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

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16th November 2021
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
Motivation: PV Will/Must Reach Terrawatt Scale in ~10 Years
Production Landscape Has to Adapt to Allow Massive Grows

Key factors (amongst others)\textsuperscript{1} are

- Efficient and sustainable use of materials
  - CO\textsubscript{2} / energy consumption
  - Metals for conductors / electrodes\textsuperscript{3,4}
- High conversion efficiency
  - Tandem cell technology

→ Substantial innovation along the PV landscape mandatory

\textsuperscript{1} J.C. Goldschmidt et.al. (2021), DOI: 10.1039/d1ee02497c
\textsuperscript{2} https://www.un.org/sustainabledevelopment/sustainablegoals/
\textsuperscript{3} E. Gervais et al, Renewable and Sustainable Energy Reviews 137 (2021)
\textsuperscript{4} Y Zhang et al, Energy Environ. Sci., 14, 5587 (2021)
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

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4 x 0.25 cm$^2$
7 x 2 cm$^2$
1 x 274 cm$^2$

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1A. ur Rehman et al, PIP (2021) [https://doi.org/10.1002/pip.3499](https://doi.org/10.1002/pip.3499)
Tandem Technology: Low-Current / High-Voltage Devices
Higher Tolerance for Series Resistance

\[ P_{\text{loss,TCO}} = \frac{I_{\text{mpp}}}{V_{\text{mpp}}} \frac{1}{12} R_{\text{TCO}} d_{\text{finger}}^2 \]

\[ P_{\text{loss,finger}} = \frac{I_{\text{mpp}}}{V_{\text{mpp}}} \frac{1}{12} \rho_{\text{finger}} d_{\text{BB}}^2 d_{\text{finger}} \]
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 % $\eta$ loss
- Tandem cell ~ 1.5 % $\eta$ loss

![Diagram of tandem cell technology with labels for $R_{s,grid}$, $R_{TCO,lateral}$, $R_{metal/TCO}$, $R_{absorber,lateral}$, and $R_{e-contact}$]

![Graph showing $V_{oc,1Sun}$ vs $J_{sc}$ for cSi single junction cell, PK single junction cell, and PK / cSi tandem with different $R_s$ related FF loss (%/Wcm²) at various $V_{oc,1Sun}$ levels (630, 730, 1100, 1700 mV).]
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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Compared to SHJ cells\(^1\)

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- High \( \mu \)-TCOs can not be applied
  - Indium in the TCO is used less efficiently \((g/W)\)

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Compared to SHJ cells, the higher series resistance tolerance is partly compensated by:

- No additional lateral transport provided by absorber
- Ideal TCO thickness is much thinner since TCO does not provide anti-reflection properties
- High \( \mu \)-TCOs are not applicable since annealing > 150°C needed
- Higher finger resistance (lower annealing temperature)

\(^1\)C. Messmer et al. PIP (2021), https://doi.org/10.1002/pip.3491
\(^2\)L. Tutsch et al. PIP 29/7 (2021), https://doi.org/10.1002/pip.3388
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- TCO does not provide anti-reflection properties, hence ideal TCO is thinner
- High \(\mu\)-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)

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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 $\mu$-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
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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FHG-SK: ISE-INTERNAL

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

E. Gervais et al, Renewable and Sustainable Energy Reviews 137 (2021)
Capacity Expansion Limit by TCO-, Grid- and Cell Interconnection Electrodes
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<td>20/20/70 170 / 260 / 70</td>
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Supply potential allocated to tandem
- In
- Ag
- Bi
Demand tandem
- In
- Ag-SP + wire
- Bi solder

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<td>ECA BB</td>
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Graph:
- Supply potential allocated to tandem
- Demand tandem
- Materials: Bi / Ag / In

Figure from E. Gervais et al, Renewable and Sustainable Energy Reviews 137 (2021)
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<td>D</td>
<td>ECA_{BB}</td>
<td>Cu-plating</td>
<td>20 / - / -</td>
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E. Gervais et al, Renewable and Sustainable Energy Reviews 137 (2021)
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
Optimizing and adapting screen printing to lower temperatures and different substrate
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$^{1,2}$

$^{1}$ Gensowski et al., EU PVSEC (2020)
$^{2}$ Gensowski et al., Solar RRL (2020)
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

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\(^1\) J. Schube et al., *PhD thesis*, 2021
\(^2\) J. Schube et al., *pss RRL*, 2019
\(^3\) J. Schube et al., *8th Met. Workshop*, 2019

*PV Nano Cell is acknowledged for providing the paste*
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\textsuperscript{1,2}
- FlexTrail for ultra-narrow fingers below 10 µm
  - And very good aspect ratio
- Substitute Ag by Cu
  - Paste, ECA, Plating
Cu contacts can be electroplated on perovskite cells.

Perovskite solar cells survive wet-chemical electroplating process.

Also addressing Cu grid lines on TCO+glass for thin film modules.

More Efficient Use / Avoidance of Ag, In and Bi

Proof of Concept For Cu Plating on Perovskite
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)
Thank you for your Attention! Thank you for your Attention! Thanks to all Co-Workers! Thanks to all Co-Workers!

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MaNiTu
Fraunhofer Leitprojekt