Lead-free Solders for Ribbon Interconnection of Crystalline Silicon PERC Solar Cells with Infrared Soldering

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- Characterization of melting and solidification with differential scanning calorimetry
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Motivation and Aims

**Motivation**
- Removal of toxic lead from PV module
- Reduction of thermomechanical stress by low melting point solders
- Interconnection of temperature-sensitive cells

**Aims**
- Measurement of melting and solidification temperatures
- Microstructural analysis of solder bonds
- Analysis of peel strength and fracture pattern
- Obtaining indications for reliability

**Challenge**
- Brittleness of bismuth
Experimental Approach

Differential scanning calorimetry (DSC)

Connection of 5-busbar industrial mono PERC solar cells

Connected cells

One-cell modules
Cross section analysis
Peel test / fracture analysis

Reliability tests

Sn43Bi57 Sn60Bi40 Sn60Bi38Ag2 Ecosol Sn60Pb40

Metallography

Infrared stringer
Peel test

Sn43Bi57 Sn60Bi40 Sn60Bi38Ag2 Ecosol Sn60Pb40

0.22 mm
0.9 mm

F_peel

Joint 200 µm Cell Ribbon
DSC and Infrared Stringing

- Analysis of endothermic and exothermic reactions with DSC
  - 80 mg coated ribbon in sealed Al crucible
  - Heating and cooling from 35 °C to 250 °C at 10 K/min
- DSC-analysis according to [1]
  - Eutectic and liquidus temperature during heating and cooling
  - Undercooling [2]
- Infrared stringer TT1800 with 2.2 s/cycle
- One-cell modules with EVA, TPT-backsheet and non AR-coated glass

<table>
<thead>
<tr>
<th>Coating</th>
<th>Peak soldering temp. (°C)</th>
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<tbody>
<tr>
<td>Sn43Bi57</td>
<td>160</td>
</tr>
<tr>
<td>Sn60Bi40</td>
<td>180</td>
</tr>
<tr>
<td>Sn60Bi38Ag2</td>
<td>180</td>
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<tr>
<td>Ecosol</td>
<td>200</td>
</tr>
<tr>
<td>Sn60Pb40</td>
<td>220</td>
</tr>
</tbody>
</table>

DSC – Melting and Solidification

Sn43Bi57

- Melting of Sn43Bi57 at single temperature 137 °C
- Solidification at 134 °C
- Undercooling: 3 K
- Assumption: Undercooling is an advantageous effect to reduce thermo-mechanical stress
DSC – Melting and Solidification
Sn60Bi40 and Sn60Bi38Ag2

- Melting of Sn60Bi40 in a range from 138 °C to 165 °C
- Solid-liquid-phase and liquid phase
- Beginning of solidification at 152 °C, end at 130 °C
- Undercooling: ~8–13 K
- No difference for Sn60Bi38Ag2
DSC – Melting and Solidification

Ecosol

- Melting of Ecosol in a range from 137 °C to 171 °C
- Beginning of solidification at 157 °C and end at 131 °C
- Undercooling: ~6−14 K
- Higher process temperatures will be necessary
Cross Section Analysis

Sn60Pb40

- Low (< 30°) and high wetting angles (90°)
- Good solder bond is established anyways
- Solder thickness front often lower than on the rear
- Downholders in the stringer
Cross Section Analysis

Sn60Pb40

- Usually fine grain structure
- Sn-rich grains inside large Pb-rich grains (“sponge”)
- High ductility expected

Sn60Pb40 details
Cross Section Analysis

Sn43Bi57

- Sn43Bi57 tends to have larger grain sizes of Bi (often > 30 μm²)
- Problem: brittleness and growth during aging
- Good wetting
- Again, usually front solder layer is thinner than rear
Cross Section Analysis

Sn60Bi40

- Good wetting and usually smaller grain sizes
- Lower risk of large and brittle Bi-rich grains
Cross Section Analysis

Sn60Bi38Ag2

- Mixture of large and small Bi-rich grains
- Ag forms separate phases (Ag₃Sn) → usually intermetallic phases are considered as problematic
Cross Section Analysis

**Ecosol**

- Good wetting with usually < 90° wetting angle
- Mixture of large and small Bi-rich grains, seems to be lower Bi-content
- Coarse boundaries within solder or caused by sample preparation
Peel and Fracture Analysis

- Peel strength is on average more than 1 N/mm except from Sn43Bi57 rear side.
- Pads with low adhesion for lead-free types.
- Sn60Pb40 highest peel strength due to better ductility.
- Weakest link at the Si-busbar-interface, not inside the solder.
- Ductile fracture for Sn60Pb40.
- Brittle fracture for lead-free solders.
- Fracture of Ecosol sometimes at the solder-ribbon interface.
Results

Reliability

- Similar degradation of all solders after reliability tests
- Finger interruptions observed due to ribbon misalignment regardless of solder coating
- Intermediate conclusion: All solders seem to be capable of passing IEC certification
Summary

- Melting and solidification characterized with DSC
- Tailoring of liquidus by adapting solder composition
- Sn43Bi57 has large areas with brittle Bi-rich phases (> 30 μm²)
- Hypoeutectic Sn-Bi-compositions contain mix of large and small grains
- No obvious advantage of Ag-addition in Sn-Bi (Ag₃Sn, additional costs)
- Adequate peel strength of around 1 N/mm for all solders
- Signs of brittle fracture for Sn-Bi-X / Ecosol
- All tested solders pass rudimentary reliability tests

Preliminary conclusion and recommendation

- Lead-free Bi-based solders are suitable for the interconnection
- Hypoeutectic Sn-Bi-composition (less Bi) with moderate process temperature
Thank you for your Attention!

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