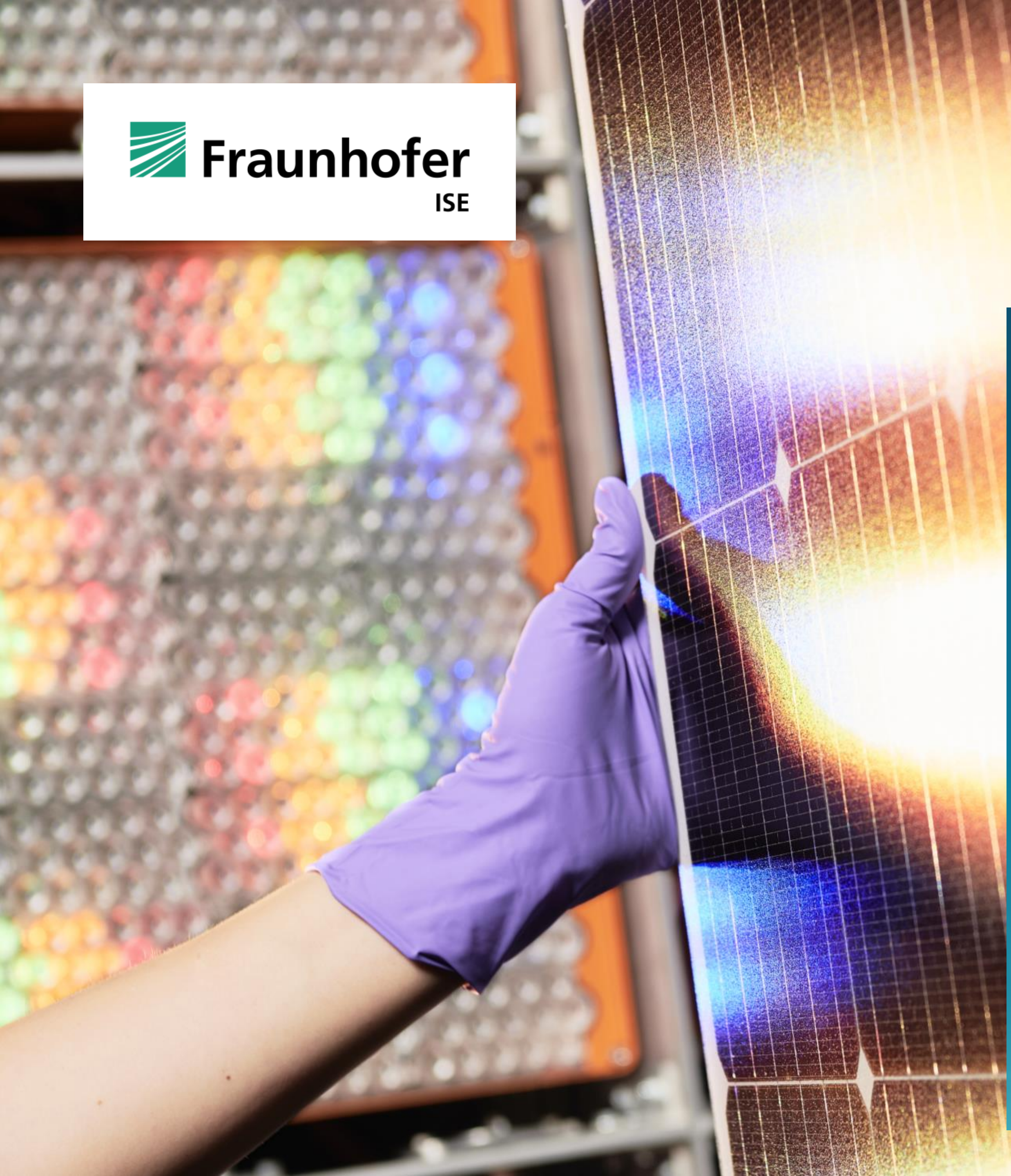

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Effect of Lowering Curing Temperature of Electrically Conductive Adhesives on Ribbon Connected Solar Cells

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Presented at 41st EUPVSEC, Vienna (Austria)
Session 3CO.11
September 25th, 2024

Introduction

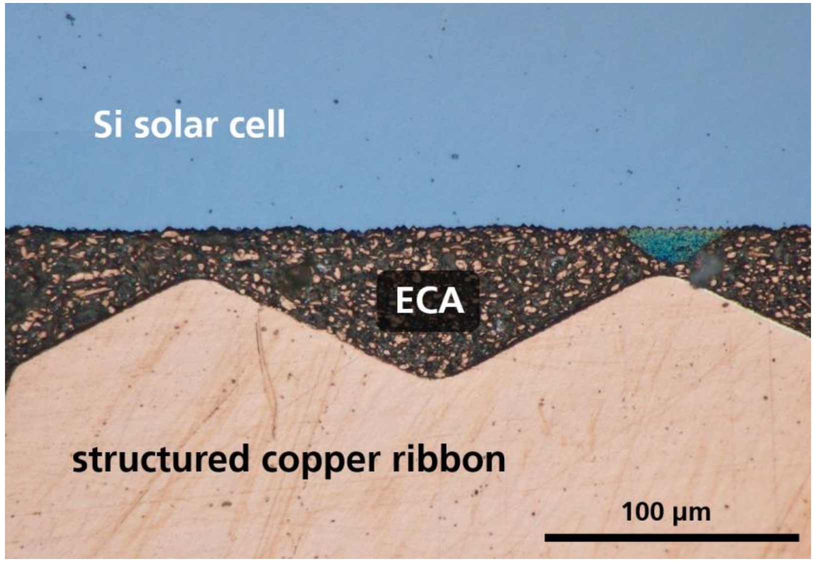
Electrically Conductive Adhesives (ECAs)

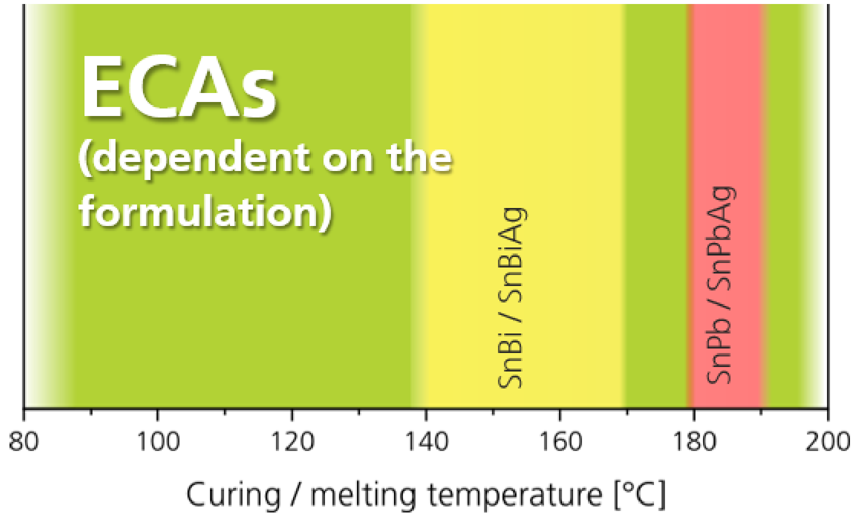
Working principle

- ECAs consist of a polymer matrix with conductive filler (typically Ag)
- Conductive paths are formed upon curing
- Thermal curing – most common in PV

Advantages of ECAs for solar cell interconnection

- Possibility to tailor the characteristics to process requirements (Rheology, curing scheme, conductive filler type, etc.)
- No busbar metallization required → 1BO.4.1 (Tuesday)
- Wide processing window in terms of temperature
- Compatibility with temperature sensitive high-efficiency cell types like perovskite-Si tandem (PVST)





Introduction

Perovskite-Silicon Tandem Cells (PVST)

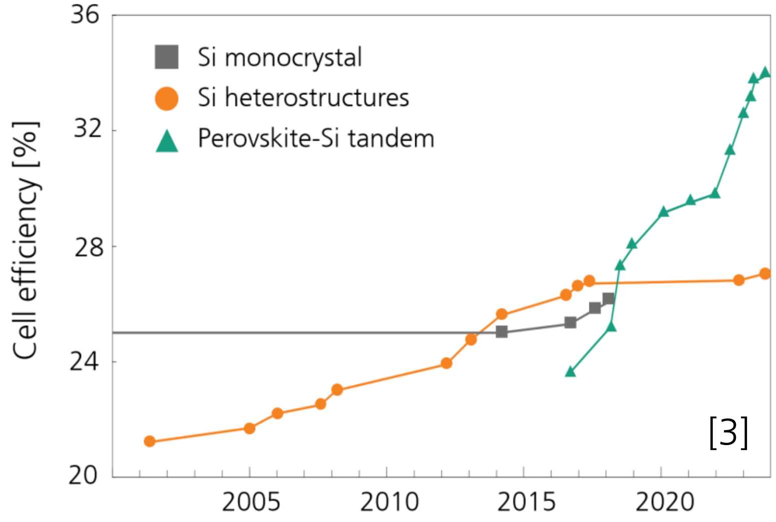
- Current PVST efficiency record: 34.6 % (lab device) and 30.1 % (M6) [1]
- Expected to appear at the market after 2025 with efficiencies ~26 % [2]

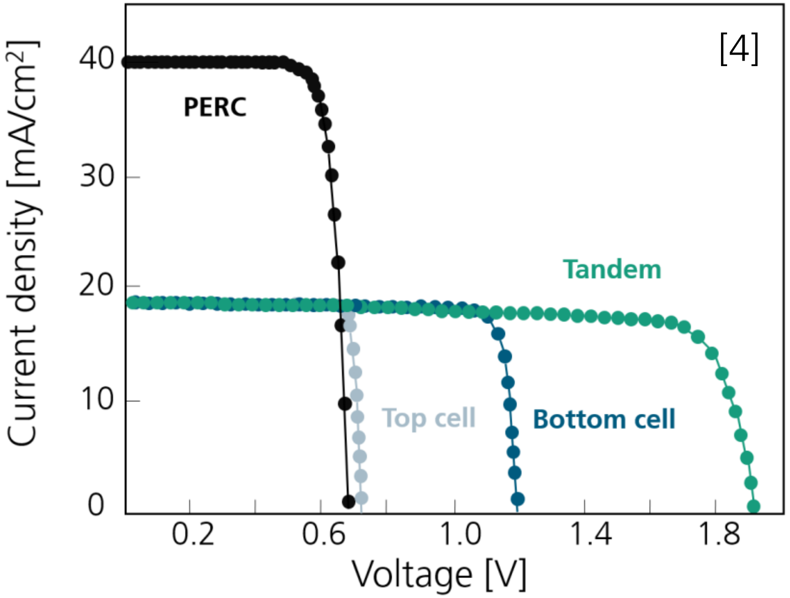
Advantages

- High power conversion efficiency (PCE) potential and steep learning curve
- Low current density → less power loss attributed to series resistance
- Potential to reduce silver consumption per Watt due to relaxed metallization requirements

Two main challenges of ECA interconnection of PVST

- Low process temperature required → ECA
- Silver reduction





[1] LONGI, 14.06.2024 and 19.06.2024, respectively
[2] ITRPV roadmap, 14. Edition, April 2023
[3] Modified after NREL, Best Research-Cell Efficiencies, rev. 20.08.2024
[4] Modified after Zhang *et al.*, Energy Environ. Sci. 14: 5587-5610 (2021)

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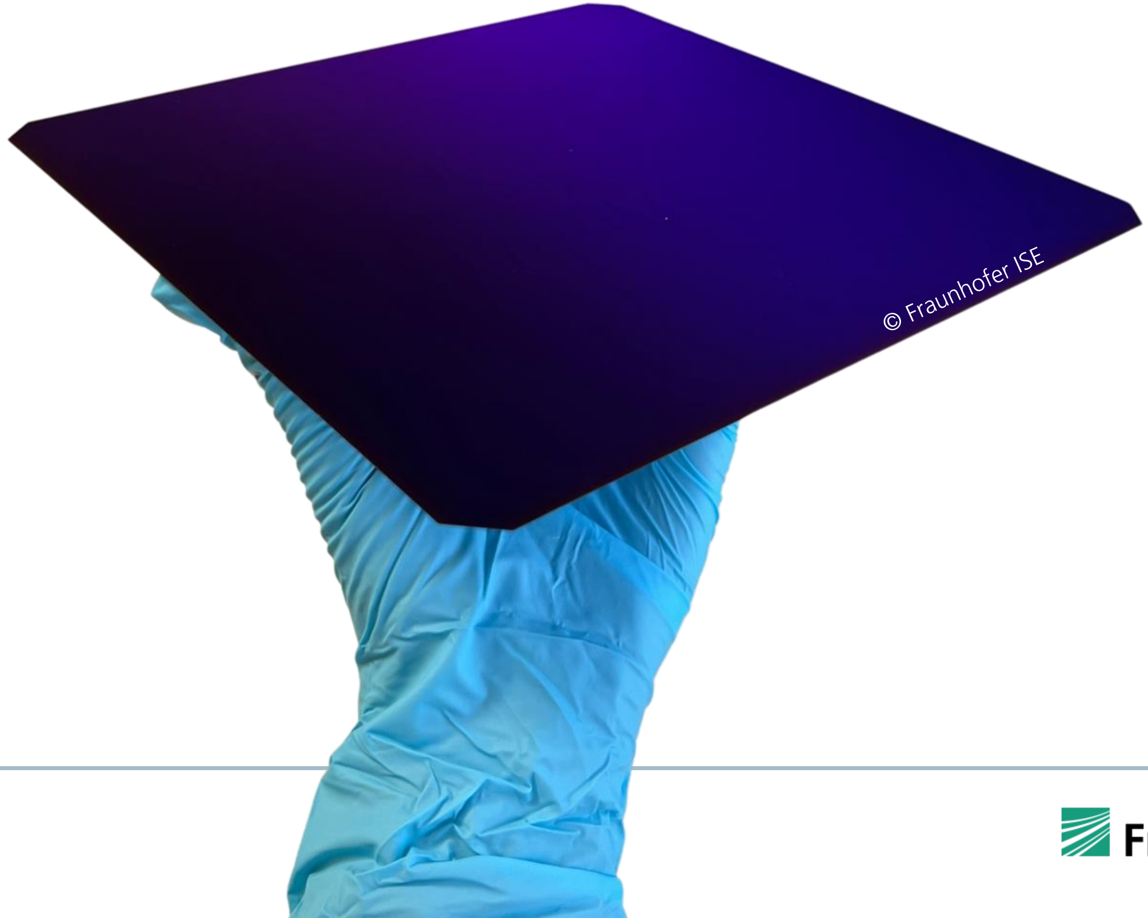
Silver Consumption in a PVST Module

Silver-containing module components

- Bifacial M6 (166 mm × 166 mm) wafer is considered

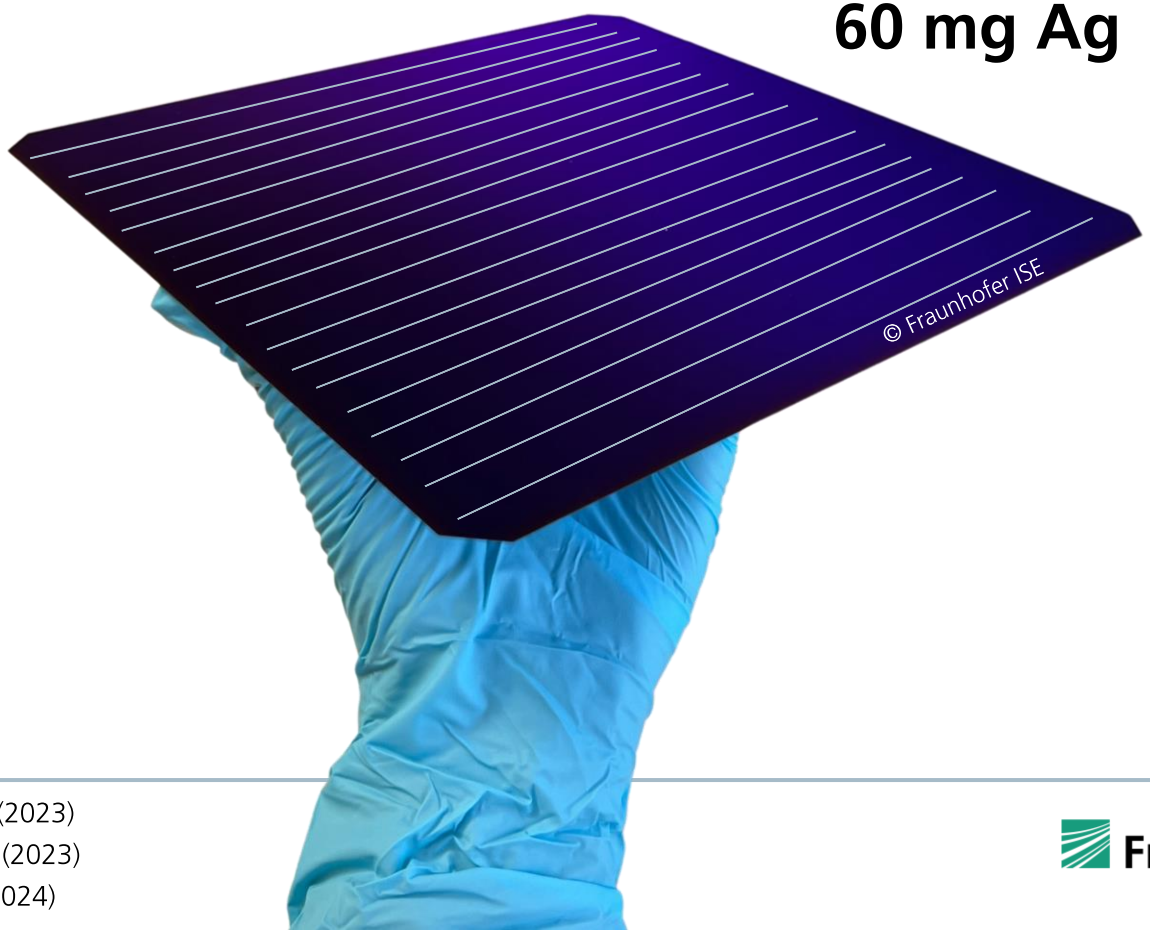


Silver Consumption in a PVST Module

Metallization Fingers

Silver-containing module components

- Fingers (bifacial cell)
  - Front – 60 pcs. [5]
  - Rear – 120 pcs.
  - Finger width = 25 µm [6]
  - Finger height = 8 µm [7]



60 mg Ag

fingers

[5] Nikitina *et al*, Sol. Energy Mater. Sol. Cells. 263: 112590 (2023)
[6] De Rose *et al*, Sol. Energy Mater. Sol. Cells. 261: 112515 (2023)
[7] Pingel *et al*, Sol. Energy Mater. Sol. Cells. 265: 112620 (2024)

Silver consumption in a PVST module

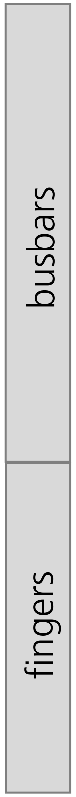
Busbar metallization

Silver-containing module components

- Fingers (bifacial cell)
- Busbars
  - 6 busbars [8]
  - Busbar design - redundancy line with interconnection pads

60 mg Ag

+ 75 mg Ag



[8] Messmer *et al*, Prog. Photovolt. Res. Appl. 30: 374–383 (2022).

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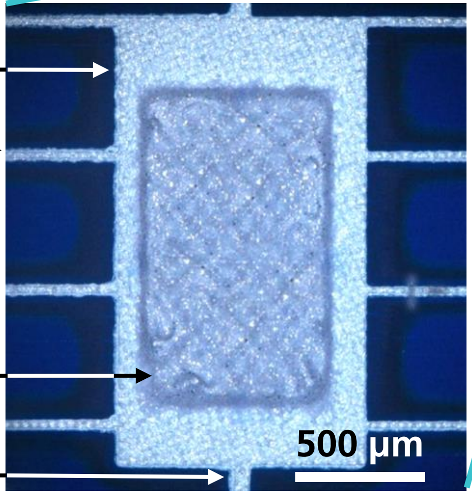
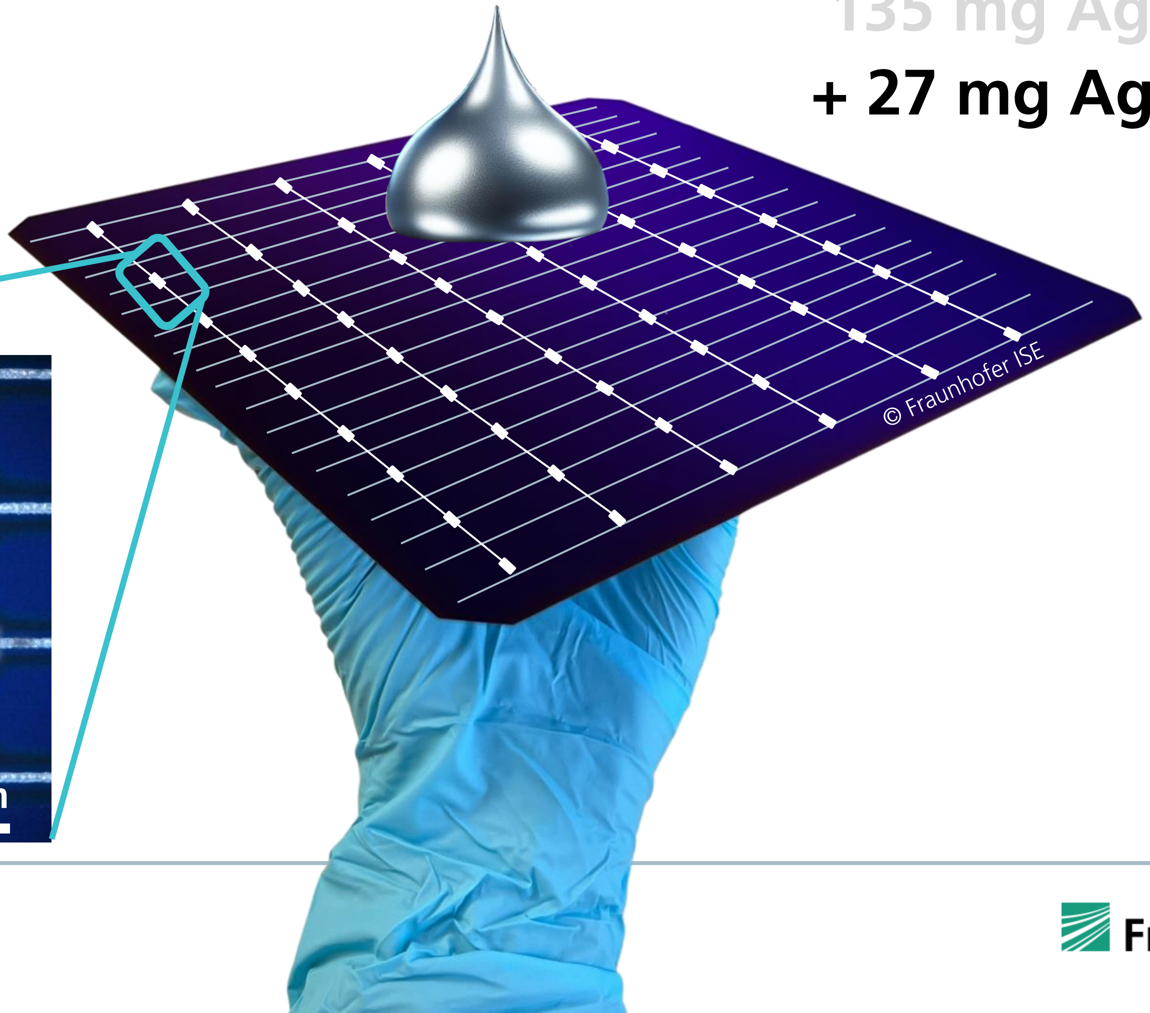
Silver Consumption in a PVST Module

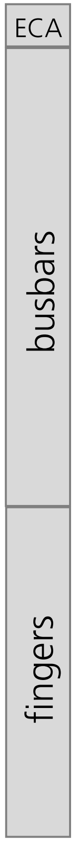
Electrically Conductive Adhesive

Silver-containing module components

- Fingers (bifacial cell)
- Busbars
- Electrically conductive adhesive
    - ECA Density = 4.4 g/cm^3
    - Ag content – 70 wt%







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Silver Consumption in a PVST Module

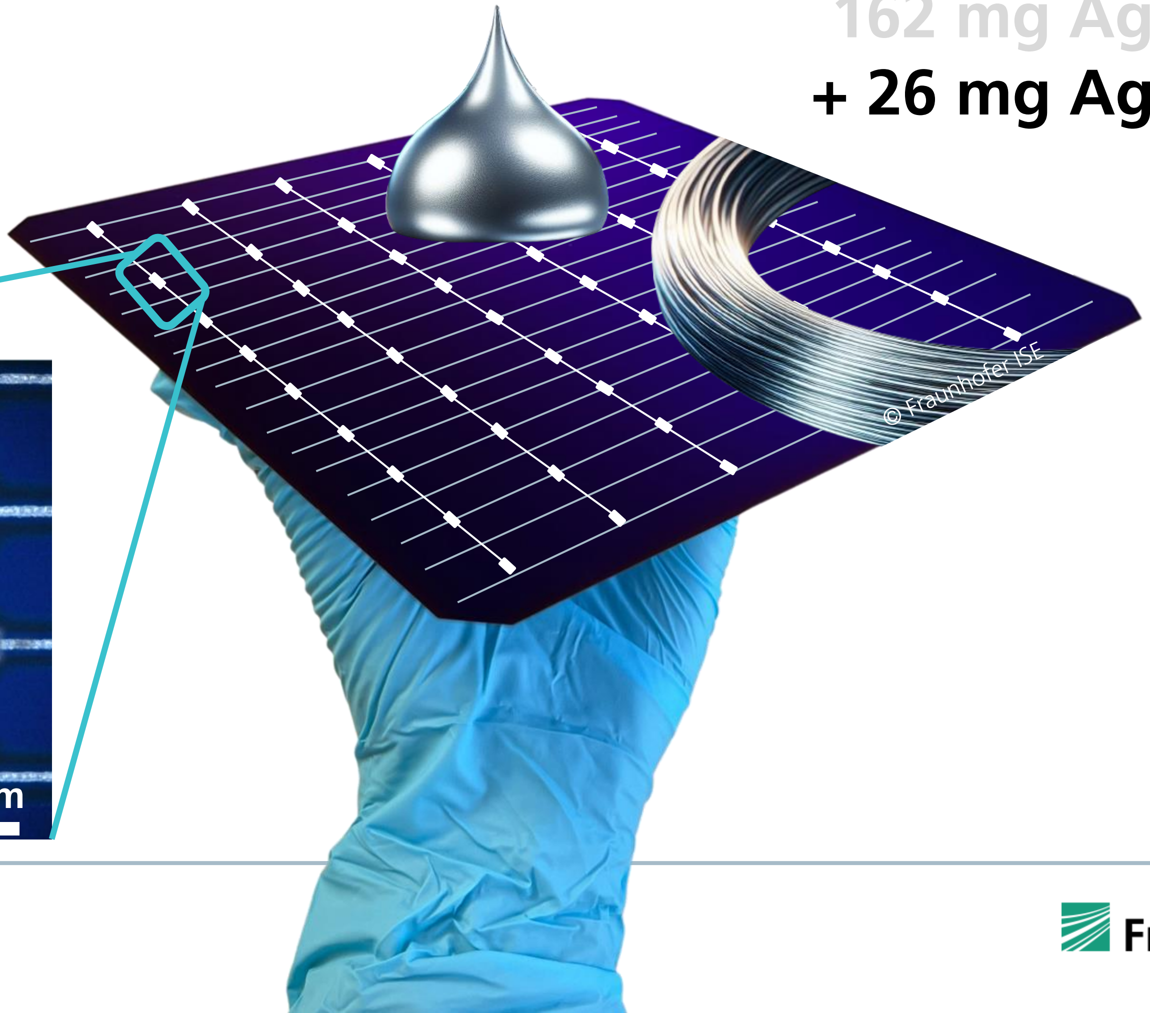
Interconnector

Silver-containing module components

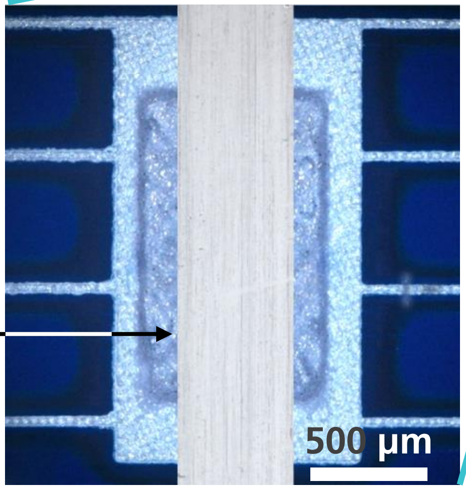
- Fingers (bifacial cell)
- Busbars
- Electrically conductive adhesive
- Interconnector
  - Flat ribbon
  - 1 µm Ag coating

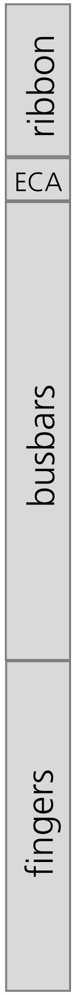
162 mg Ag

+ 26 mg Ag



Silver-coated interconnector

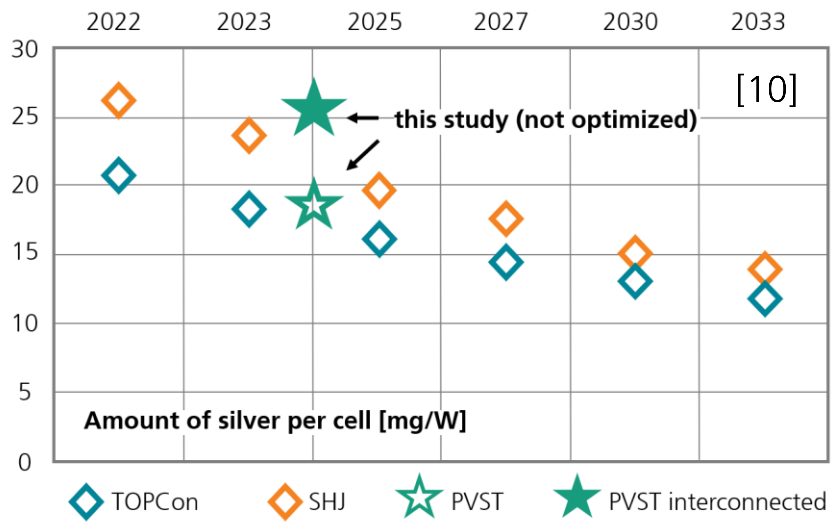




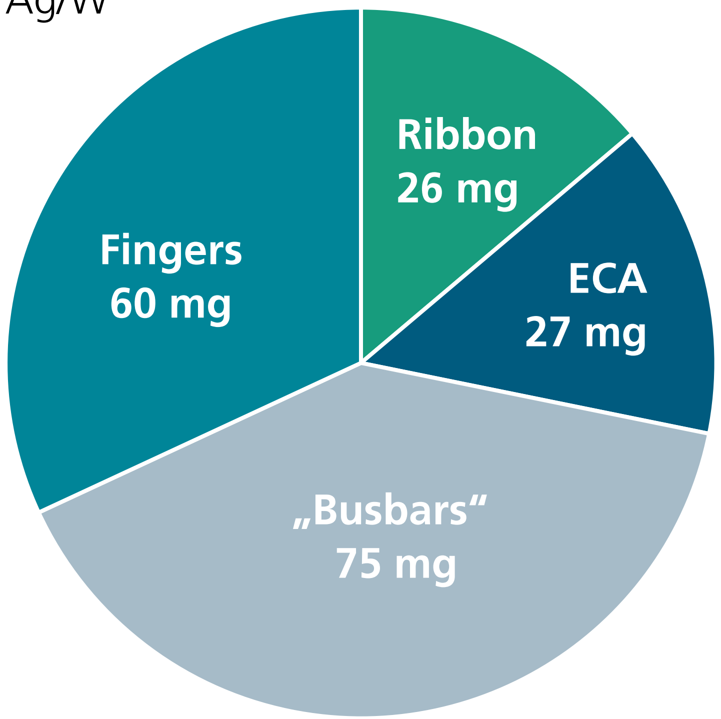
Silver Consumption in a PVST Module

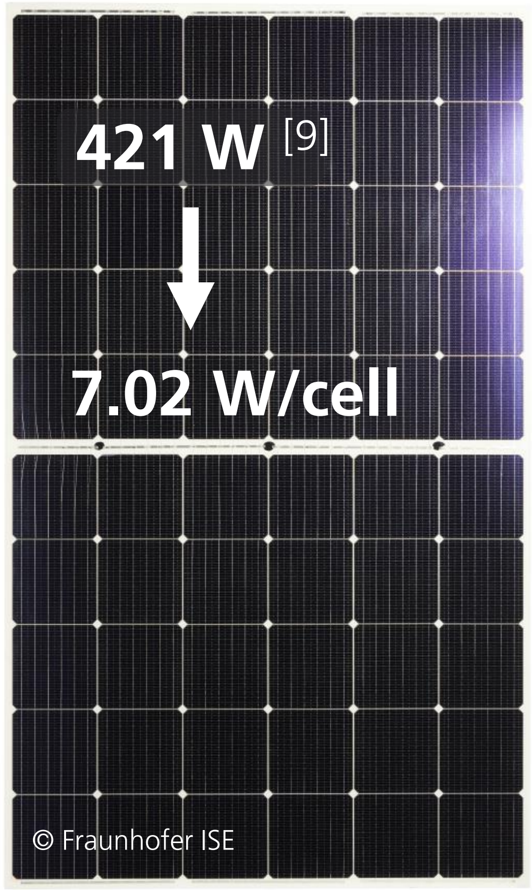
Overview

- Ag consumption / cell power
  - PVST M6 cell → ~ 19 mg Ag/W
  - PVST M6 cell + ECA interconnection → ~ 27 mg Ag/W



188 mg Ag / M6 cell





[9] Fraunhofer ISE, Oxford PV: Oxford PV and Fraunhofer ISE Develop Full-sized Tandem PV Module with Record Efficiency of 25 Percent (31.01.2024)
[10] Modified after ITRPV roadmap, 14. Edition, April 2023

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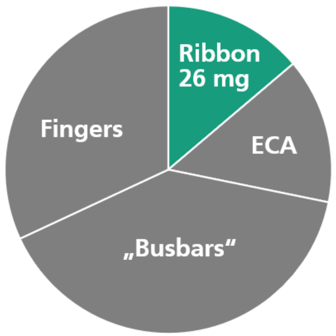
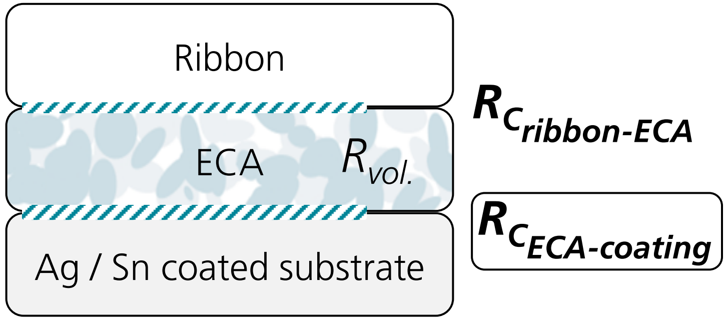
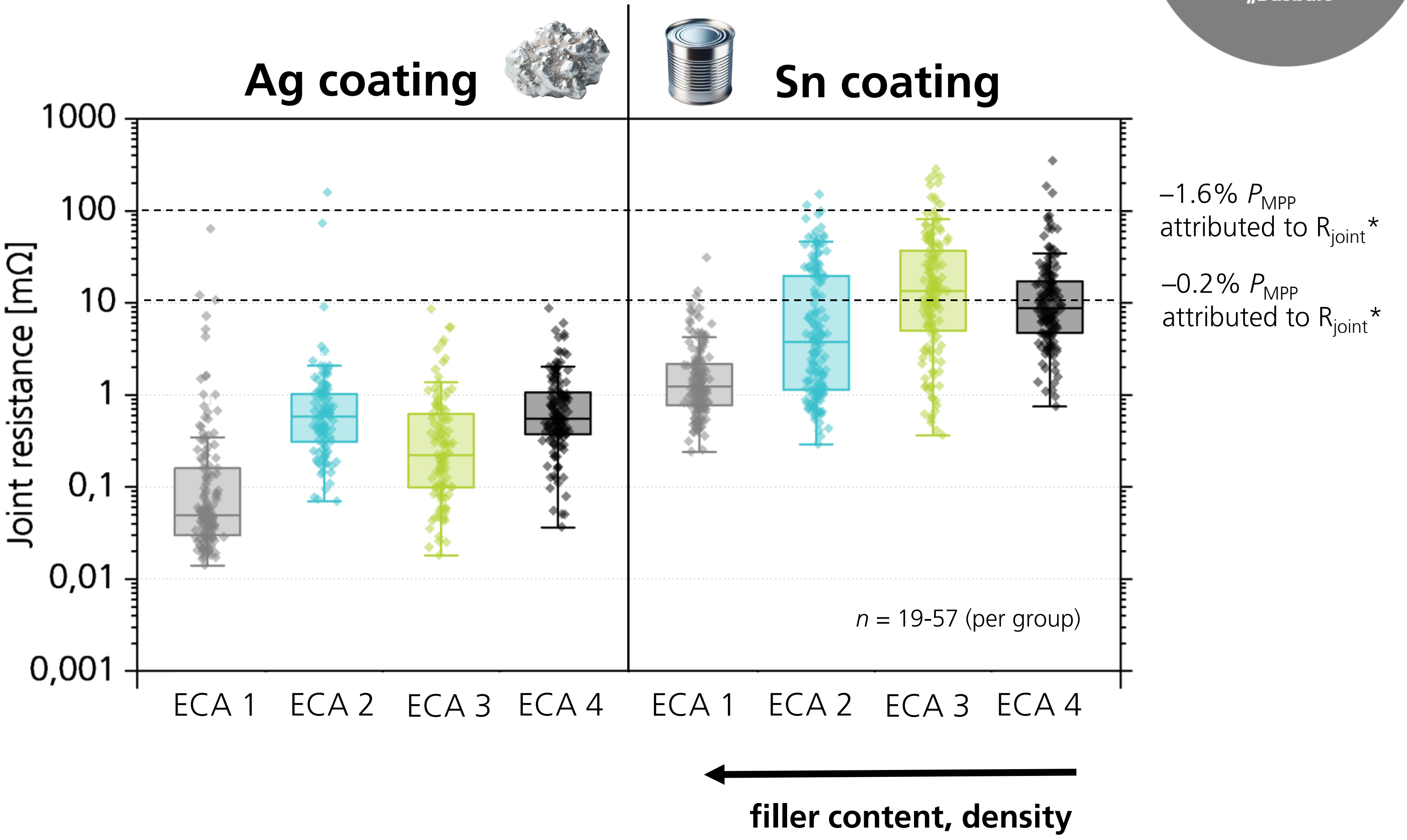
Low-Temperature Interconnection with Sn-Coated Ribbons

Joint Resistance



Overall higher R_{joint} for Sn coating is observed





For method description, s. Böck *et al.*, Proceedings of 14th SiliconPV, 2024

*Value calculated for a PVST module design used for Ag consumption esimation. Larger contact area would correspond to less ohmic losses.

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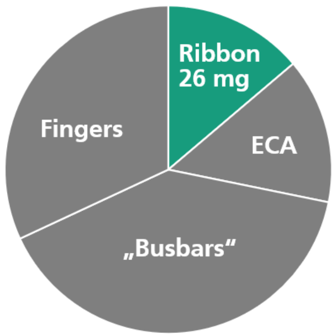
Low-Temperature Interconnection with Sn-Coated Ribbons

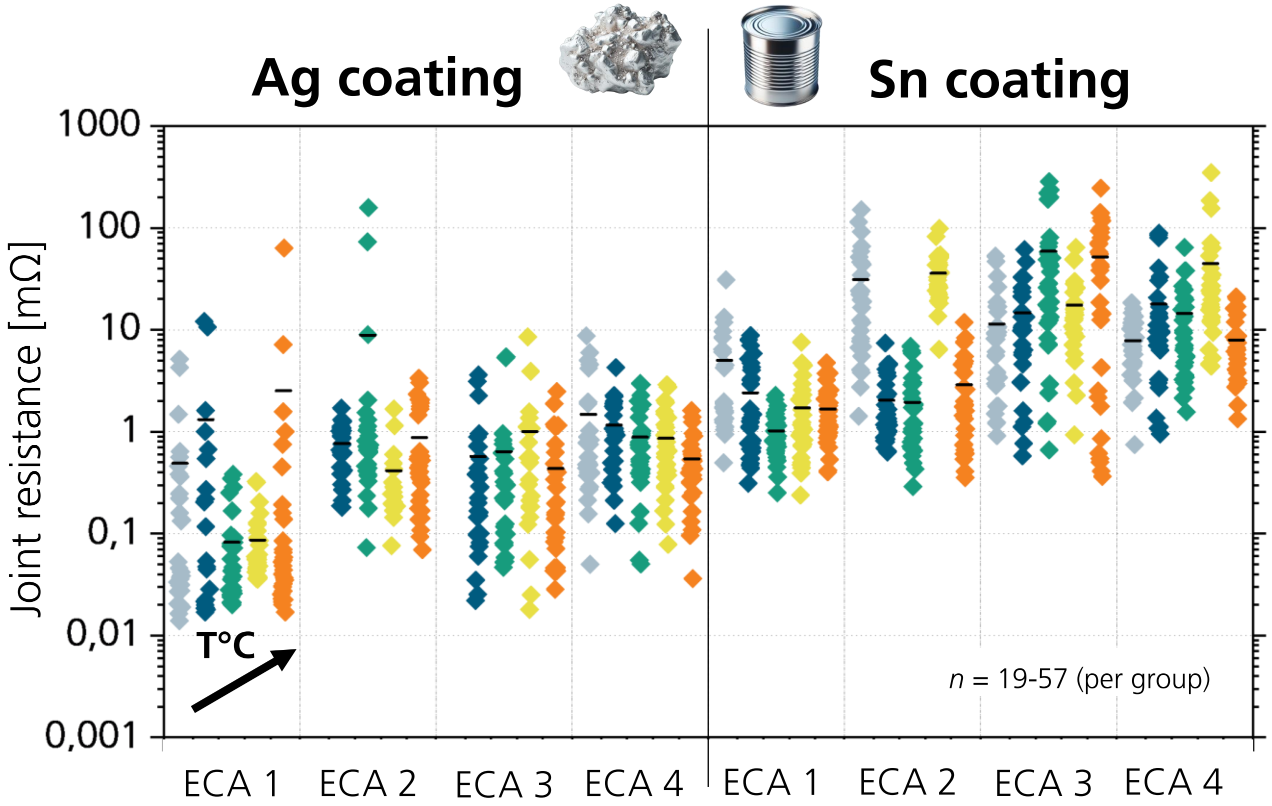
Joint Resistance



Due to strong R_{joint} scattering,
no trends related to curing temperature
of the ECAs can be determined

Curing T°C:

- 100 °C
- 110 °C
- 120 °C
- 130 °C
- 140 °C



For method description, s. Böck *et al.*, Proceedings of 14th SiliconPV, 2024

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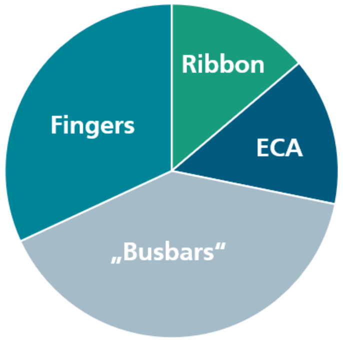
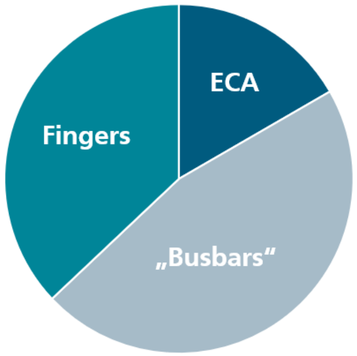
Potential for Ag Reduction

Sn Ribbon Coating

188 mg Ag

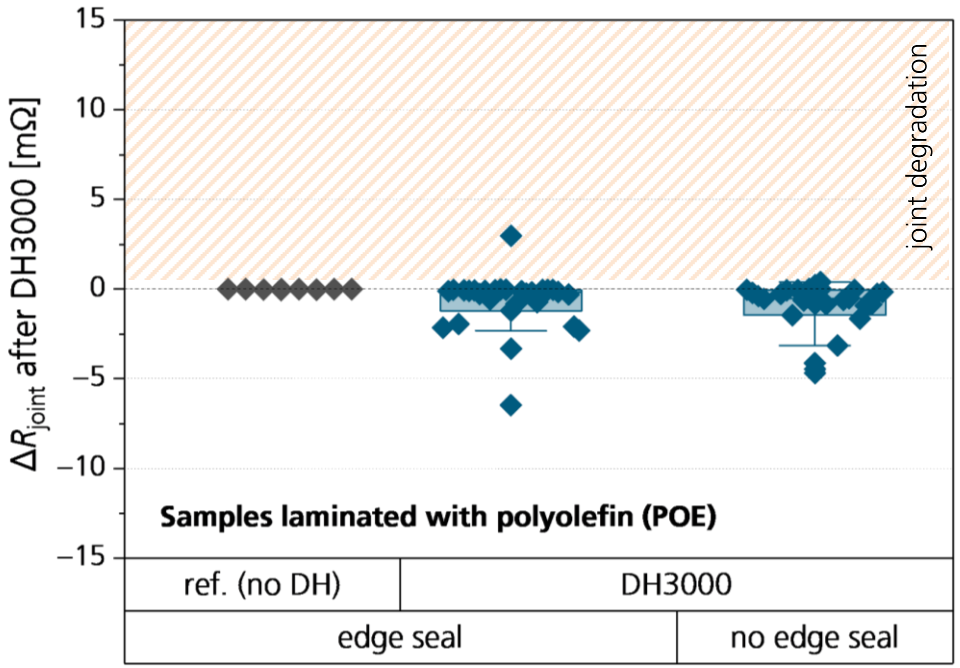


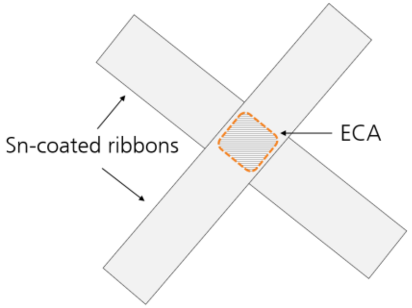
162 mg Ag

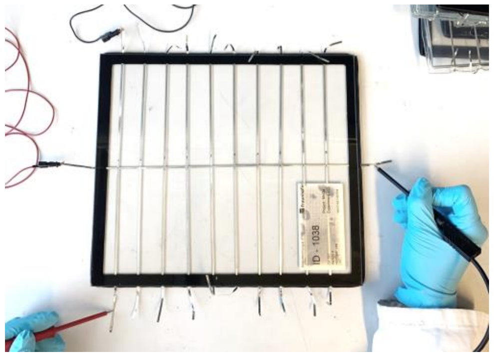


Ag interconnector coating can be replaced by Sn

- Galvanic corrosion* risk is low in solar modules
- POE module encapsulation (low WVTR) and edge seal facilitates joint protection
- Sn / Ag-based ECA / Sn joints show <u>no joint degradation after DH3000</u>







* Anodic index of Ag = -0.15 V, whereas of Sn = -0.65 V. Depending on the environment, various defference in anodic index is tolerated.

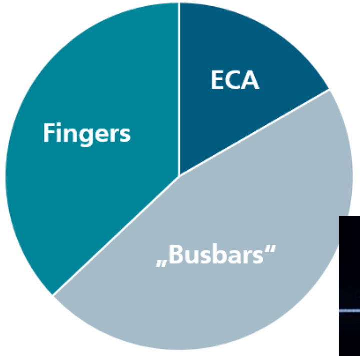
Potential for Ag Reduction

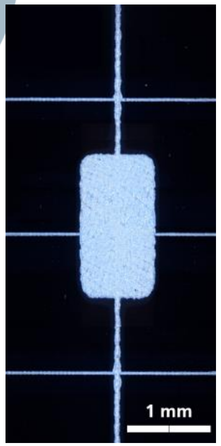
Optimization of the Busbar Design

Leaving out the busbars entirely requires additional ECA

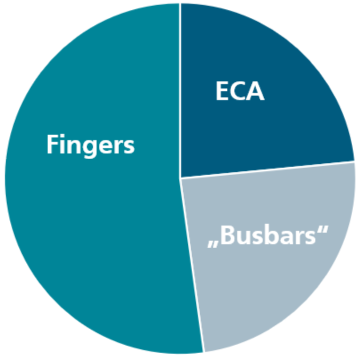
Interconnection pads can be replaced by the redundancy line

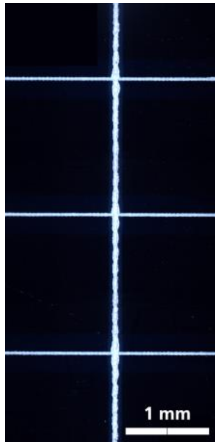
162 mg Ag/cell



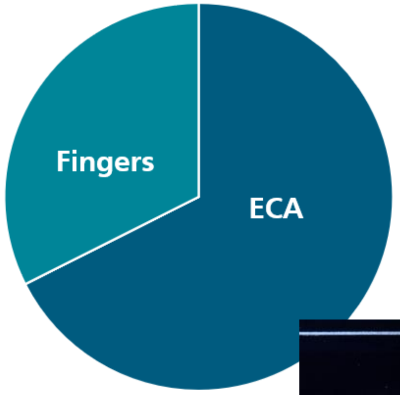


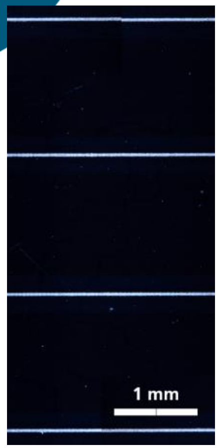
115 mg Ag/cell





185 mg Ag/cell





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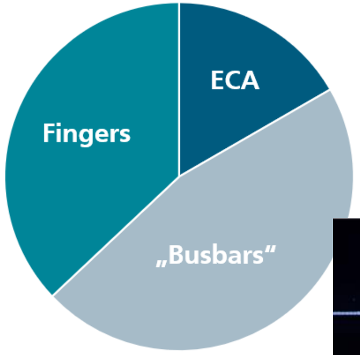
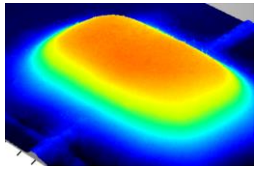
Potential for Ag Reduction

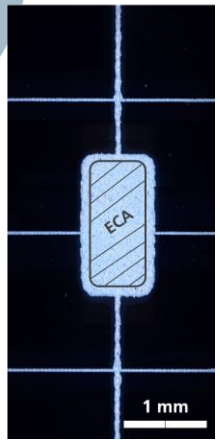
Optimization of the Busbar Design

Busbarless cells require continuous ECA application

162 mg Ag/cell

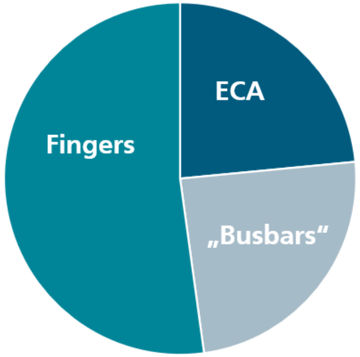


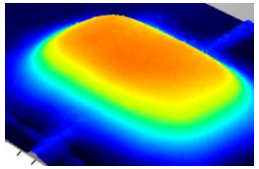


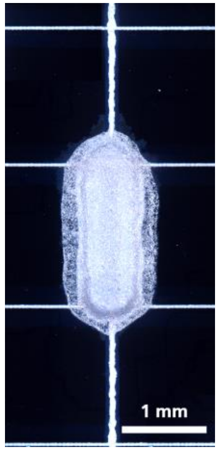


ECA can be printed directly on the cell

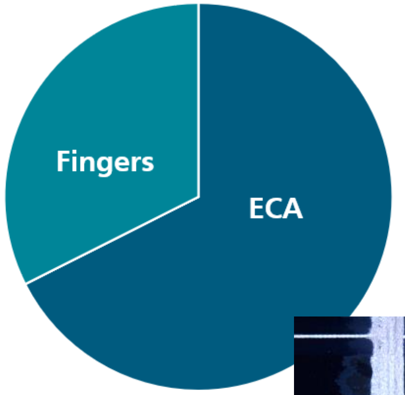
115 mg Ag/cell

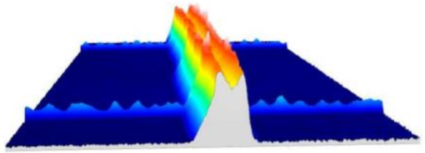


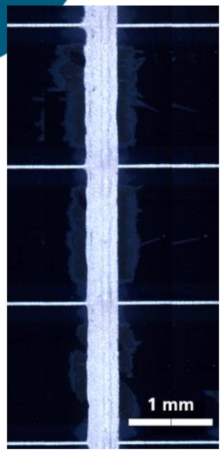




185 mg Ag/cell



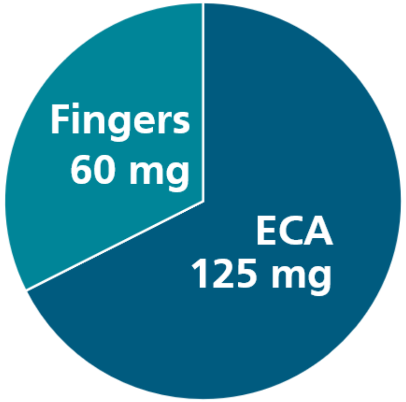




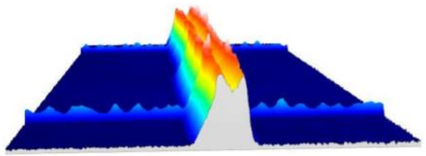
Potential for Ag Reduction

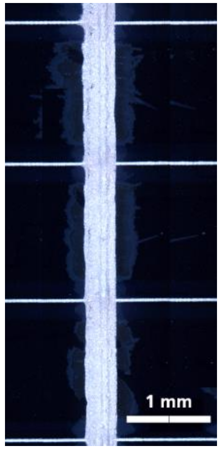
Optimization of the ECA silver content (busbarless)

185 mg Ag/cell



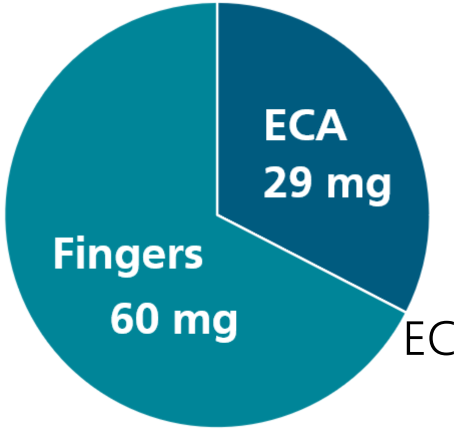
ECA Density = 4.4 g/cm^3
Ag content – 70 wt%





- Significant Ag reduction by using ECA with low Ag content
- When metallization between fingers is absent, conductivity of the ECA is crucial

89 mg Ag/cell



busbarless cell

ECA Density = 4.2 g/cm^3
Ag content – 17 wt%

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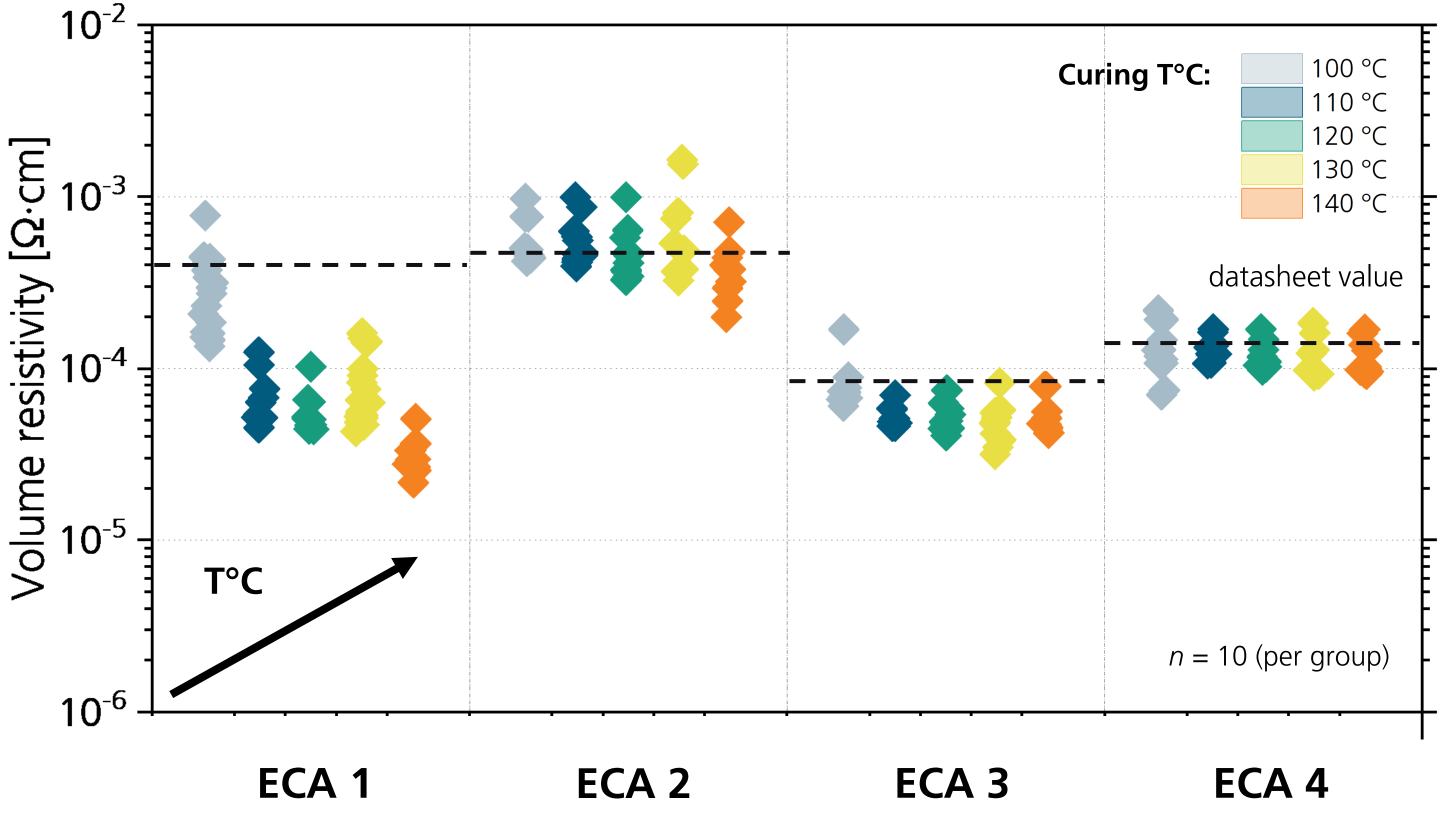
Conductivity of the ECAs

Effect of Curing Temperature

- ECA 1 - ECA 3: curing at higher temparature results in lower volume resistivity
- ECA 4: volume resistivitiy is not influenced by the curing temperature



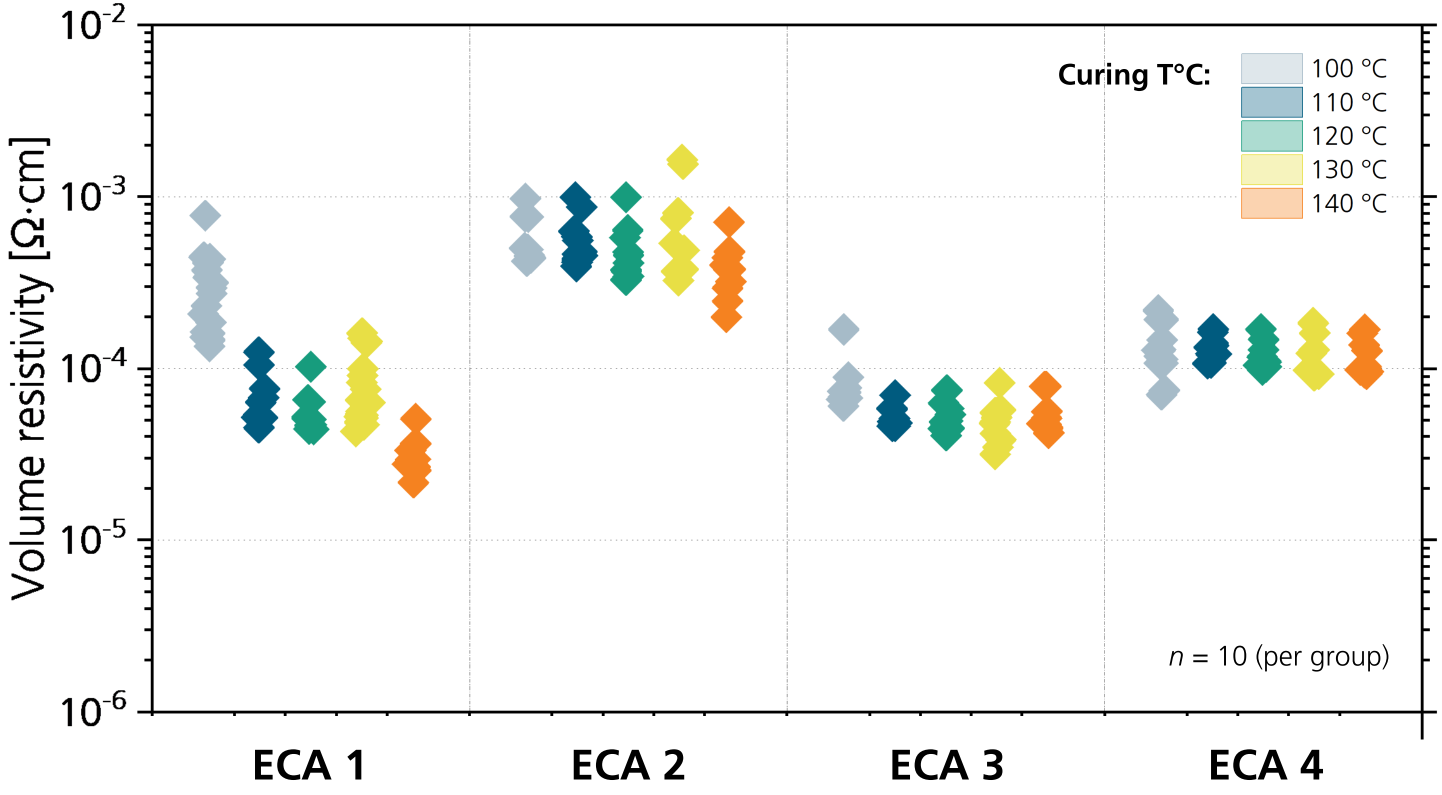
For method description, s. Böck *et al.*, Proceedings of 14th SiliconPV, 2024

Conductivity of the ECAs

Effect of Silver Content

- ECAs with higher silver content demonstrate lower volume resistivity

- ECA 2 (Cu/Ag filler) shows $R_{vol.} < 10^{-2}\ \Omega\cdot cm$ → value compatible with solar cell interconnection

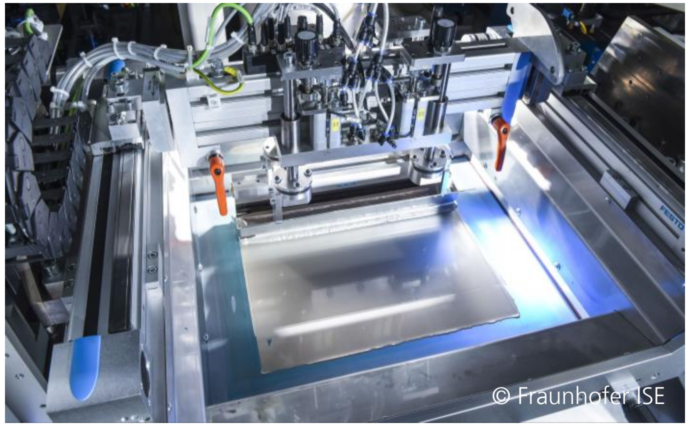


> 70 wt.%	17 wt.%	70 wt.%	60 wt.%
ρ = 4.4 g/cm³	ρ = 4.2 g/cm³	ρ = 3.0 g/cm³	ρ = 2.4 g/cm³

For method description, s. Böck *et al.*, Proceedings of 14th SiliconPV, 2024

Low-Temperature ECA Interconnection Performance
Sample Production

- Automatic interconnection with Ag-coated ribbons
- Curing schemes compatible with industrial PVST cell interconnection
  - $T \leq 140$ °C
  - $t \leq 90$ sec



- Application of ECA with the integrated screen printer
- Continuous design to ensure current transport between metallization fingers

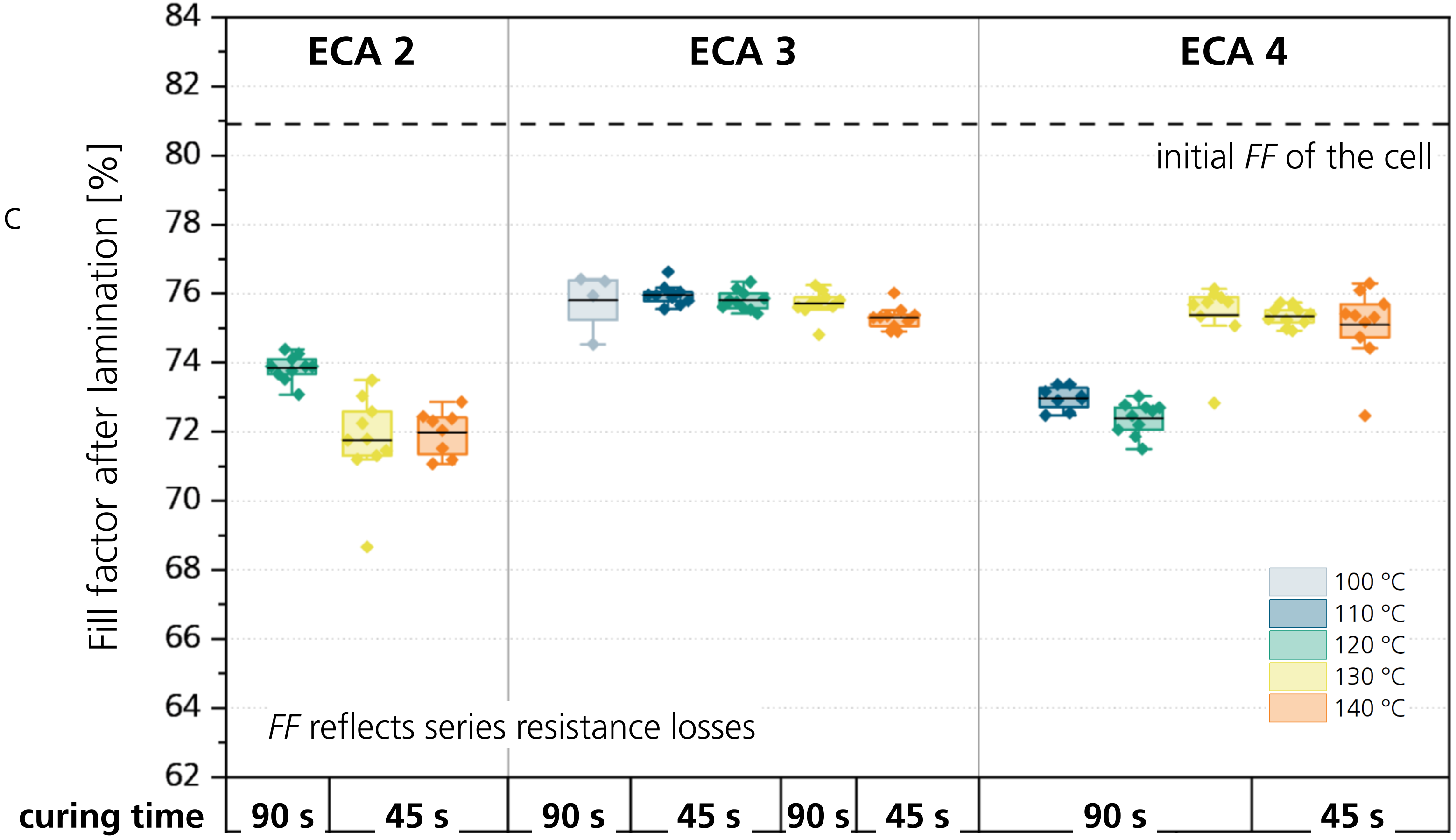
- ECA interconnection of busbarless SHJ cells
- ECA silver consumption* (differs due to different Ag content)
  - ECA 2: 40 mg
  - ECA 3: 119 mg
  - ECA 4: 82 mg

*5BB, unoptimized application design, per M6 wafer

Low-Temperature ECA Interconnection Performance in the Module

After Module Production

- Processing at PVST-compatible temperatures under 1 min is possible
- Behaviour of the ECA is product-specific
- Each ECA has to be tested before introducing it in the production*

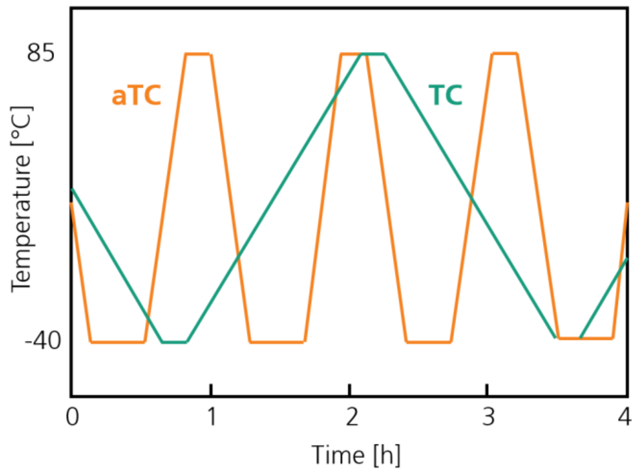


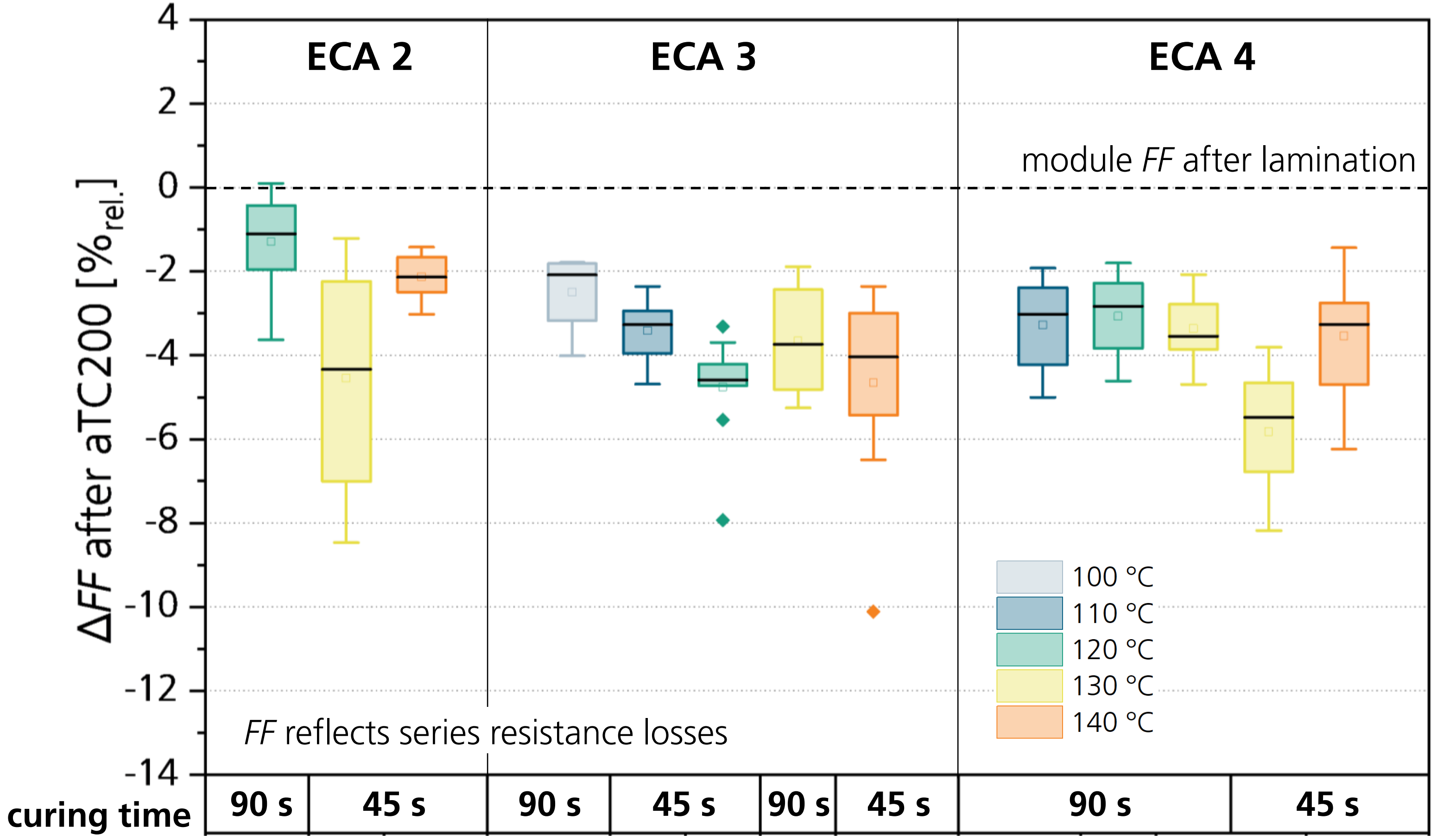
*call us. We know how to do it!

Performance in the Module

Reliability of the Low-Temperature ECA Interconnection

- Samples were exposed to accelerated thermal cycling [11] (aTC), 200 cycles
- All groups show fill facotor loss after aTC200





[11] Schiller *et al.*, Proc. of the 36th EUPVSEC, pp. 995–999 (2019).

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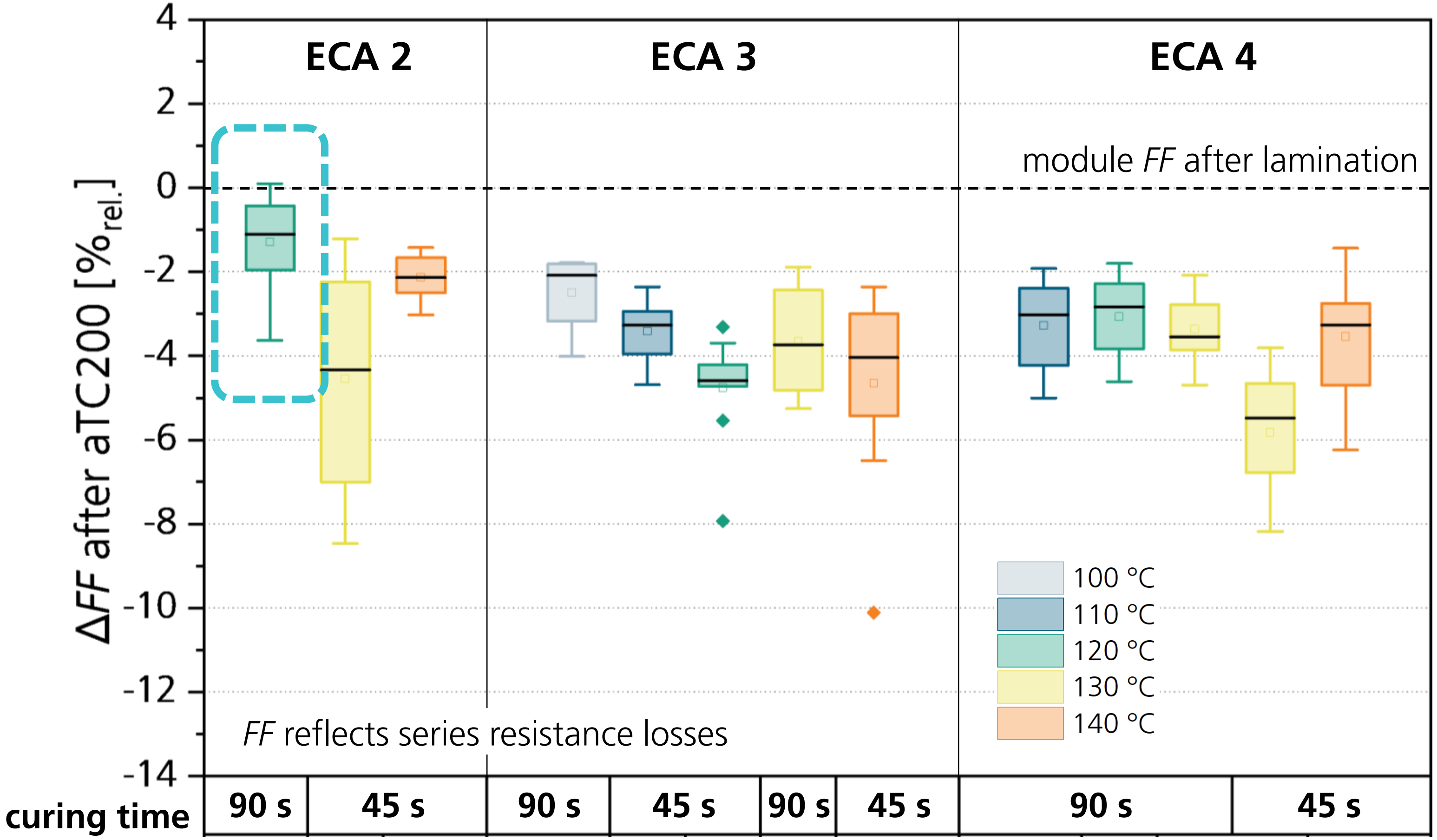
Performance in the Module

Reliability of the Low-Temperature ECA Interconnection

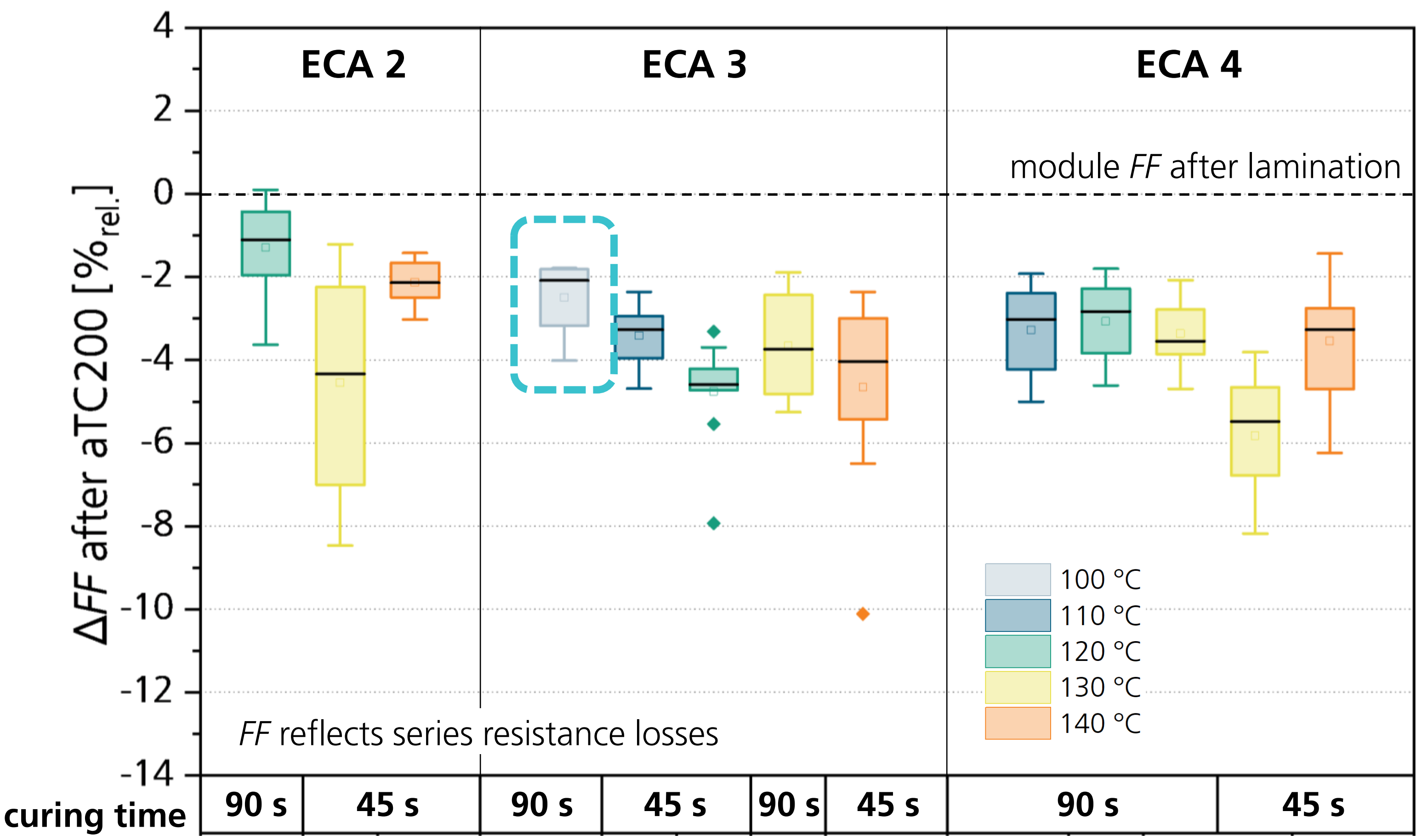
- Least degradation after aTC200:
  - ECA-2 (17 wt% Ag)
    cured at 120 °C for 90 s



Performance in the Module

Reliability of the Low-Temperature ECA Interconnection

- Least degradation after aTC200:
  - ECA-2 (17 wt% Ag)
    cured at 120 °C for 90 s
- Best combination of CTM* loss and least degradation:
  - ECA-3 (70 wt% Ag)
    cured at 100 °C for 90 s



*cell-to-module

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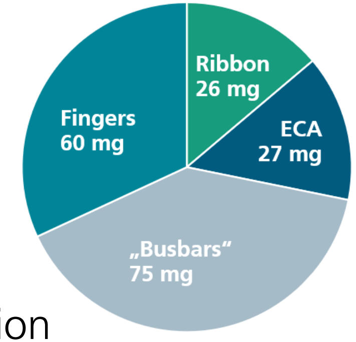
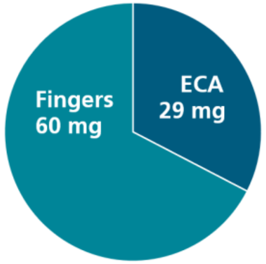
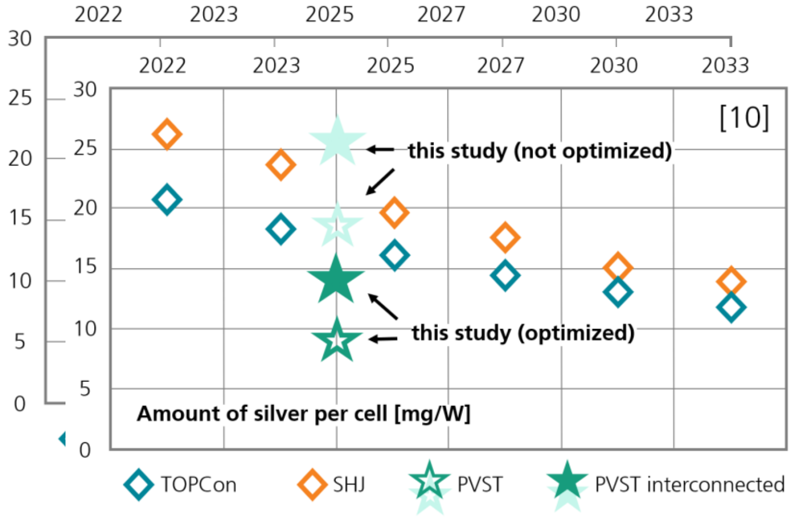
Summary

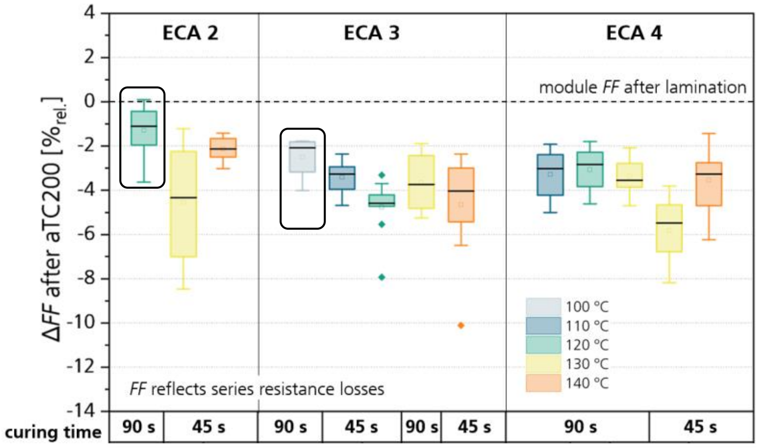
- Silver consumption for M6 PVST cell estimated ~ 19 mg Ag/W (~ 27 mg Ag/W including ECA interconnection) before optimization
- Silver reduction strategies can include
  - Replacement of Ag ribbon coating with Sn (–26 mg Ag/cell)
  - Optimization of busbar metallization and ECA application (–73 mg Ag/cell)
- Busbarless PVST cell with low-Ag ECA interconnection is estimated ~ 13 mg Ag/W







- Automatic ECA interconnection process at $T \leq 140$ °C and $t \leq 90$ sec demonstrated
- Curing longer at lower temperatures is preferable
- ECA interconnection testing on busbarless SHJ cells with aTC200 show
  - Least degradation: ECA-2 (17 wt.% Ag)
  - Least CTM loss and degradation: ECA-3 (70 wt.% Ag)



Thank you for your attention!

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