Improvement of solder interconnections applied on back contact solar cells with low-T Cu paste busbars

Dominik Rudolph
Motivation: do we have enough silver?

- Current Ag consumption (PERC cell) is ~ 12-13 mg/Wp
- World silver mining: 27,800 t/a in 2019 [3] (~24,000 t/a in 2020 and 2021)
- With today's technology 50% of world silver mining would allow for only 1 TWp/a PV production

-> Alternative metallization and metal quantity reduction strategies are required

Motivation: Copper as replacement material

- Copper is much cheaper and features similar conductivity

<table>
<thead>
<tr>
<th>Raw material comparison:</th>
<th>Silver</th>
<th>Copper</th>
<th>Copper vs. Silver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price per kg in US Dollar</td>
<td>818</td>
<td>8.9</td>
<td>~100x cheaper (12.04.23)</td>
</tr>
<tr>
<td>Conductivity in $10^{-8} , \Omega m$ [4]</td>
<td>1.59</td>
<td>1.68</td>
<td>5% less conductive</td>
</tr>
<tr>
<td>Carbon footprint in kgCO$_2$/kg [5]</td>
<td>155</td>
<td>3.97</td>
<td>40x better</td>
</tr>
<tr>
<td>Max level in drinking water (EPA) in mg/liter [6]</td>
<td>0.1</td>
<td>1.0</td>
<td>10x less toxic</td>
</tr>
<tr>
<td>Abundance in Earth's crust in ppm</td>
<td>0.08</td>
<td>68</td>
<td>~1000x more abundant</td>
</tr>
</tbody>
</table>

[5]. R. Schindler, N. Schmalbein, V. Steltenkamp, J. Cave, B. Wens, A. Anhalt,. SMART TRASH: Study on RFID tags and the recycling industry. 1776 Main Street, P.O. Box 2138, Santa Monica, CA 90407-2138 : Rand Corporation, 2012.
Screen printed Cu

- IBC ideal for Cu screen printing
- Technology well-known from PCB
- 100% compatible with standard PV equipment
- Curing fast and at low temperature
  - Standard drying
  - “Snap curing” (300°C, few seconds with direct solid-to-solid heat transfer)

How to avoid direct contact with Si?
Ag replacement routes for ZEBRA IBC cells

1) Replacement of **BBs** in ZEBRA

2) Replacement of **fingers** in ZEBRA

Route 1: soldering optimization & module results

ZEBRA with Cu BBs
Previous results

- High throughput process capability
- **No contamination** of the cell
- Series resistance
- Long time durability and reliability
- Solderability
- Adhesion

- Screen printing & short drying/curing
- pFF & Climate chamber tests
- Line resistance & FF
- Climate chamber tests
- Stringer
- Peel force

[8] D. Rudolph et al., “Screen printable, non-fire-through copper paste applied as busbar metallization for back contact solar cells”, 10th Metallization and Interconnection Workshop for Crystalline Solar Cells, 2022
Soldering optimization

• Initial optimization by manual soldering
  • A combination of higher soldering temperature and hot plate temperature improves the adhesion

• Further optimization using automatic stringing
  • Best recipe 6 results in peel force values between 0.6 and 0.9 N/mm
  → Stable interconnection of Cu busbars by soldering, obtained using stringer with adjusted settings.
Module fabrication: Comparing encapsulation methods

<table>
<thead>
<tr>
<th>Group</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell type</td>
<td>ZEBRA M6 with 6 busbars</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Busbar paste</td>
<td><strong>Reference Ag</strong></td>
<td><strong>Cu A</strong></td>
<td><strong>Cu B</strong></td>
<td><strong>Cu A</strong></td>
</tr>
<tr>
<td>Soldering process</td>
<td>Automatic soldering at Teamtechnik stringer using recipe 6&lt;br&gt;Ribbon: SnPb 60/40 1 x 0.24 mm²&lt;br&gt;Cross connectors: SnPb 60/40 6 mm x 0.3 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module BOM</td>
<td>Glass - <strong>POE</strong> – transparent backsheet</td>
<td>Glass - <strong>POE</strong> – transparent backsheet</td>
<td>Glass - <strong>POE</strong> – transparent backsheet</td>
<td>Glass - <strong>EVA</strong> – transparent backsheet</td>
</tr>
</tbody>
</table>

- **POE**: PolyOlefin Encapsulant
- **EVA**: Ethylene Vinyl Acetate Encapsulant
Module I–V results

- Module results before climate chamber tests are comparable
- Slightly lower FF for group 3
Climate chamber results Damp Heat (DH): $J_{SC}$ and $V_{OC}$

- Stable $J_{SC}$ until DH 3000 for all groups
- $V_{OC}$ stable until DH 2000 for all groups and until DH 3000 for group 4
- Break down in $V_{OC}$ for groups 1, 2 and 3 during DH 3000

→ Highest stability obtained with glass-EVA-backsheet BOM
Climate chamber results DH: pFF, FF and P_{mpp}

- No degradation in pFF until **DH 3000**
- Break down in FF and P_{mpp} at DH 3000 for group 1 to 3
- Group 4 stable in FF and P_{mpp} until DH 3000 → **3 x IEC DH for soldered Cu busbars** with EVA encapsulation and backsheet
Climate chamber results DH: EL fault detection

Module defect is only visible for POE encapsulated groups 1-3 after DH3000

→ Contact between BB and fingers

Initial          | DH 3000
---|---
G1 Ag-ref  |  
G2 POE  |  
G3 Cu 1 |  
G4 EVA |  
G4 EVA |  

11th edition of the Metallization and Interconnection Workshop for Crystalline Solar Cells (MIW)

11.05.2023
Climate chamber results: Thermal Cycling (TC)

- All modules remain stable until TC600
- No degradation of the contact → Soldering connection is no issue
Climate chamber results TC: EL fault detection

<table>
<thead>
<tr>
<th>G1</th>
<th>Ag-ref</th>
<th>initial</th>
<th>TC200</th>
<th>TC600</th>
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<table>
<thead>
<tr>
<th>G3</th>
<th>Cu 2</th>
<th>initial</th>
<th>TC200</th>
<th>TC600</th>
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<table>
<thead>
<tr>
<th>G2</th>
<th>Cu 1</th>
<th>initial</th>
<th>TC200</th>
<th>TC600</th>
</tr>
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<table>
<thead>
<tr>
<th>G4</th>
<th>Cu 1</th>
<th>initial</th>
<th>TC200</th>
<th>TC600</th>
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• No severe issues visible in EL images
• More finger interruptions visible for Cu paste groups
  • Thermal stress between silver finger and Cu busbar?
Outlook on route 2: Cu finger and BB metallization

For Cu cells

- Comparable $V_{OC}$, pFF and cell efficiency $\eta$
- Lower $J_{SC}$ of 0.1 mA/cm$^2$
- Better FF of 0.3%$_{\text{abs}}$ but not statistically significant

<table>
<thead>
<tr>
<th>Paste</th>
<th>Data type</th>
<th>$V_{OC}$ (mV)</th>
<th>$J_{SC}$ (mA/cm$^2$)</th>
<th>FF (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>Best cell</td>
<td>687.2</td>
<td>41.92</td>
<td>80.32</td>
<td>23.14</td>
</tr>
<tr>
<td></td>
<td>Avg. of 34 cells</td>
<td>688.9±1.2</td>
<td>41.85±0.05</td>
<td>79.54±0.36</td>
<td>22.94±0.11</td>
</tr>
<tr>
<td>Cu</td>
<td>Best cell</td>
<td>690.2</td>
<td>41.80</td>
<td>80.56</td>
<td>23.25</td>
</tr>
<tr>
<td></td>
<td>Avg. of 34 cells</td>
<td>689.6±0.9</td>
<td>41.75±0.06</td>
<td>79.81±0.41</td>
<td>22.98±0.13</td>
</tr>
</tbody>
</table>

Conclusion

• Stable interconnection of Cu busbars by soldering

• Cu BB modules with EVA+backsheet passed $3 \times$ IEC DH and TC

• Comparable result for Ag BB modules and Cu BB modules encapsulated in POE + backsheet: pass $2 \times$ IEC DH)

• $V_{OC}$ and pFF are not degrading for the Cu BB modules $\rightarrow$ Cu indiffusion is no issue
All requirements fulfilled

- High throughput process capability
- **No contamination** of the cell
- Series resistance
- Long time durability and reliability
- Solderability
- Adhesion

- Screen printing & short drying/curing
- **pFF & Climate chamber tests**
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