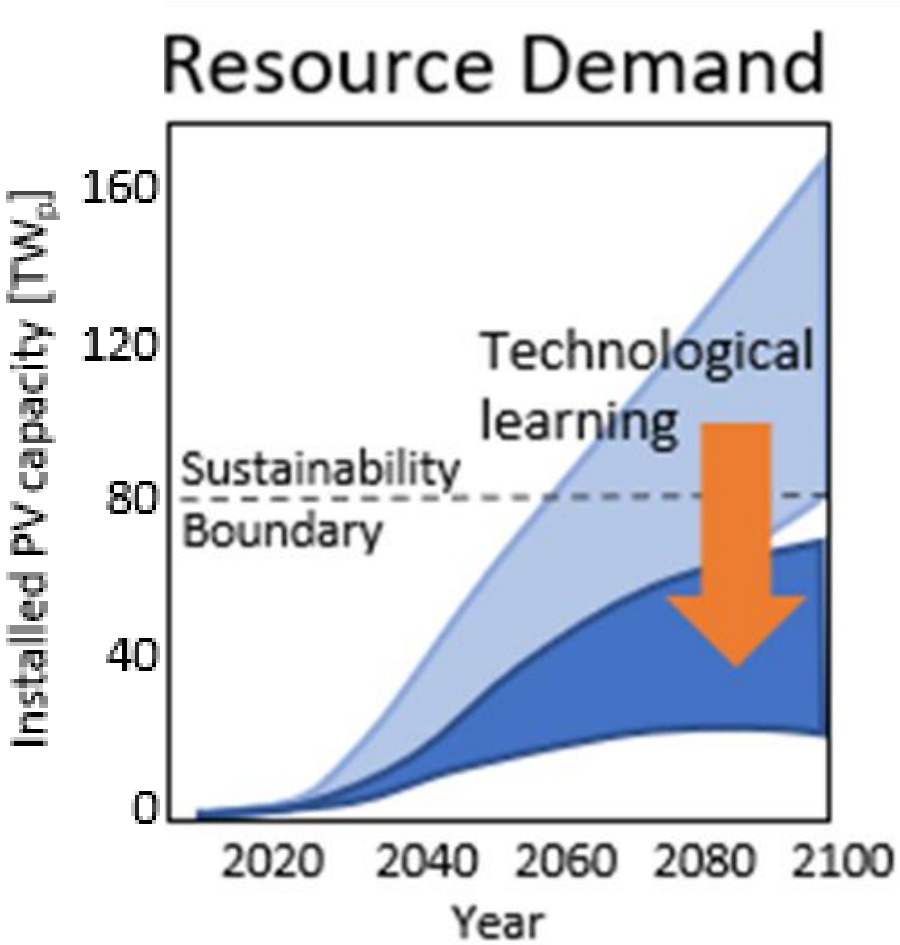
Motivation: PV Will/Must Reach Terrawatt Scale in ~10 Years

Production Landscape Has to Adapt to Allow Massive Grows

- Key factors (amongst others)[1] are
  - Efficient and sustainable use of materials
  - CO_2 / energy consumption
  - Metals for conductors / **electrodes**[3,4]
  - High conversion efficiency
  - **Tandem** cell technology

→ Substantial innovation along the PV landscape mandatory



[1] J.C. Goldschmidt et.al. (2021), DOI: 10.1039/d1ee02497c

[2] https://www.un.org/sustainabledevelopment/sustainable-development-goals/

[3] E. Gervais et al, Renewable and Sustainable Energy Reviews 137 (2021)

[4] Y Zhang et al, Energy Environ. Sci., 14, 5587 (2021)

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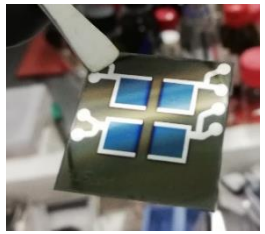
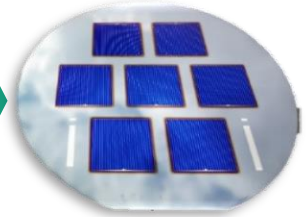
Perovskite Based Tandem Technology
Towards 30% Module Efficiency

- High efficiency proven on lab-scale
- Strong focus on upscaling challenges
  - High-throughput processing
  - Large-area processing

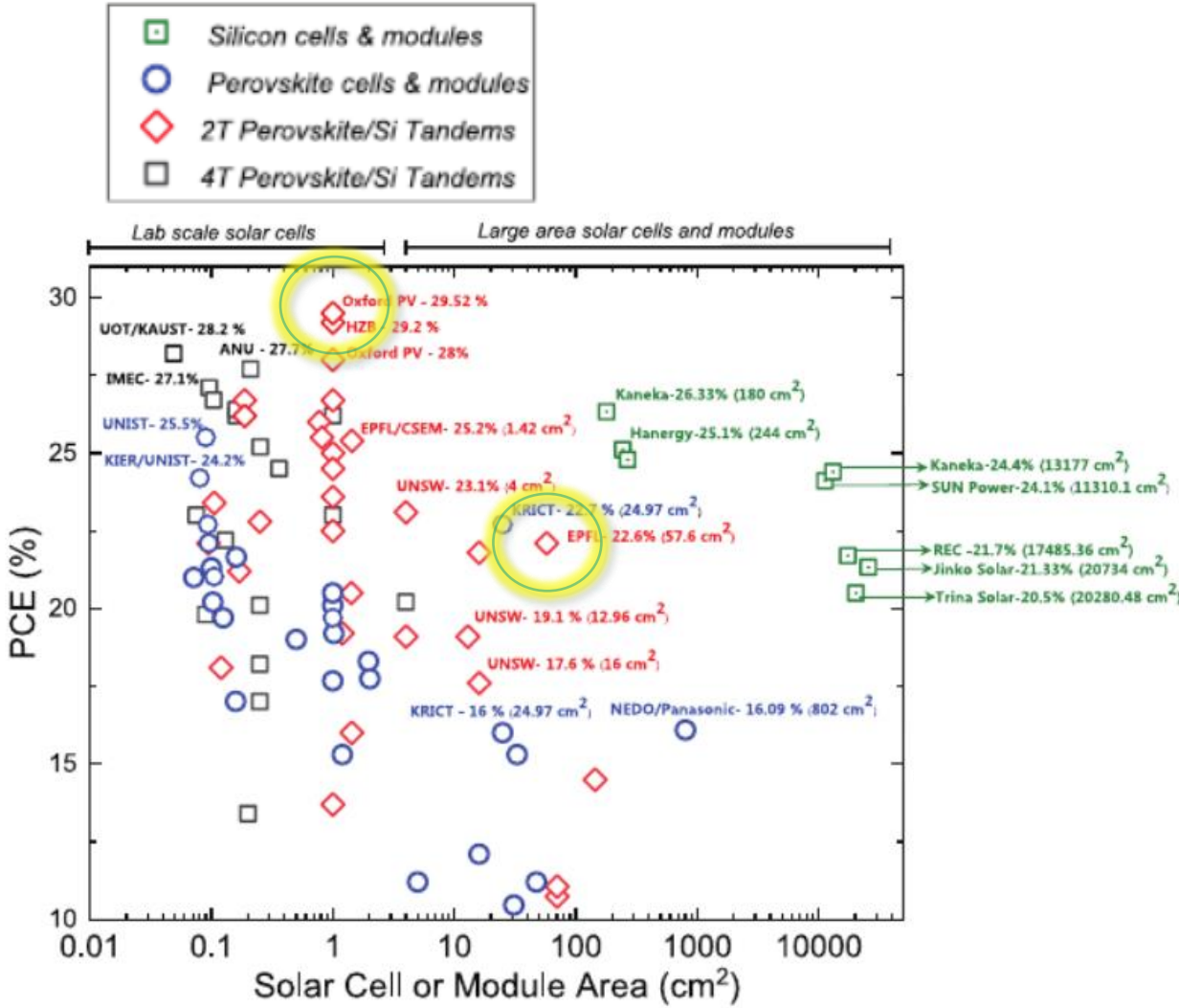


4 x 0.25 cm²



7 x 2 cm²

1 x 274 cm²



[1]A. ur Rehman et al, PIP (2021) https://doi.org/10.1002/pip.3499

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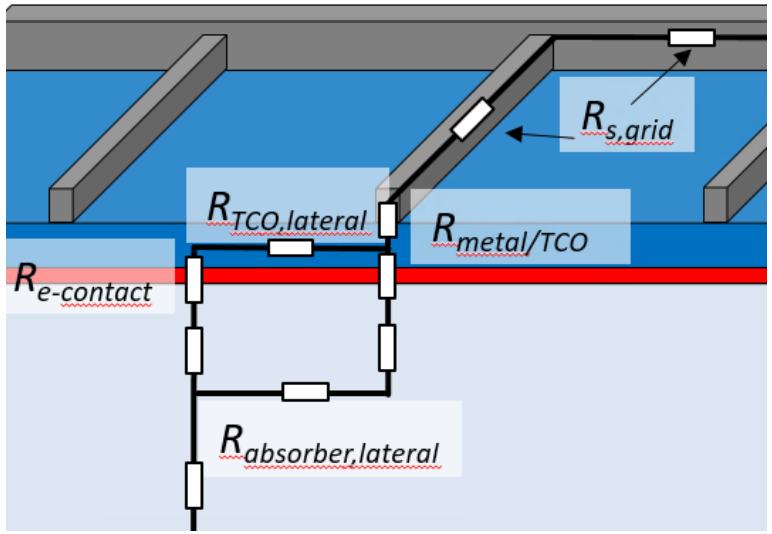
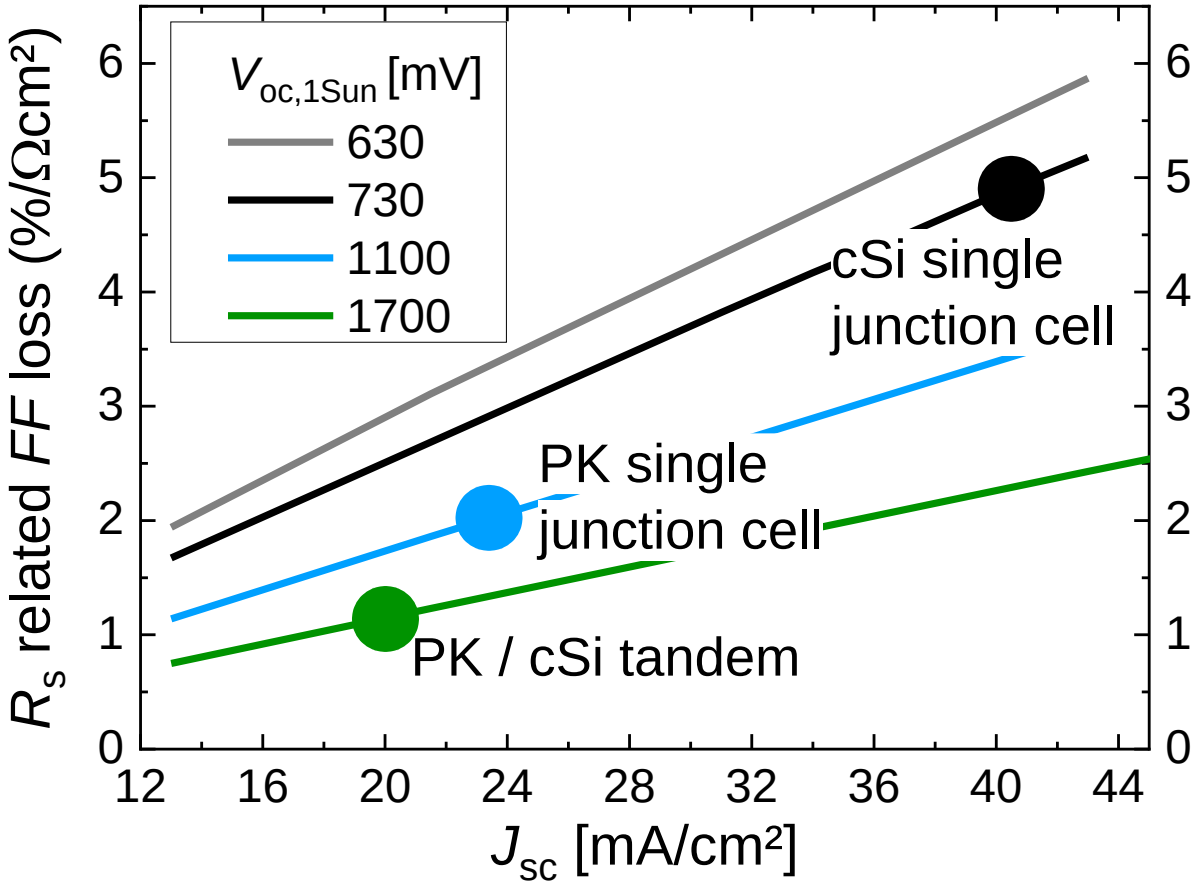
Tandem Technology: Low-Current / High-Voltage Devices

Higher Tolerance for Series Resistance

- $P_{loss,TCO} = \frac{J_{mpp}}{V_{mpp}} \frac{1}{12} R_{\blacksquare TCO}\, d_{finger}^2$
- $P_{loss,finger} = \frac{J_{mpp}}{V_{mpp}} \frac{1}{12} \rho_{finger}\, d_{BB}^2\, d_{finger}$





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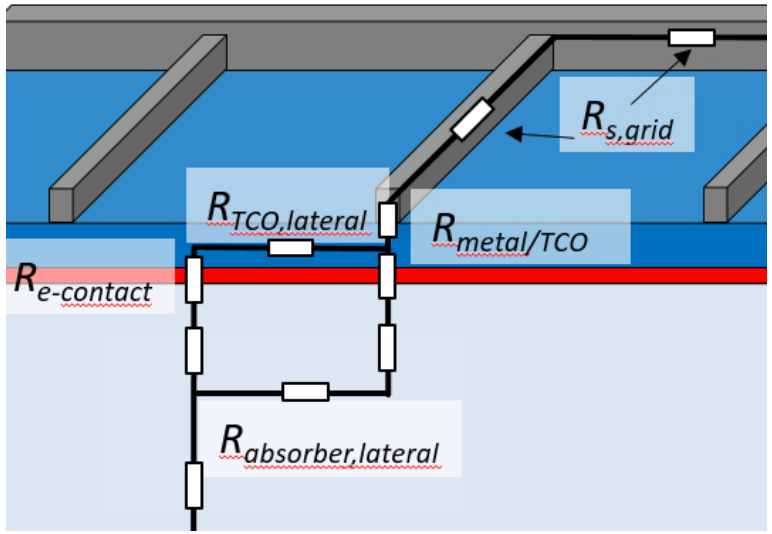
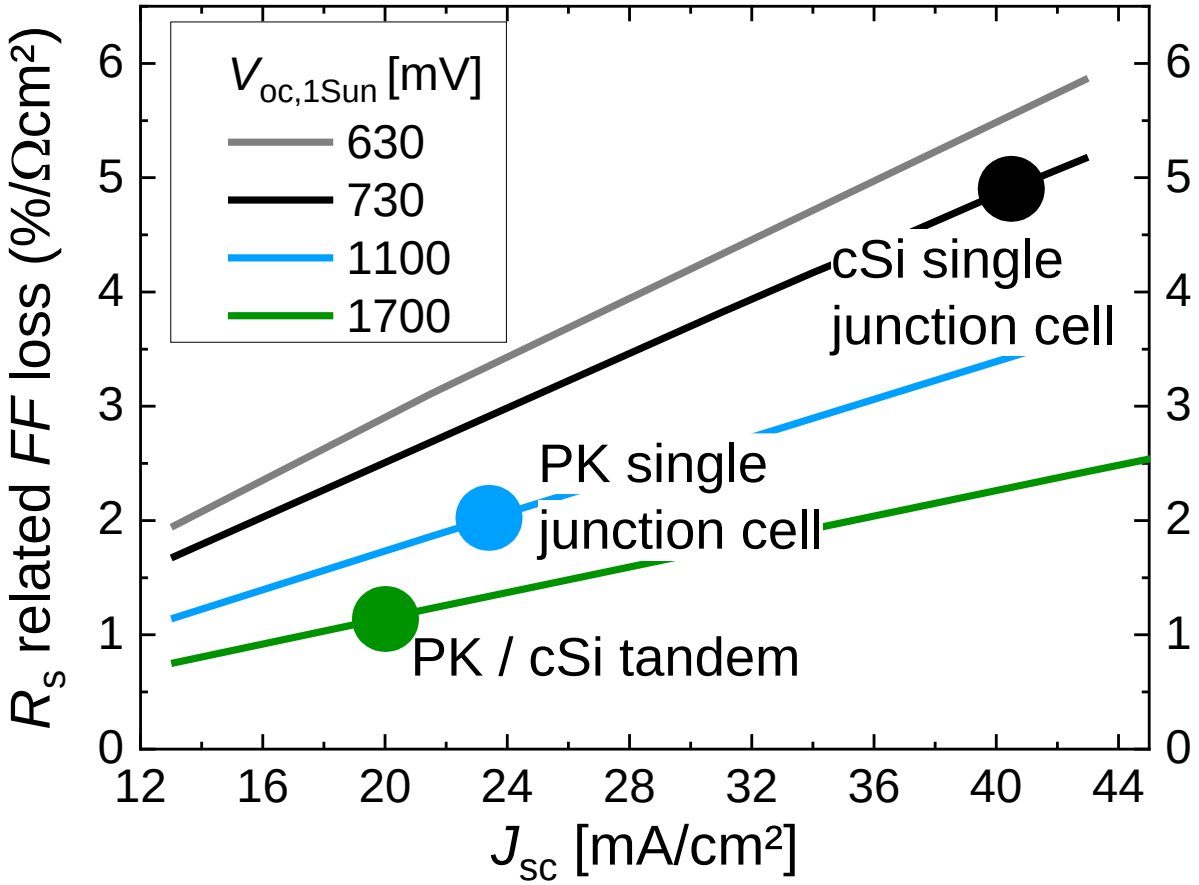
Tandem Technology: Low-Current / High-Voltage Devices

Higher Tolerance for Series Resistance / Lower Tolerance for Optical Losses

- 1 mA/cm² J_{sc} loss
  - Si cell ~ 0.6 % η loss
  - Tandem cell ~ 1.5 % η loss





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Perovskite / Si Tandem Modules

Higher Series Resistance Tolerance Partly Offset by ……

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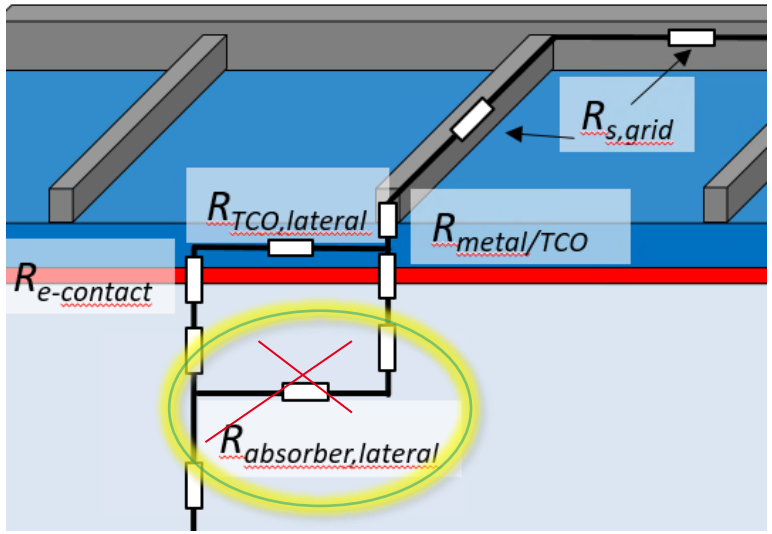

Compared to SHJ cells[1]

- No addition lateral transport provided by absorber

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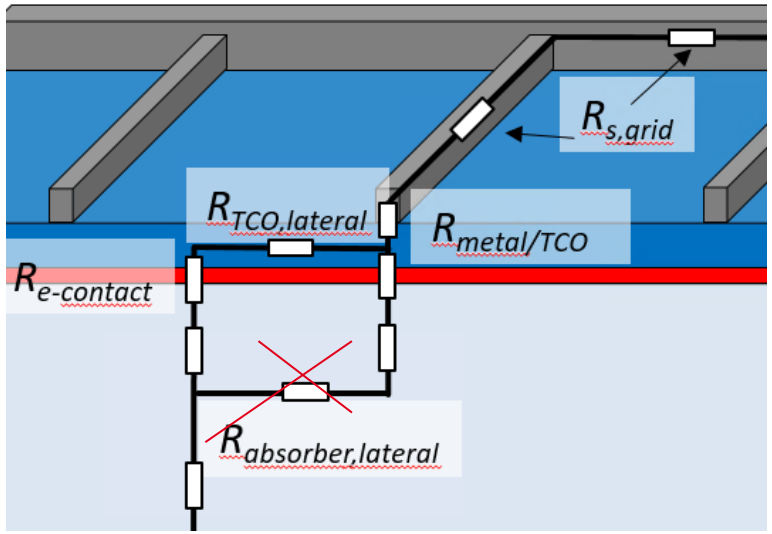

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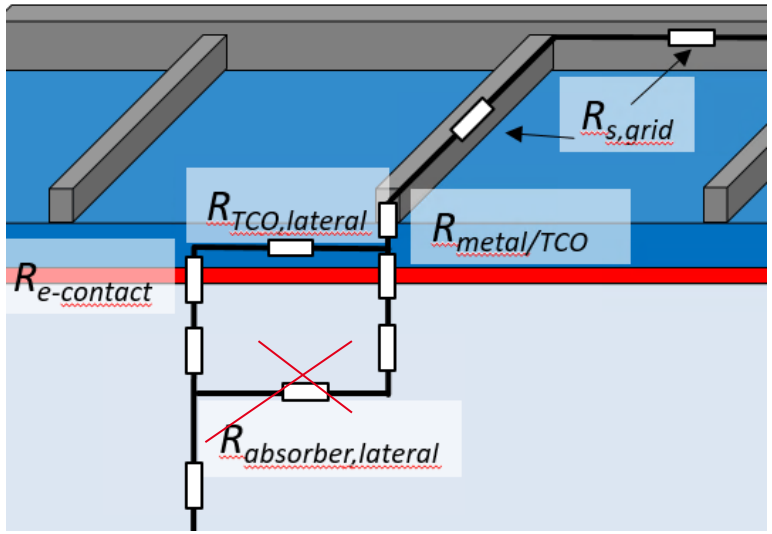

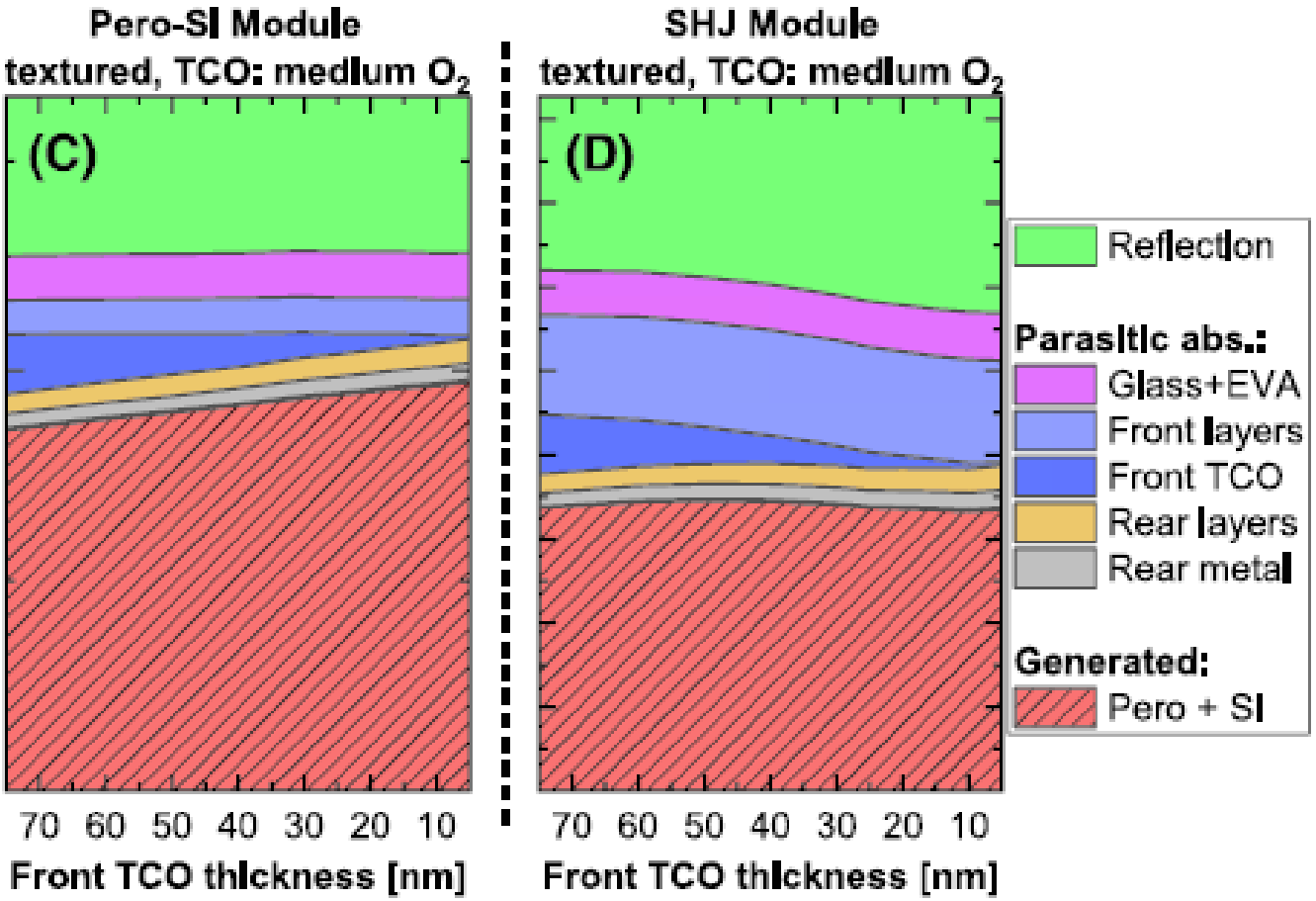

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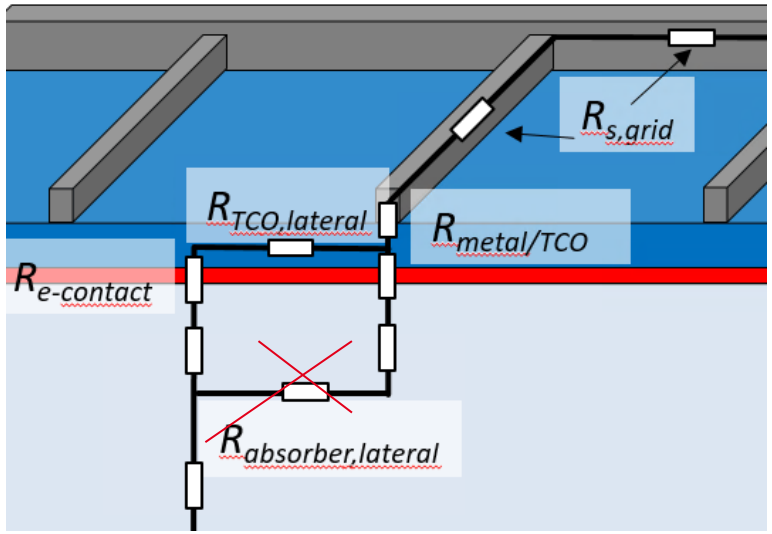

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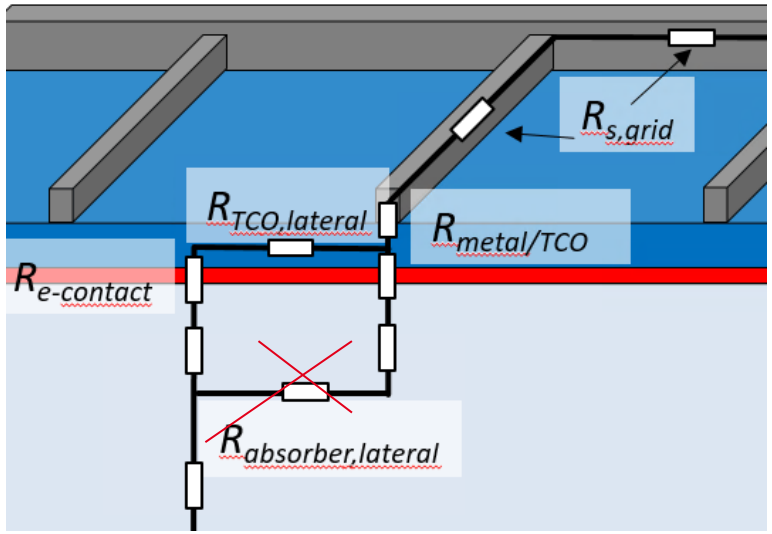

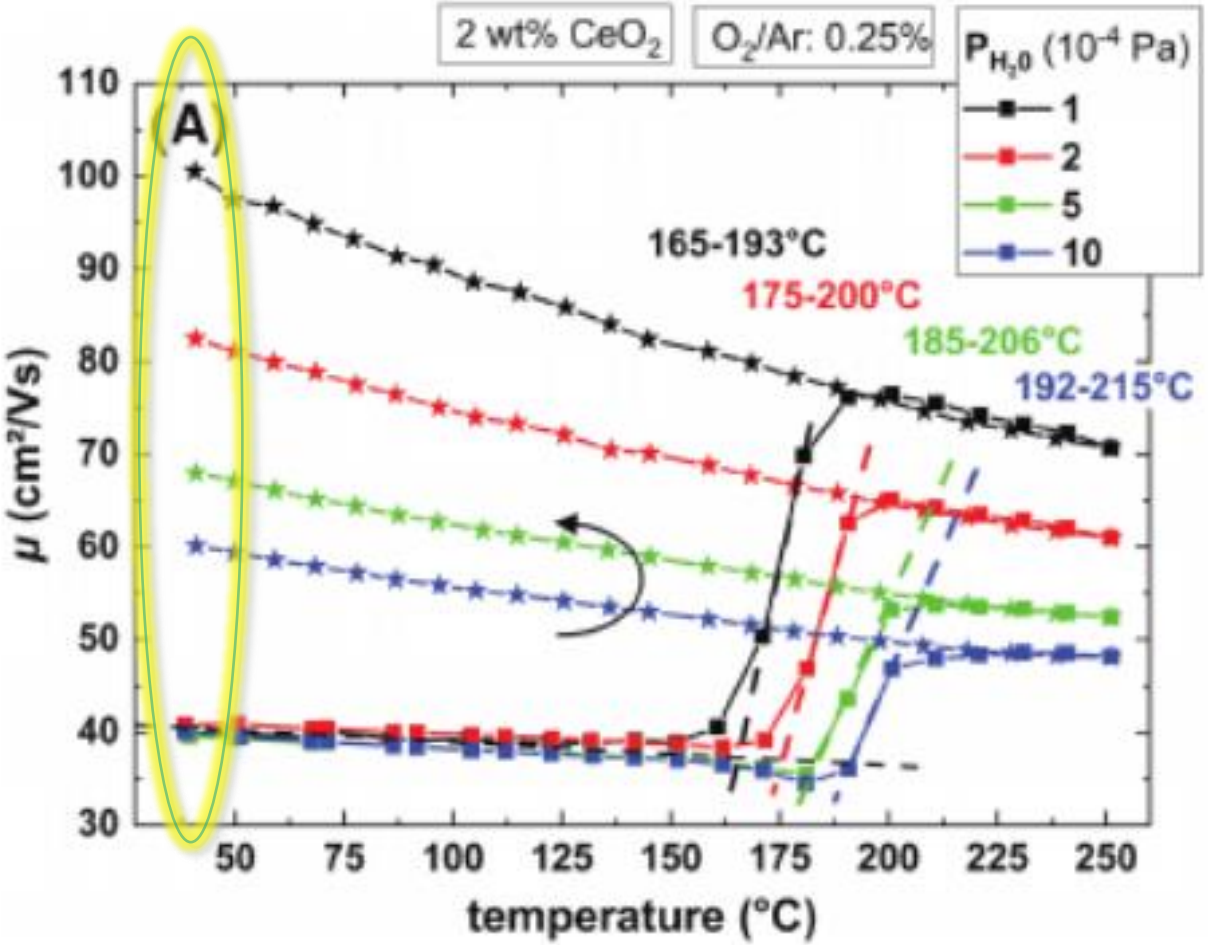

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[2]L. Tutsch et al. PIP 29/7 (2021) , https://doi.org/10.1002/pip.3388

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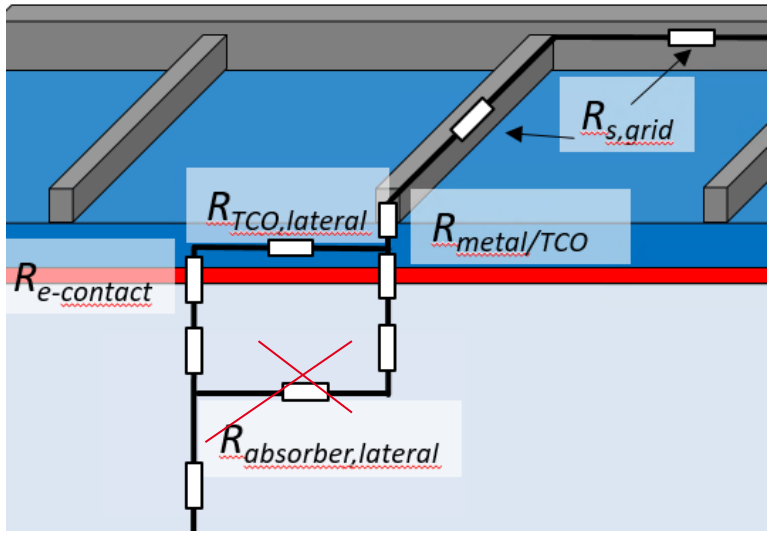

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  - Indium in the TCO is used less efficiently (g/W)
- Finger resistivity is rather high
  - Ag in the paste is used less efficiently (g/W)

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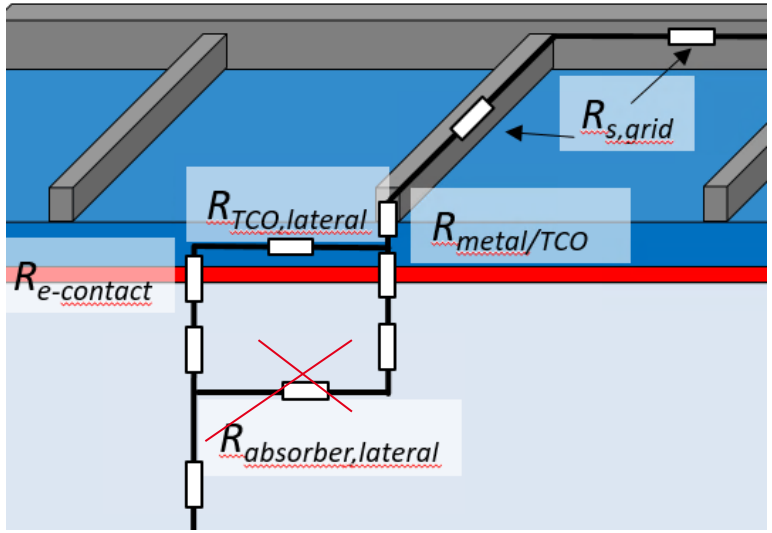

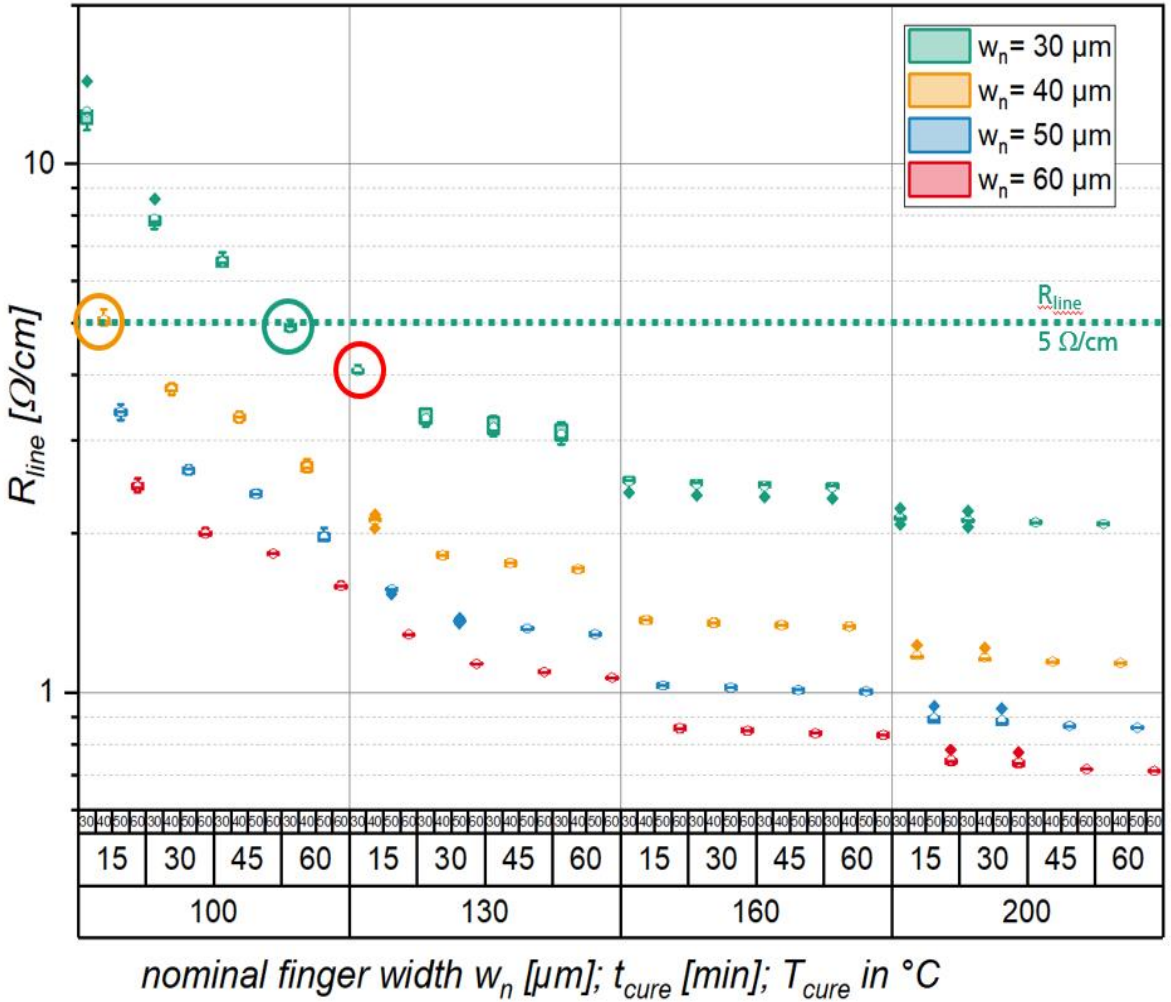

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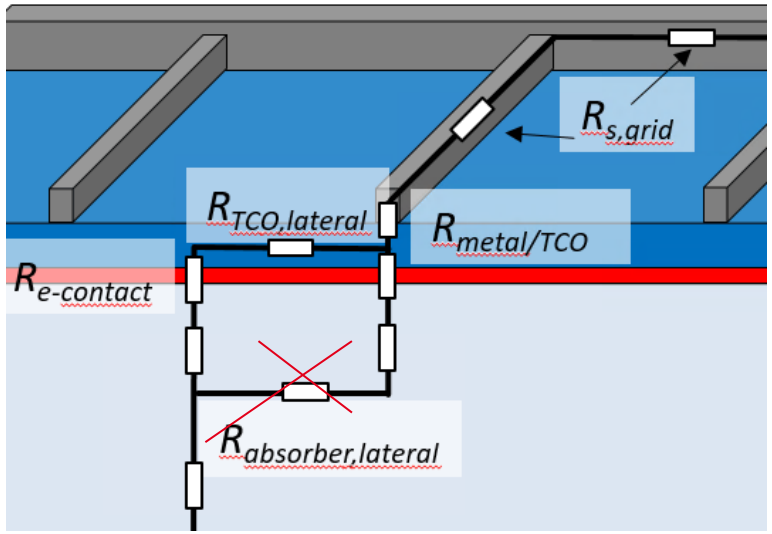

Compared to SHJ cells[1]

- No addition lateral transport provided by absorber
- TCO does not provide anti-reflection properties, hence ideal TCO is thinner

→ **Conductivity-transparency trade-off is more pronounced**

- High µ-TCOs can not be applied
  - Indium in the TCO is used less efficiently (g/W)
- Finger resistivity is rather high
  - Ag in the paste is used less efficiently (g/W)

→ **Current back-end temperature constrains limit TCO´s and metal´s conductivity**

[1]C. Messmer et al. PIP (2021), https://doi.org/10.1002/pip.3491

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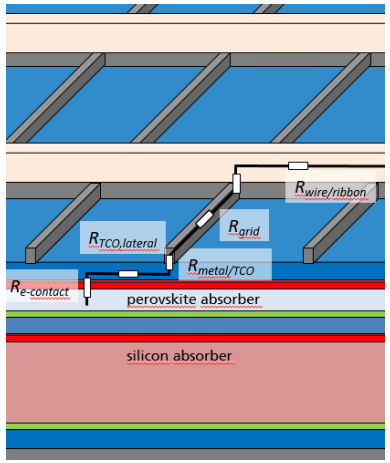
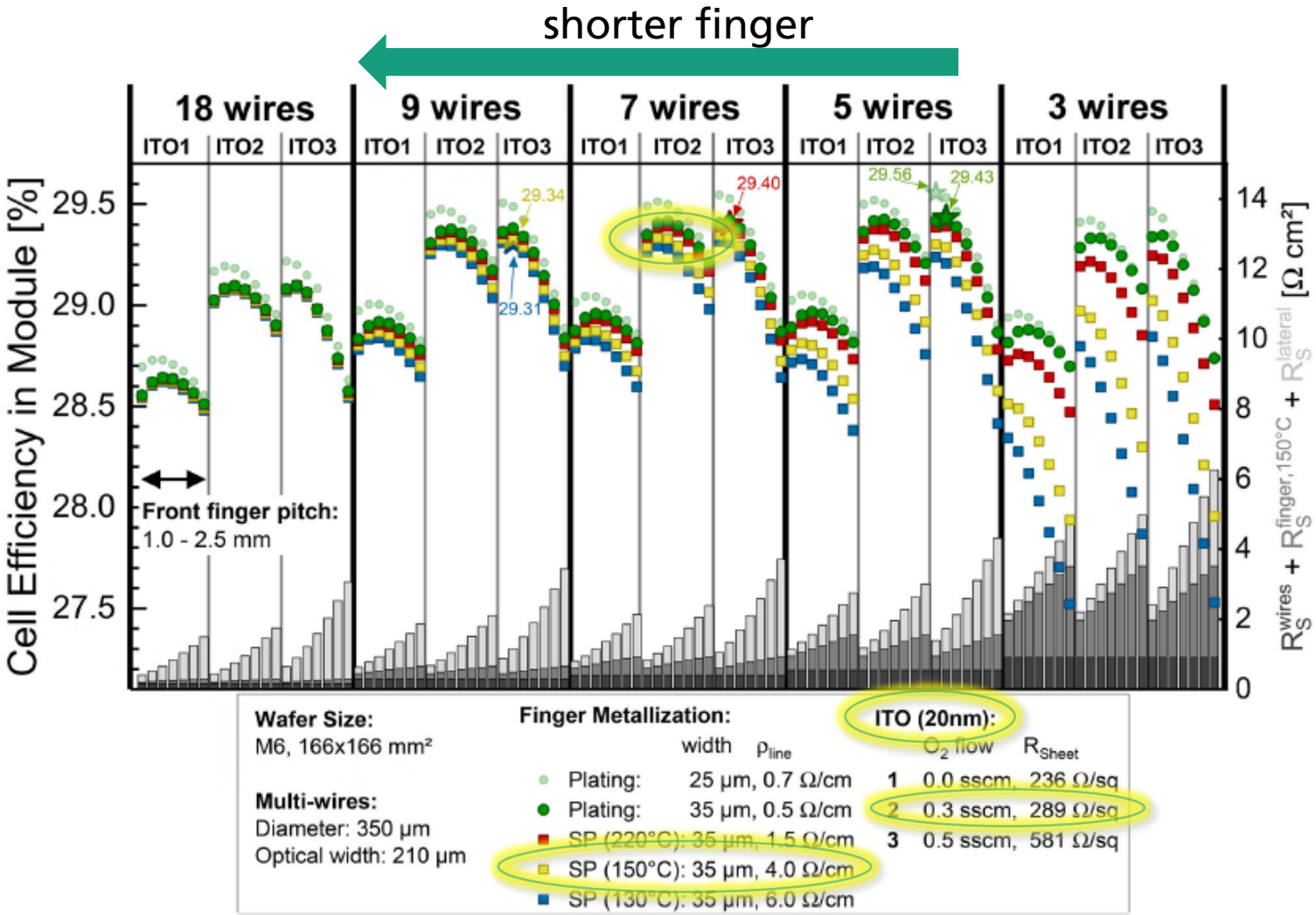
Simulation Based Technology Evaluation

The Interplay Between TCO-, Grid- and Cell Interconnection Electrode

- Thin high-μ front side TCO (~70 nm)
- Pitch 1.5 mm (~2 mm)
- Lowest LCOE → 57 mg Ag (~40 mg)
- 7 wires / shingle segments

→ Higher requirements for front side TCO and Ag compared to SHJ





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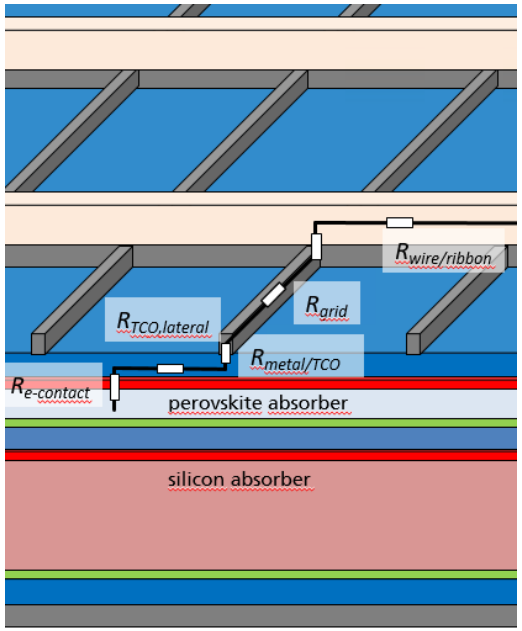
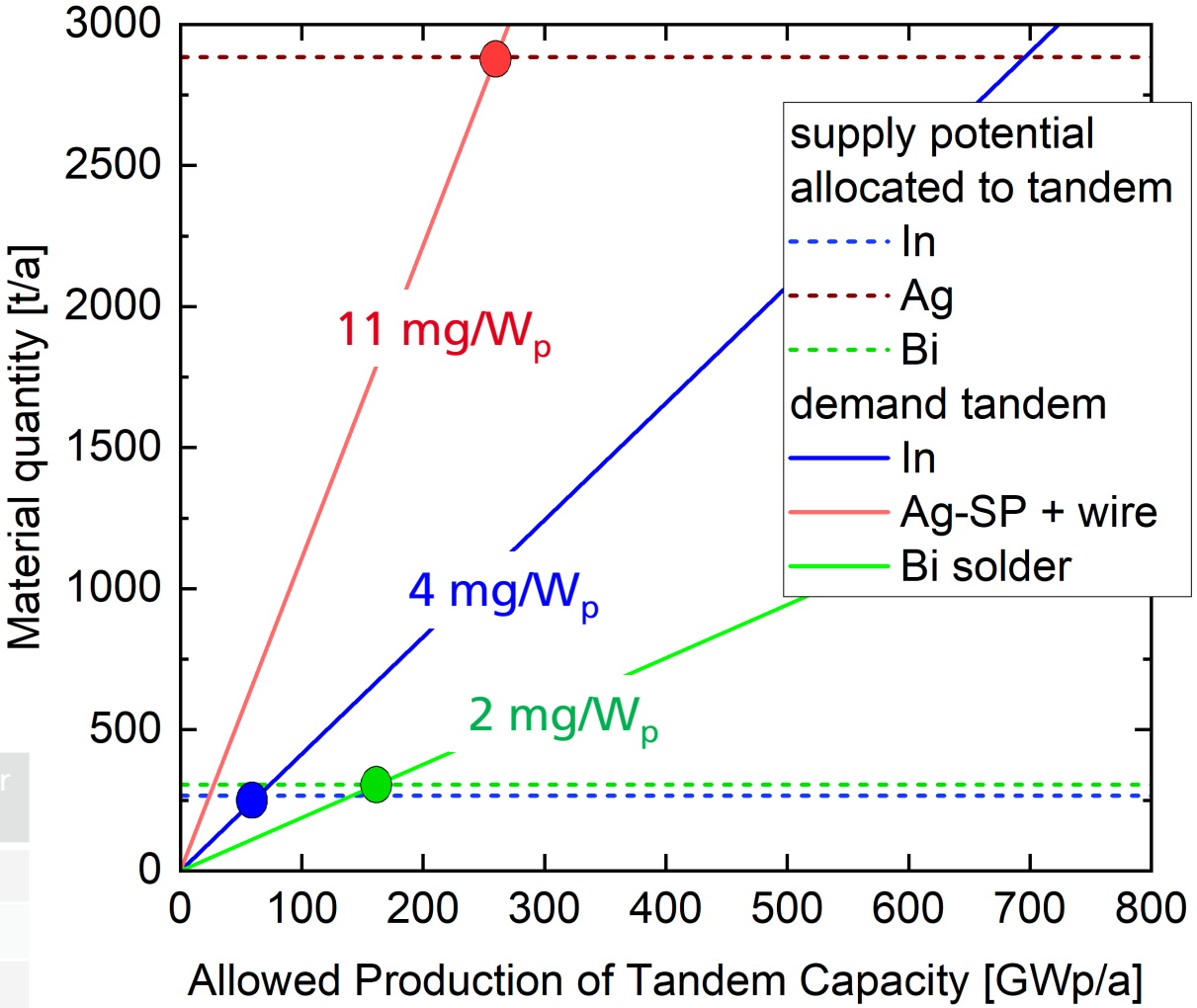
Capacity Expansion Limit by TCO-, Grid- and Cell Interconnection Electrodes

Efficient Use / Avoidance of Ag, In and Bi



	Supply potential / t	Share for PV / %	Allocated for tandem / %
Ag	28840	10	100
Bi	10901	2.8	100
In	2961	9	100



[1]E. Gervais et al, Renewable and Sustainable Energy Reviews 137 (2021)

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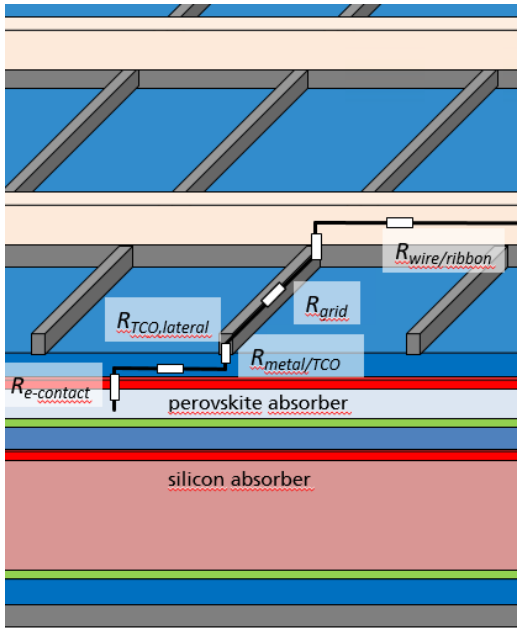
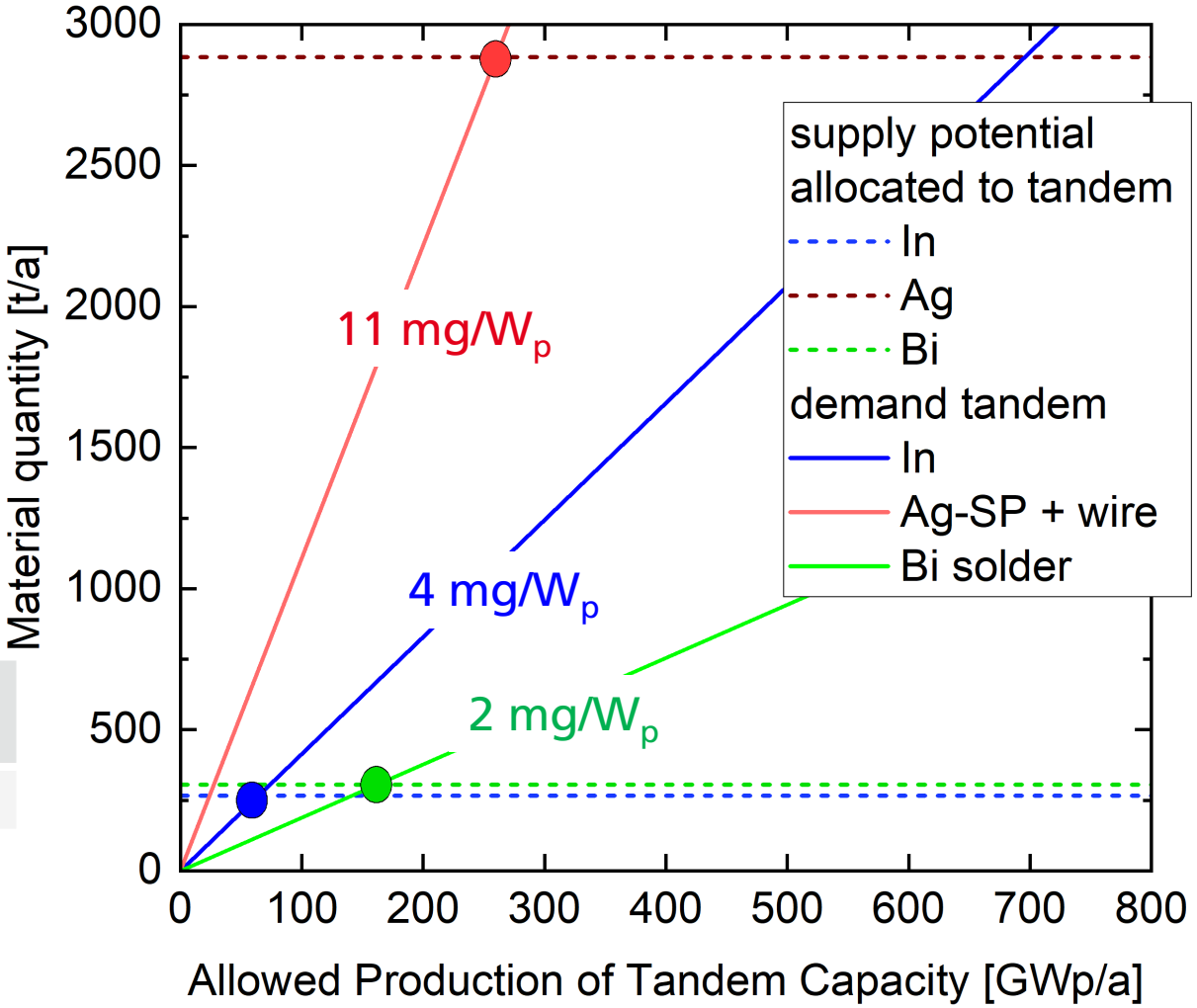


	Intercon-nection	Grid	TCO / nm (ITO)	Capacity Limit / GWp/a Bi / Ag / In
A	$solder_{wire}$	Ag-SP	20/20/70	170 / 260 / 70



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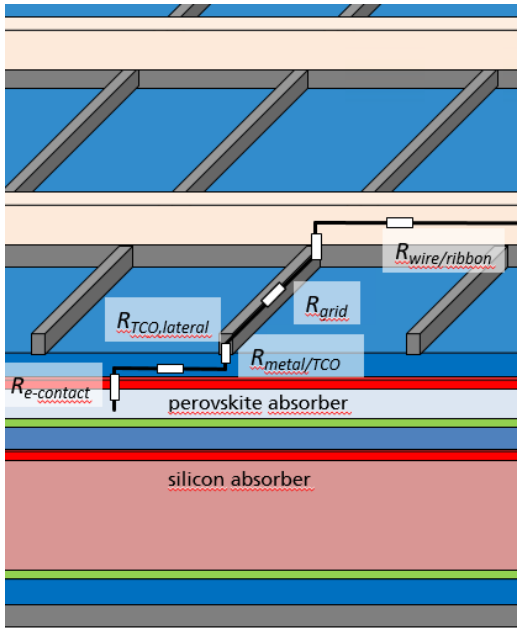

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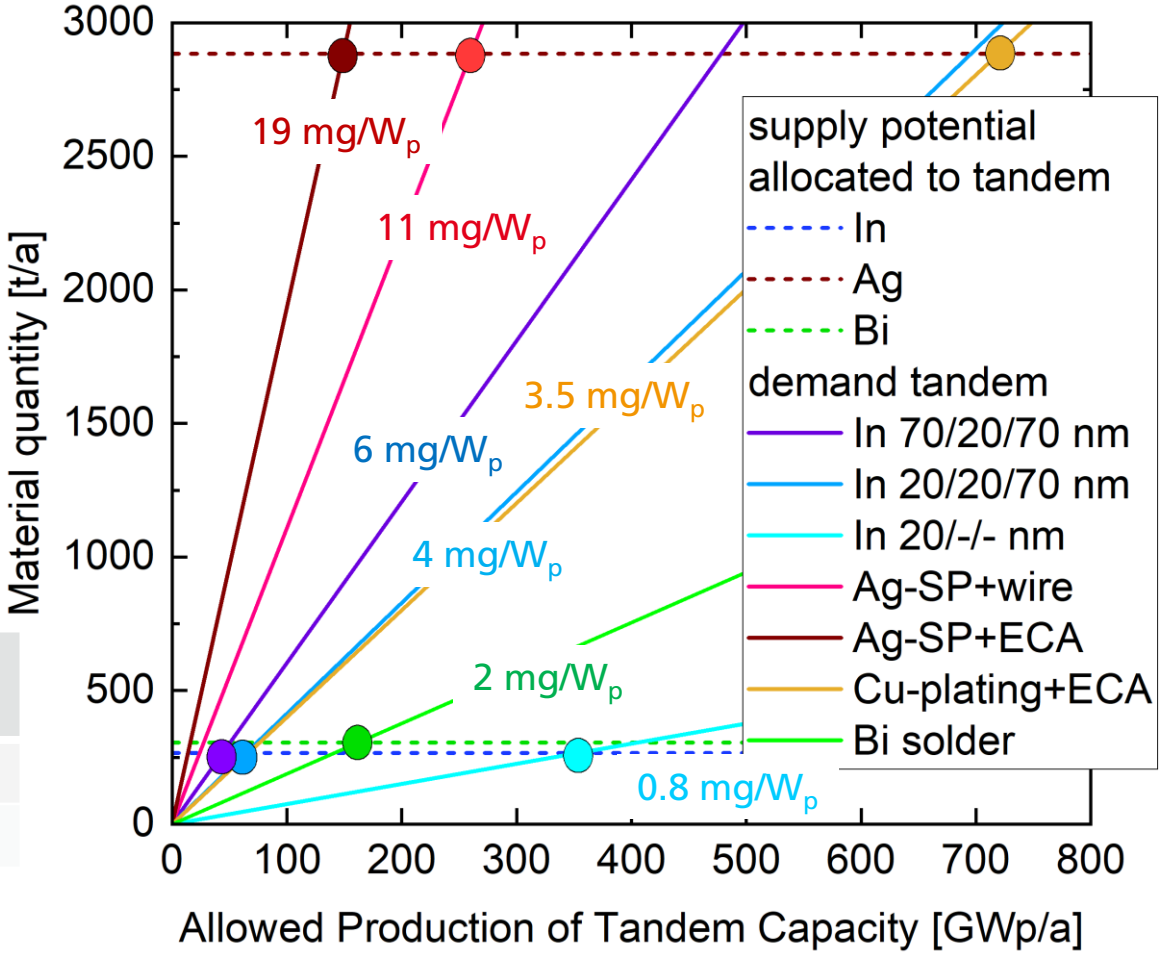

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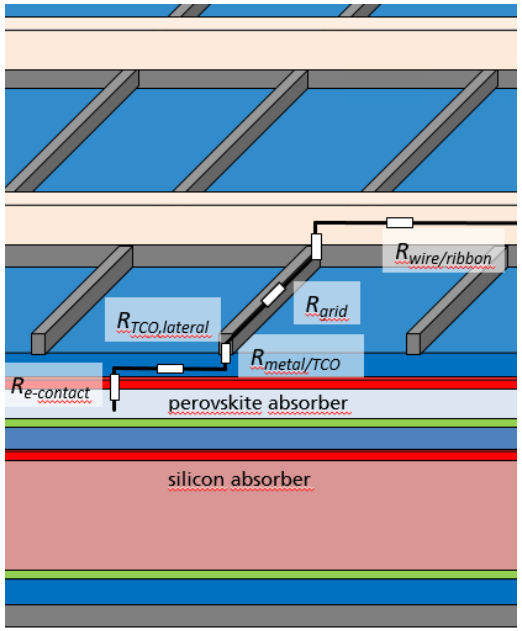

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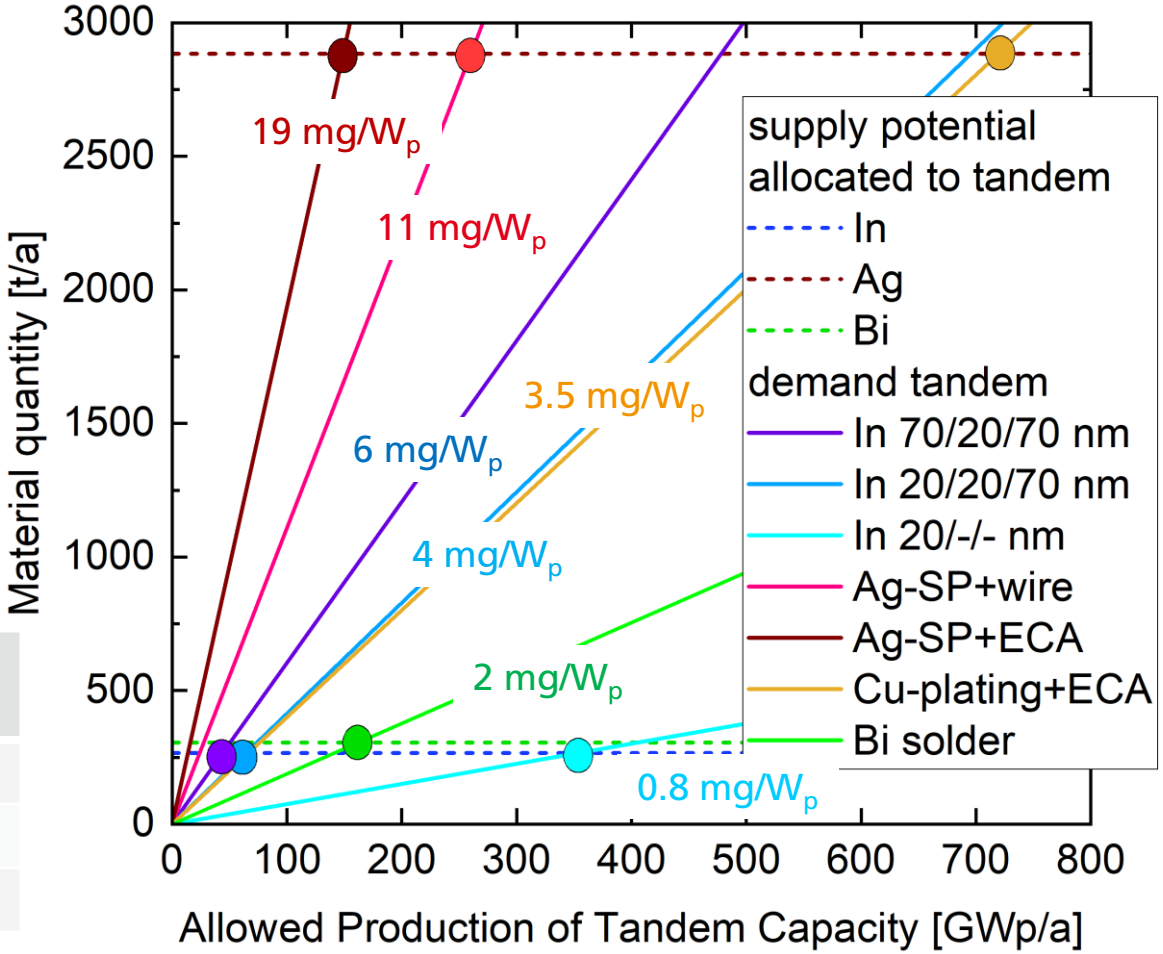
C	ECA_{BB}	$Ag\text{-}SP_{BB}$	20 / - / -	- / 150 / 380



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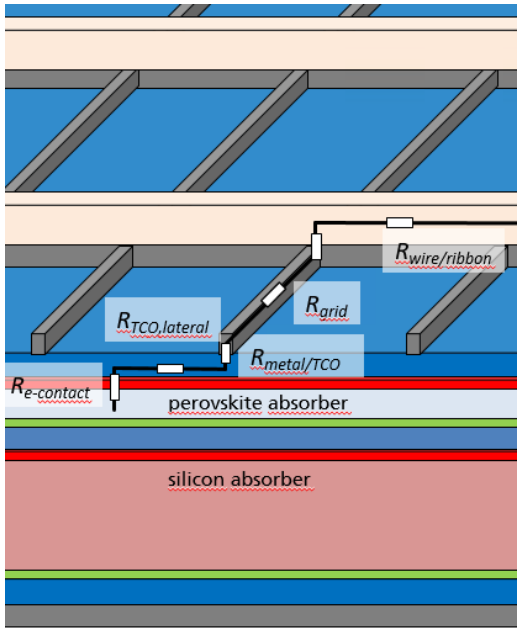

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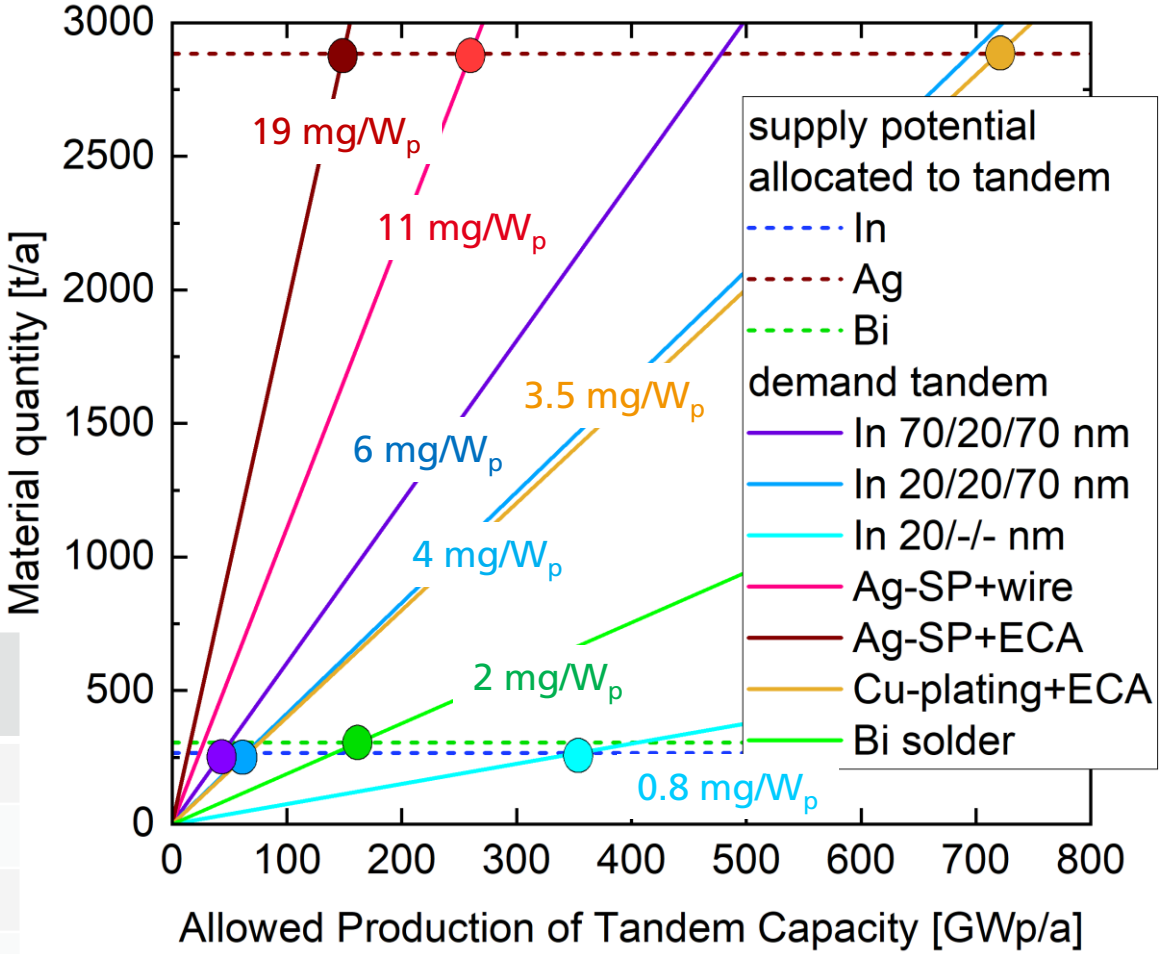
C	ECA_{BB}	$Ag\text{-}SP_{BB}$	20 / - / -	- / 150 / 380
D	ECA_{BB}	Cu-plating	20 / - / -	- / 740 / 380



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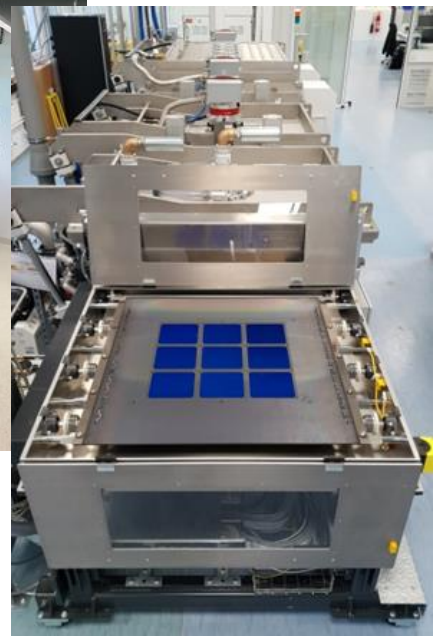
More Efficient Use / Avoidance of Ag, In and Bi

Printing and Cell Interconnection Activities at Fraunhofer ISE

- Wide scope on screening and optimizing TCOs, pastes, curing and printing techniques for industrial ultra-low temperature metallization



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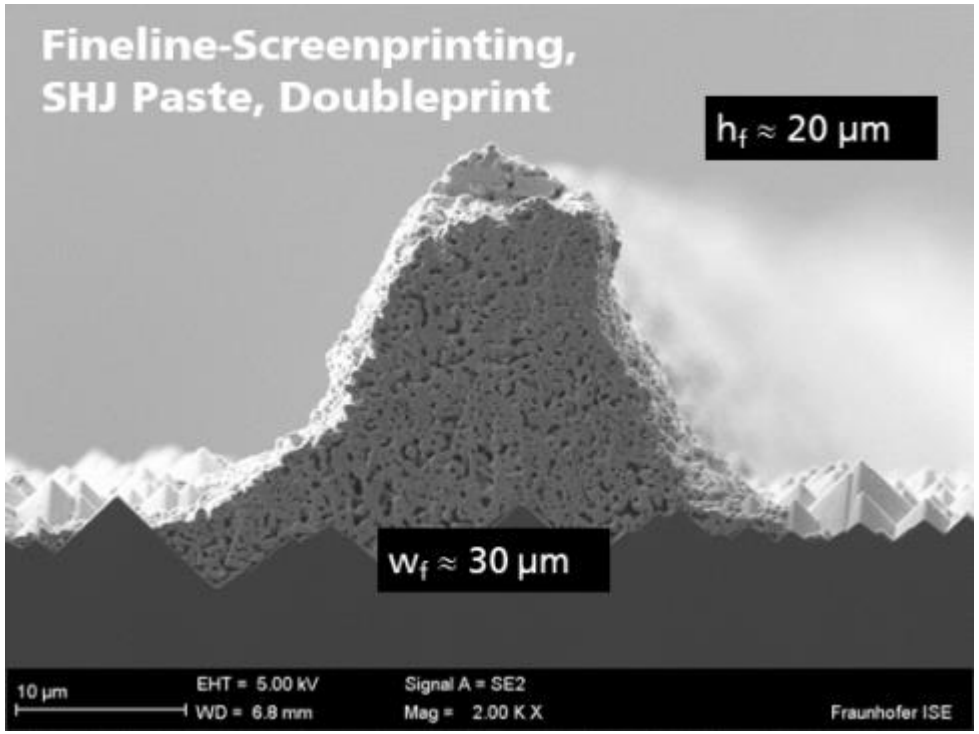
- Optimizing and adapting screen printing to lower temperatures and different substrate



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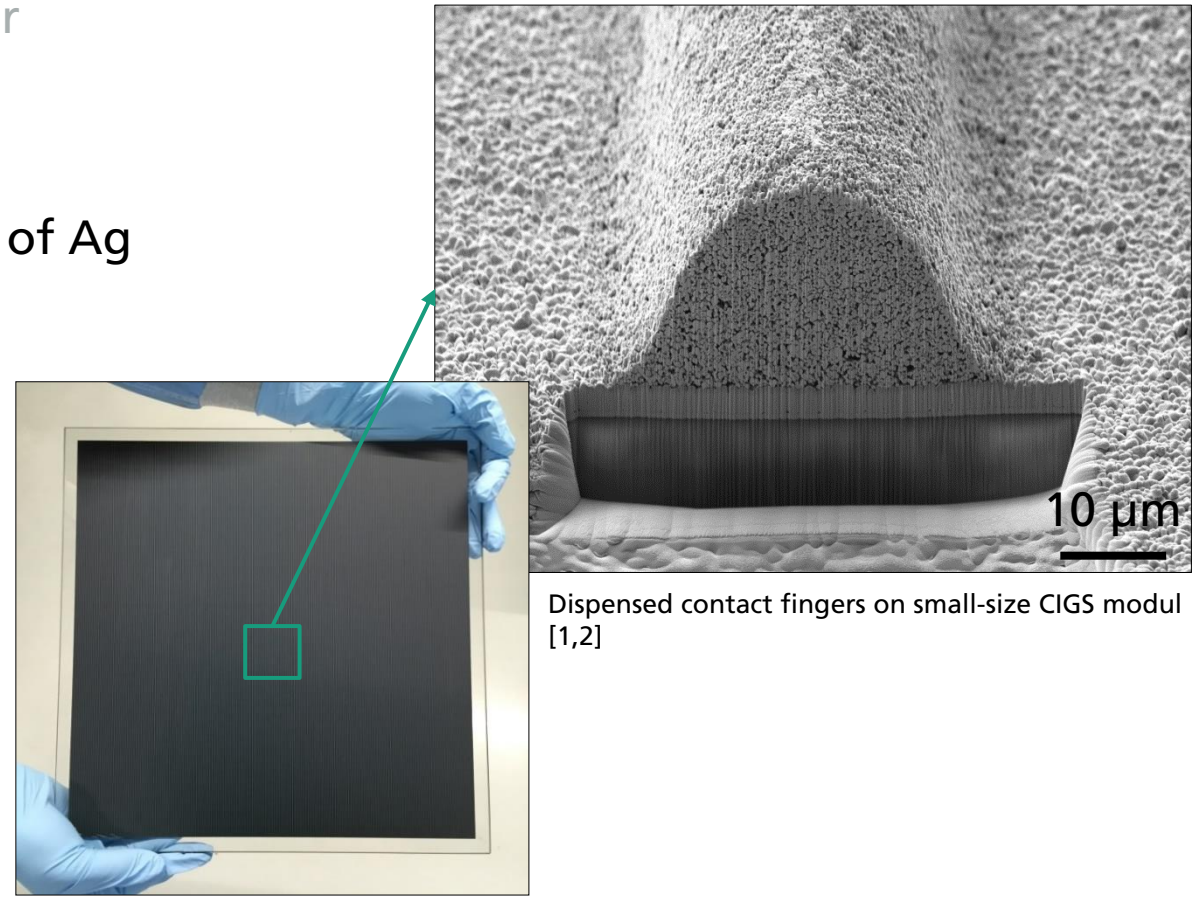
- Parallel dispensing to further improve utilization of Ag
  - Promising results for thin-film PV[1,2]



Dispensed contact fingers on small-size CIGS modul [1,2]

[1] Gensowski et al., EU PVSEC (2020)

[2] Gensowski et al., Solar RRL (2020)

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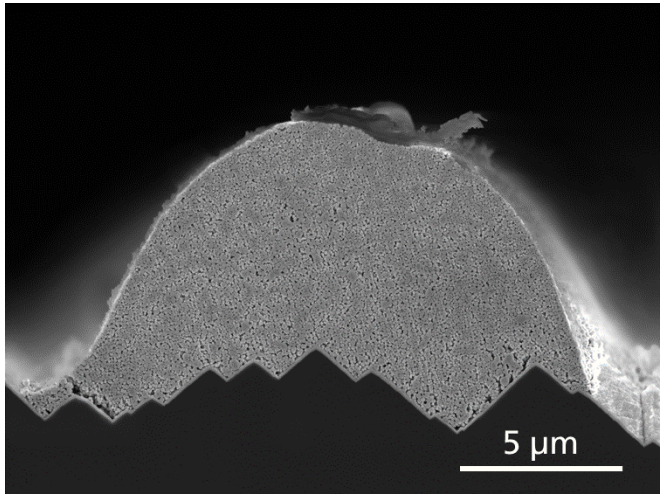
More Efficient Use / Avoidance of Ag, In and Bi

Printing and Cell Interconnection Activities at Fraunhofer ISE

- Optimizing and adapting screen printing to lower temperatures and different substrate
- Parallel dispensing to further improve utilization of Ag
  - Promising results for thin-film PV[1,2]
- FlexTrail for ultra-narrow fingers below 10 µm[3,4,5]
  - And very good aspect ratio



[3] J. Schube et al., *PhD thesis*, 2021
[4] J. Schube et al., *pss RRL*, 2019
[6] J. Schube et al., *8th Met. Workshop*, 2019

*PV Nano Cell is acknowledged for providing the paste

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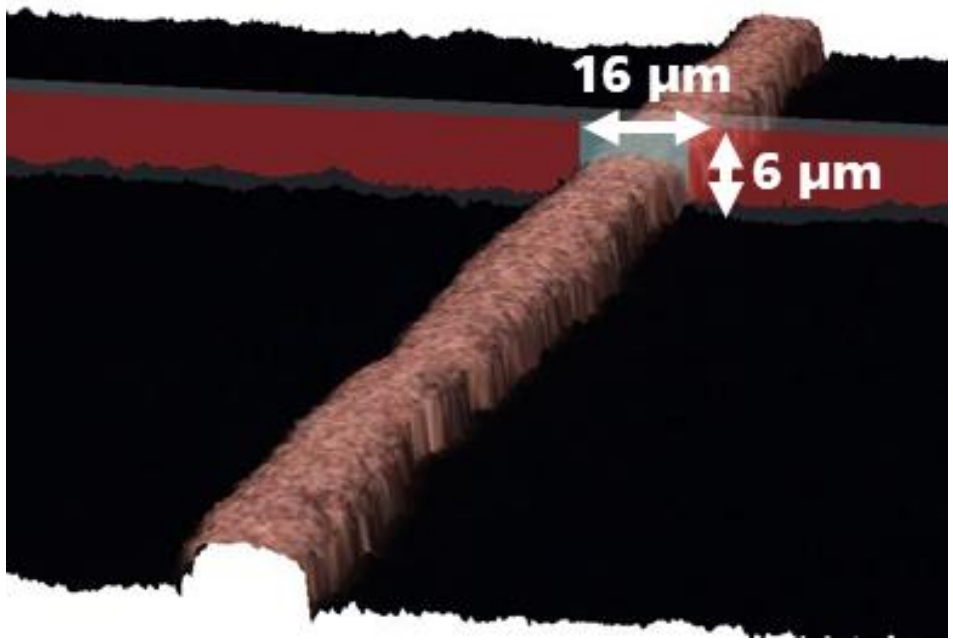
  - And very good aspect ratio
- Substitute Ag by Cu
  - Paste, ECA, Plating



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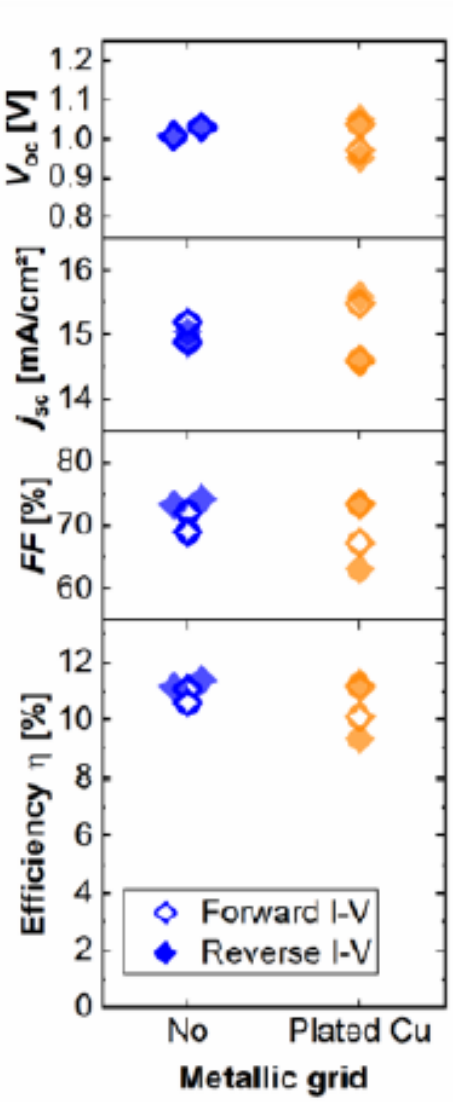
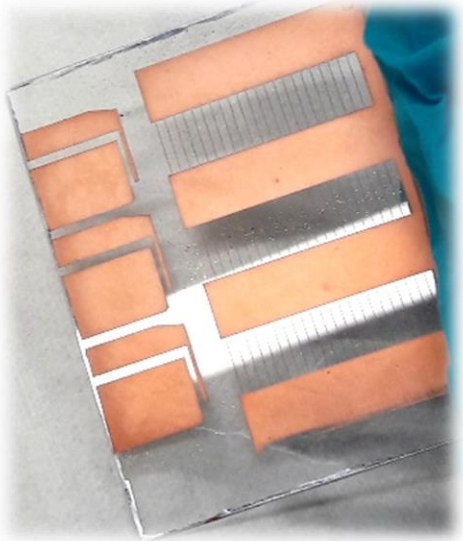
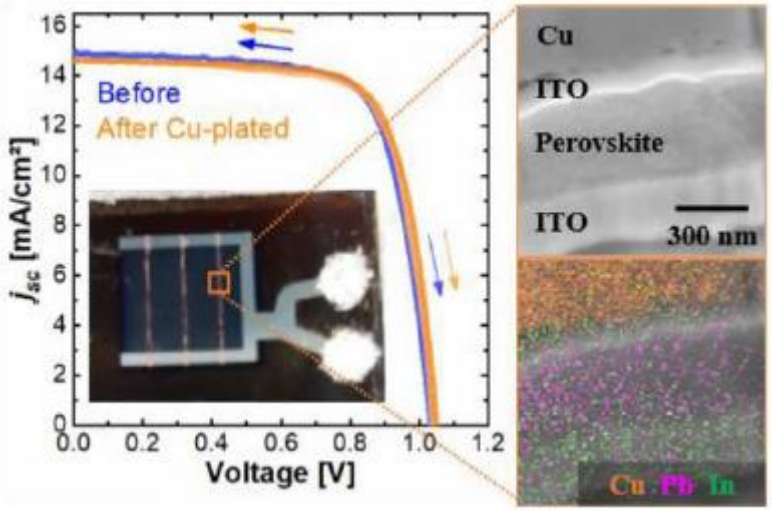
More Efficient Use / Avoidance of Ag, In and Bi

Proof of Concept For Cu Plating on Perovskite

- Cu contacts can be electroplated on pero cells
- Perovskite solar cells survive wet-chemical electroplating process
- Also addressing Cu gride lines on TCO+glass for thin film modules







T. Hatt, RRL 5.9 2021, https://doi.org/10.1002/solr.202100381

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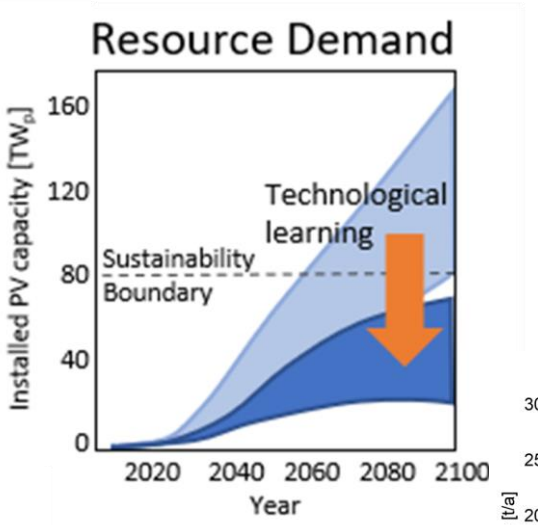
Summary

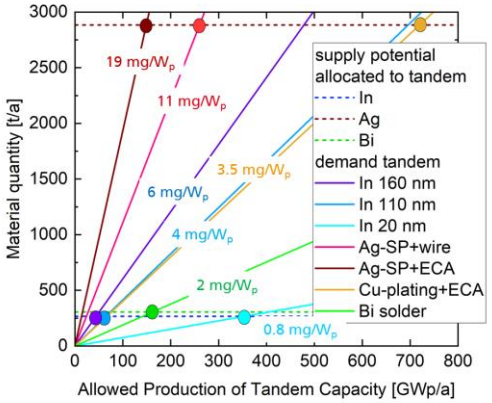
- **Further technological learning** mandatory to address the upcoming challenges of the Terrawatt market
  - **Sustainability** aspects **must** be considered for **engineering of cells / modules**
  - Very high efficiency for mainstream market

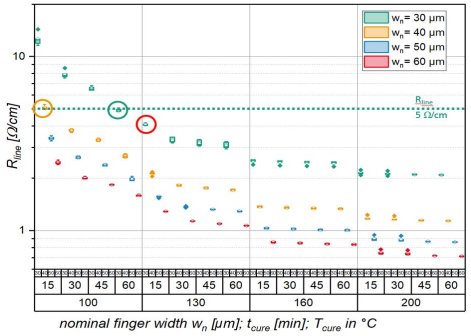
→ Perovskite based tandems would be ideal candidate

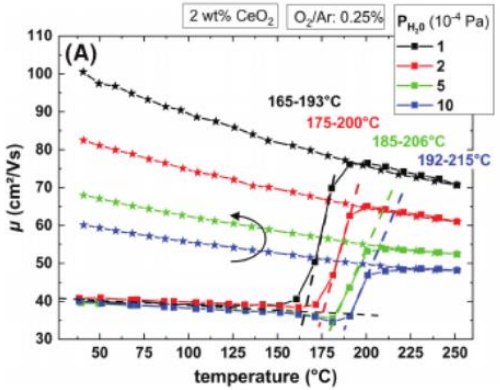
- **Current design** of **electrodes** likely **limit** the projected **upscaling** of Pero/Si tandem, despite the higher series resistance tolerance

- Increasing the back-end temperature is an important step to benefit from learnings of Si technology (SHJ)









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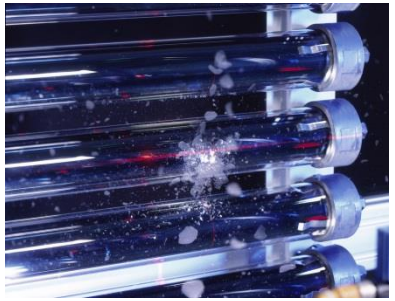
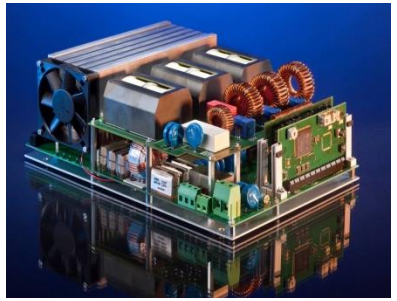
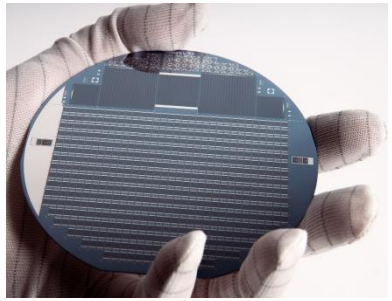
Thank you for your Attention!
Thanks to all Co-Workers!




Presto
(FKz. 03EE1086A)

MaNiTu
Fraunhofer Leitprojekt

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