Ag Sinter Joining for WBG Interconnects

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Outline

✔ Introduction
  - Wide band gap power device
  - Die-bonding for power electronics

✔ Sinter joining
  - Ag sinter joining
  - Thermal stability and its improvement
  - Ag film stress migration bonding
  - Low temperature sintering mechanism

✔ Ceramic substrate

✔ Summary and future
WBG benefits and market

Benefits:

- Energy consumption reduction
- Size reduction
- Less or no cooling
- High frequency

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>1.12</td>
<td>3.26</td>
</tr>
<tr>
<td>Breakdown voltage (MV/cm)</td>
<td>0.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Thermal conductivity (W/m·K)</td>
<td>160</td>
<td>490</td>
</tr>
</tbody>
</table>

From Fuji Keizai

WBG market growth

SiC-SBD

SiC-FET

GaN

WBG device

Home & Office

Renewable energy

Transportation

Industry
SiC power devices in market

- Toyota FCV
  - SiC-SBD
- Mitsubishi Electric
  - Power conditioner
- Fuji Electric
- Toshiba
- Suzuki

- ~ 40% energy loss reduction
- ~ 1/5 size reduction

--- etc.
New generation power interconnections

- Resistance to severe thermal cycles: -50°C-250°C
- 250°C exposure & oxidation resistant interface design

- Electrode materials
- Bonding method
- Wire/ribbon/planer bonding

- Si₃N₄, AlN, Al₂O₃

- Ag sinter joining
- Stress migration bonding
- Pure Zn soldering
- Active metal brazing
- Ag sinter joining

- Cu or Al?
- Plating or other oxidation/reaction protection?

- Molding compound

- Tᵢ = 250 °C

K. Sukanuma, ISIR, Osaka University
Old sinter joining


Very high pressure: 100 MPa/1GPa
Ag sinter joining with hybrid paste

at 200-250 °C in air with no/low-pressure

- High bonding strength > 40 MPa
- High thermal conductivity > 140 W/mK
- Excellent heat shock resistance : -50 – 300 °C

K. Suganuma, ISIR, Osaka University
Low temperature & no pressure at 200 °C

Resistivity (x10⁻⁶ Ω⋅cm) vs Temperature (°C)

Micron/submicron hybrid paste
Nanoparticles paste

5 x 10⁻⁶ Ω⋅cm
Low temperature, no pressure, O₂ is needed!

Ag metallization is the best

O₂ is required


SiC$_p$ addition and metallization effect in heat exposure

- SiC$_p$ addition stabilize sintered microstructure
- Ti underlayer has a great effect to avoid degradation

![Graph showing shear strength over storage hours at 150, 250, and 350 °C]

- At 150 °C, shear strength is relatively stable.
- At 250 °C, shear strength decreases slightly.
- At 350 °C, shear strength drops significantly.

Initial: Ag thickness = 2 μm, Ti thickness = 500 nm
150 °C: Ag thickness = 2 μm, Ti thickness = 500 nm
250 °C: Ag thickness = 2 μm, Ti thickness = 500 nm
350 °C: Ag thickness = 2 μm, Ti thickness = 500 nm

- Voids and oxide formation are observed at 350 °C.
Imide-based nano-composite molding

No pressure, 250°C-30min

As-molded

No change on SiC-SBD

NEDO funded project in collaboration with Nippon Shokubai, Funaki-labo.
Delamination after thermal cycles

Sn-Pb solder

Hybrid Ag paste

Ag nanoparticle paste and Au-12Ge solder also failed by delamination.
Ag thin film stress migration bonding

1μm thick Ag film can make perfect bonding

at 250 °C in air with no pressure

Joining temperature and substrate effects

Low temperature Ag sinter joining mechanism

Self-generation of nanoparticles realizes to low temperature bonding
Ag-O liquid formation along G.B.


250 °C
Self-healing of Ag sinter joint layer

Initial

200 °C - 50 h + 300 °C - 10 h

under the support of NEDO in collaboration with DENSO Corp.
Ceramic substrate fracture after thermal cycles

-40 °C ~ 200 °C / 500 cycles
Typical substrate die-attach materials

Table Selected properties

<table>
<thead>
<tr>
<th></th>
<th>Al₂O₃</th>
<th>AlN</th>
<th>Si₃N₄</th>
<th>Cu</th>
<th>Al</th>
<th>Ag</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W/m·K)</td>
<td>30</td>
<td>170</td>
<td>27</td>
<td>398</td>
<td>236</td>
<td>420</td>
<td>73</td>
</tr>
<tr>
<td>Thermal expansion (x10⁻⁶/K)</td>
<td>7.2</td>
<td>4.8</td>
<td>2.8</td>
<td>17.7</td>
<td>23.8</td>
<td>14.2</td>
<td>14.0</td>
</tr>
<tr>
<td>Strength* (MPa)</td>
<td>300</td>
<td>350</td>
<td>900</td>
<td>70</td>
<td>11</td>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>Fracture toughness (MPa·m¹/²)</td>
<td>4</td>
<td>3</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ΔT (Degree)</td>
<td>200</td>
<td>600</td>
<td>800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* 0.2 proof stress for metals

Previously proposed structure

Problems:
- High cost of Si₃N₄
- Poor thermal conductivity of Si₃N₄
- Oxidation of Cu
- ... etc.
DBA invented from TEM

Al/ceramic interfaces were direct and clean.

IGBT with DBA was released in 1998

Last proof given to engineers
DBA can survive up to 300 °C temperature cycles

In collaboration with Siemens, Showa Denko, Uyemura Senju Metals

Ni plating
Ni-1%P electroless plating
Ni electroplating

Ag sinter joining
Ni plating
Al braze

SiC
Al heat spreader
AlN insulator
Al interlayer
Al cooling plate

after - 40 ~ 300 °C/110 cycles
Electroplated Ni is better

-40 ~ 300 °C / 110 cycles

presented at TMS2016
Ag sintered die-attach and Al/AlN interfaces

-40 ~ 200 °C / 100 cycles

Ni electroplating

presented at TMS2016
Summary

- The Ag sinter joining is one of the most promising die-attach methods for WBG applications.
- SiC submicron particles addition improves durability up to 250 °C.
- The imid based molding nano composite exhibits excellent thermal/power cycling stability with a Ag porous interlayer.
- Sintering Ag at low temperature in air can be achieved by self-generated Ag nanostructure with oxygen. Ag-O formation in grain boundary has a key role for low temperature joining with Ag.
- DBA has potentials up to 300 °C.

Acknowledgement

The power interconnection was supported by a Grant-in-Aid for Scientific Research (S), no.24226017. Transfer mold test was carried out under the support of NEDO in collaboration with Nippon Shokubai and Prof. Funaki. Self-healing of Ag bond layer was carried out under the support of NEDO in collaboration with DENSO Coop.
Thank you!

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