Low-Cost Direct Bonded Aluminum (DBA) Substrates

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Overview

Timeline
• Project start: October 2010
  (actual funding starts: Jan 2011)
• Project end: September 2013
• Percent complete: 75%

Budget
• Total project funding
  – DOE 100%
• FY11: $200k
• FY12: $200k
• FY13: $130k ($80k allocated to-date)

Barriers*
• High cost per kW
• Low energy per kg
• Low energy density
• Insufficient performance and lifetime

Targets
• DOE VTP* 2020 target: $3.3/kW
• DOE VTP* 2020 target: 14.1 kW/kg
• DOE VTP* 2020 target: 13.4 kW/l
• 15 year life

Partners
• NTRC – ORNL
• Marlow (thermoelectric manuf.)
• Materion (metal cladding supplier)

* VTP Multi-Year Program Plan 2011-2015
Objectives

- Develop low-cost, high quality, and thermomechanically robust direct-bonded aluminum (DBA) substrates.
- Use ORNL's in-house unique processing capabilities to fabricate innovative DBA substrates using a process that is amenable for mass production and that produces high adhesive strength of the ceramic-metal interfaces.
- Consider the fabrication and use of low-cost AlN as a potential (and alternative) contributor.

Example of a commercial DBA (with AlN) substrate

Example of Al to AlN bonding in 2010 Prius IGBT

Photo used with permission of Z. Liang (NTRC/ORNL)
Milestones

- **FY13 - 1:** Complete optimization of fabrication processing parameters for DBA substrates with alumina (Al$_2$O$_3$) and aluminum nitride (AlN) ceramic.

- **FY13 - 2:** Complete fabrication of silicon nitride (Si$_3$N$_4$) ceramic substrates with both high mechanical properties and thermal conductivity.

- **FY13 – 3:** Complete development of DBA and/or direct bonded copper (DBC) substrates with high performance silicon nitride ceramics (may not be completed due to budget changes).
Technical Approach

- Study patent and open literature for DBA fabrication.
- Identify alternative processing method to fabricate large-sized DBA substrates that has potential for low-cost manufacture. This is the first primary step in creating availability of low-cost DBA substrates.
- Benchmark existing commercial DBA substrates for eventual comparison against DBA substrates fabricated in this project. Also, benchmark select commercially available DBC substrates.
- Develop Si$_3$N$_4$ material with both high mechanical and thermal properties for ceramic substrate fabrication.
- Develop test method to measure interfacial shear strengths of the Al-ceramic interface.
Accomplishments

Many Bonding Methods Were Considered

Al-Si phase diagram

- Transient Liquid Phase (TLP) process via CVD Si film
- Brazing process via Al-Si alloy film

Al-Si exhibits an eutectic phase at \(~577^\circ\text{C}\)

- Commercial Al-11Si brazing paste (DayBraze 729, Johnson Manufacturing Co.)
- Al-Si alloy foil (All Foils, Inc.)
- Al-Si tape prepared from powders via atomization process (READE Advanced Materials)
- Si tape prepared from powders (Vesta Si)

Hot press conditions:

- 580 – 600°C
- 5 MPa
- Argon or \(\text{N}_2\)
Accomplishments (continued)

Insufficient Bonding Resulted in Early Trials

ORNL DBA substrates via Al-11Si brazing paste

Visual inspection looked sound, but they could be readily peeled off by hand, indicative of poor bonding.

- Low vacuum in the hot-press could cause oxidation of Al plate and paste prior to joining.
- Completed instrumentation of a mechanical testing system with high vacuum furnace.
Accomplishments (continued)

Uncompleted Reaction of Al-Si Paste Combined with High Oxygen Content Were Probably the Cause of Poor Bonding

SEM EDAX element map of ORNL DBA substrate bonded with commercial Al-11Si brazing paste
Accomplishments (continued)

Poor Wettability Existed Between Both Grades of Al-Si Foil and Ceramic Substrate

5250 alloy (Al-Mg-Mn-Si)

6061 alloy (Al-Si-Cu-Cr)

SEM micrographs of polished cross section of as-received Al-Si alloy foils

Hot press at 610°C in N₂

SEM micrographs of Al plate surface after bonding
Accomplishments (continued)

Microstructure of Al-Si-Mg and Si Powders

READE Advanced Materials

SicoMill® Si powder (Vesta Si)

Al-Si and Si film prepared by tape casting will be used to bond Al and Al₂O₃ (AlN) ceramic in the remaining FY13.
Accomplishments (continued)

Cu-clad Al foil was Evaluated as a Candidate Cladding

Developmental Cu-clad Al foil was acquired from Materion Corp., Cleveland, OH.

- The Cu-clad Al material could eliminate the need for interfacial brazing layer.
- Cu-clad Al material exhibits 45% higher thermal conductivity and 30% higher current density.
Accomplishments (continued)

Poor Bonding Resulted Between Cu-Clad Al Foil & Ceramic

- 1: 100% Cu
- 2: 79%Cu-21%Al
- 3: 75%Cu-25%Al
- 4: 53%Cu-47%Al

- Cu-Al exhibits an eutectic point at 550°C lower than Al-Si eutectic point of 577°C
- Active brazing alloy might be needed to prevent early Al-Cu eutectic formation
Accomplishments (continued)

Wide Band Gap Technology (GaN or SiC) Requires High Performance Substrates Such as Si$_3$N$_4$ DBC Substrates

The use of Si$_3$N$_4$ ceramic substrate (1/2 of AIN thickness) with excellent mechanical performance could minimize tensile stress and thus improve mechanical reliability.

\[
\begin{align*}
\sigma &= 400 \text{ MPa} \\
m &= 13 \\
K_{IC} &= 3 \text{ MPa} \cdot \text{m}^{0.5}
\end{align*}
\]

\[
\begin{align*}
\sigma &= 800 \text{ MPa} \\
m &= 18 \\
K_{IC} &= 6 \text{ MPa} \cdot \text{m}^{0.5}
\end{align*}
\]

Courtesy of Hirao Kiyoshi, AIST, Japan

FEA Wereszczak
Accomplishments (continued)

**Si$_3$N$_4$ DBC Substrates Have Better Mechanical Reliability Than Traditional Substrates**

Kyocera AMT DBC

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Flexure Strength (MPa)</th>
<th>Fracture Toughness (MPa$\cdot$√m)</th>
<th>Thermal Conductivity (W/m$\cdot$k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial AIN</td>
<td>400</td>
<td>5</td>
<td>150 - 200</td>
</tr>
<tr>
<td>Kyocera SN460</td>
<td>850</td>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>Toshiba SN90</td>
<td>650</td>
<td>6.5</td>
<td>90</td>
</tr>
<tr>
<td>Curamic SN*</td>
<td>650</td>
<td>6.5 - 7</td>
<td>90</td>
</tr>
</tbody>
</table>

*Curamic (Rogers Corp.) officially demonstrated new Si$_3$N$_4$ DBC substrates at eCarTech, Munich, Oct 2012*
Accomplishments (continued)

ORNL Si$_3$N$_4$ Ceramics Exhibit Comparable or Superior Mechanical Properties to Commercial Ones

<table>
<thead>
<tr>
<th>Composition</th>
<th>Flexure Strength MPa @ 22°C</th>
<th>Flexure Strength MPa @ 1200°C</th>
<th>Fracture Toughness MPa•√m</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN8La2Mg</td>
<td>1140</td>
<td>832</td>
<td>10-13</td>
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<tr>
<td>SN8Gd2Mg</td>
<td>1226</td>
<td>906</td>
<td>11</td>
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<tr>
<td>SN8Lu2Mg</td>
<td>1040</td>
<td>894</td>
<td>11-13</td>
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<tr>
<td>SN8La2Si</td>
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<td>SN8Gd2Si</td>
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<td>803</td>
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<td>SN8Lu2Si</td>
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<td>NT154</td>
<td>950</td>
<td>-</td>
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</tr>
<tr>
<td>SN147</td>
<td>700-800</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>SN240</td>
<td>1000</td>
<td>-</td>
<td>10</td>
</tr>
</tbody>
</table>

US patent: US 7,968,484 B2
Becher and Lin

- **SN** – developed by ORNL
- **NT154** – Saint-Gobain
- **SN147** – Ceradyne
- **SN240** - Kyocera
Accomplishments (continued)

Thermal Conductivity of Si₃N₄ Can be Tailored by Grain Boundary Microstructure and Chemistry

2nd phases, GB film (low thermal property) and lattice oxygen (more phonon scattering) could lower the thermal conductivity of Si₃N₄ ceramics by Shibata and Becher et al.
Accomplishments (continued)

Mechanical Strength of ORNL Si$_3$N$_4$ Ceramics Confirmed

- Composition:
  - 8wt% Lu$_2$O$_3$-2wt% MgO
  - 8wt% Gd$_2$O$_3$-2wt% MgO

- Si$_3$N$_3$ powder:
  - Ube E-10 and ESP

- Processing conditions:
  - Hot-press @ 1800°C, 20MPa, N$_2$

Accomplishments (continued)

ORNL Si₃N₄ Ceramics Exhibit Comparable or Superior Thermal Conductivity to Commercial Si₃N₄

- Kyocera SN460: 60 W/mk
- Toshiba SN90: 90 W/mk
- Curamic SN: 90 W/mk

Manufacturers reported data

Thermal property could be further enhanced by engineering control of Si₃N₄ grain size, oxygen content, and crystallinity of 2nd phase

Measured by laser flash method
Collaborations

- **Partners**
  - Advanced Power Electronics and Electric Motors R&D team members at NTRC of ORNL.
  - Electric and Electronic Tech Team provided constructive input.
  - Marlow (established thermoelectric manufacturer) provided their DBA substrate for ORNL to assess and conduct bench mark test.
  - Materion provided the Cu-clad Al ribbon with tailored thermal and electric property.

- **Technology transfer**
  - Potential with Marlow, GM or Delphi on the development of high performance DBA/DBC substrates with Si$_3$N$_4$ ceramic substrate.
  - Development of high performance DBA substrate with Si$_3$N$_4$ ceramic substrate would provide the high-power and high-temperature challenge for IGBT and MOSFET with SiC or GaN wide band gap material.
Future Work

- Complete fabrication of tape-cast Al-Si thin film using atomization Al-Si powders for bonding Al-AlN (and Al$_2$O$_3$) substrates. (FY 13)
- Complete fabrication of tape-cast Si thin film using commercial Si powders for bonding Al-AlN (and Al$_2$O$_3$) substrates. (FY 13)
- Complete optimization of Si$_3$N$_4$ ceramic with both high mechanical and thermal properties for power electronic ceramic substrates. (FY 14)
- Develop low-cost Si$_3$N$_4$ ceramic using high purity Si powders via sinter-reaction bonded process. (FY 14)
- Fabricate DBC (and DBA) substrates using reaction-bonded Si$_3$N$_4$ ceramics via Ti-containing active brazing element, and tech transfer and commercialize the products. (FY 15)
Summary

- **Relevance**: low cost and robust DBA substrates to improve reliability of power electronic device.
- **Approach**: develop low cost and reliable DBA substrates with AlN and Si₃N₄ ceramic via brazing and/or metallurgical process.
- **Collaboration**: EETT, substrate manufacturers, and materials suppliers.
- **Technical Accomplishments**:
  - Results confirm compromise between low cost and reliability must be struck.
  - Processing and characterization of DBA substrates with Al-Si paste and Al-Si foil.
  - Characterizations of Al-Si and Si powders
  - Re-produce ORNL Si₃N₄ ceramics with consistent excellent mechanical strength
  - Thermal property measurements of ORNL Si₃N₄ ceramics
- **Future Works**:
  - Optimization of Si₃N₄ ceramic with both high mechanical and thermal properties.
  - Development low-cost Si₃N₄ ceramic using high purity Si powder
  - Fabrication of DBC (and DBA) substrates using reaction-bonded Si₃N₄ ceramics and tech transfer and commercialize the products.