Thermal Performance and Reliability of Bonded Interfaces
Overview

Timeline

• Start – FY10
• Finish – FY12
• 10% Complete

Budget

• Total project funding to date
  – DOE - $400K.
• Funding received in FY10
  – $400K.

Barriers

• Barriers addressed
  – Interfaces with improved thermal performance and reliability enables use of high temperature coolant and/or air cooling,
  – Enables reduction in cost, weight and volume of power electronics.

• Target
  – Bonded interface materials that meet thermal performance (< 5 mm²K/W ) and reliability targets (15 year life).

Partners

• Electrical and Electronics Technical Team.
• Delphi.
• Btech.
• Virginia Tech.
• GM.
Project Relevance

- Excessive temperature can degrade the performance, life, and reliability of power electronic components.

- Advanced thermal control technologies are critical to enabling higher power densities and lower system cost.

- Interfaces pose a major bottleneck to heat removal.

- Bonded interface materials (BIMs) based on solder are associated with thermomechanical reliability concerns under temperature cycling, as well as degradation at higher temperatures (>120°C).
The Problem

- Conventional TIMs do not meet thermal performance and reliability targets.

- Due to advantages from a packaging viewpoint, industry is trending toward bonded interfaces.

- Bonded interfaces such as solder degrade at higher temperatures, and are prone to thermomechanical failure under large temperature cycling.
Objectives

• Develop/identify bonded interface material which meets the target thermal performance (< 5 mm$^2$K/W thermal resistance) and the reliability and cost constraints for power electronics applications.

• High thermal performance, reliable and cost-effective BIM helps enable the use of high-temperature coolant and/or air cooling.
## Milestones

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
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<tbody>
<tr>
<td><strong>December 2009</strong></td>
<td>In conjunction with industry partners, established workplan for characterizing thermal performance and reliability of bonded interfaces. Plan includes investigation of thermal performance and reliability of different bonding technologies – lead-based and lead-free solder, sintering based on silver micro/nano particles, brazing, and thermoplastics with embedded carbon fibers.</td>
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<tr>
<td><strong>April 2010</strong></td>
<td>Results for thermal resistance of sintered and thermoplastic materials from the ASTM test method based on bond between 31.8 mm diameter copper coupons. Ion-implantation and metal-sputtering/evaporation techniques applied on thermoplastics with embedded carbon fibers (to improve/lower contact resistance).</td>
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<td><strong>September 2010</strong></td>
<td>Synthesize (in collaboration with Virginia Tech, Btech) large-area bonded interface between DBA/DBC and aluminum/copper baseplate. Bonding based on lead-free and lead-based solder, sintered silver, brazed material, and thermoplastic with embedded carbon fibers. Acquire furnace and thermal shock chamber in-house at NREL. Initiate thermal shock experiments on the samples.</td>
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</table>
Approach

- Work with partners to identify and develop high thermal performance, reliable BIM
  - Collaborate with partners on synthesis (soldered, brazed, sintered joint, thermoplastic adhesive joint),
  - Initiate synthesis at NREL.
- Evaluate initial thermal performance using NREL's steady-state ASTM apparatus and transient technique for thermal resistance measurement.
- Subject bonded samples to thermal shock
  - Characterize thermal resistance after select cycles,
  - Subject samples to high-potential test,
  - Inspect quality of the joint under CSAM.
- Degradation data feed into a reliability/end-of-life model for the joint.
- Modeling to understand thermomechanical phenomena.
- Transfer information to industry.
Accomplishments

• In close collaboration with industry partners (GM, Delphi), developed plan for bonded interface synthesis, and characterization of thermal performance and reliability.

• Preliminary results on thermal resistance of sintered joint based on silver nanoparticles (in collaboration with Virginia Tech).

• Promising thermal resistance results for thermoplastics (collaboration with Btech and NREL materials scientists) with embedded carbon fibers
  • Thermal resistance of 8 mm²K/W at 100 microns bondline thickness,
  • Metal-sputtering and ion-implantation techniques at NREL to reduce contact resistance further.
Accomplishments

Sintered interfaces – based on silver nanoparticles

- Sintered interfaces synthesized between silvered Cu-Cu and Al-Al disks (31.8 mm diameter) at Virginia Tech.
- A nickel coating (~2 µm) followed by silver coating (~2 µm) is applied on the copper and aluminum disks.
- For comparison, lead-free solder (SN100C) interface synthesized between Cu-Cu disks (31.8 mm diameter).
- Different thicknesses fabricated (20 ~ 200 microns).

G.-Q. Lu, Virginia Tech
Synthesis of sintered interface
Accomplishments

Sintered interfaces – preliminary experimental results

<table>
<thead>
<tr>
<th>Samples</th>
<th>Thickness (µm)</th>
<th>Resistance (mm²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silvered Cu-Cu sintered interface</td>
<td>20</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>5.4</td>
</tr>
<tr>
<td>Silvered Al-Al sintered interface</td>
<td>28</td>
<td>14.9</td>
</tr>
<tr>
<td></td>
<td>103</td>
<td>25.2</td>
</tr>
<tr>
<td></td>
<td>144</td>
<td>5.0</td>
</tr>
<tr>
<td>Cu-Cu soldered interface (SN100C)</td>
<td>80</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>3.7</td>
</tr>
</tbody>
</table>

• The thermal resistance tests were performed using the NREL ASTM TIM apparatus
  – Average sample temperature ~ 65°C, pressure is 276 kPa (40 psi).
• The silvered Cu-Cu sintered interface shows promising thermal performance.
• Results hint at some problems with the bonding of the silvered Al-Al interface.
• The lead-free solder (SN100C) interface initial thermal results are very promising.
Accomplishments

Thermoplastics with embedded carbon fibers

- Thermoplastic films (provided by Btech) bonded between 31.8 mm diameter copper disks.
- Promising thermal results (8 mm$^2$K/W for 100 microns bondline thickness).
- Continuing work at NREL to further decrease contact resistance to approach target thermal performance, as well as characterize reliability.
Temperature Across a Package
- FEA analysis using Toyota package

At 100 W/cm² heat dissipation in the die, the maximum junction temperature (T_{J,max}) decreases by 16°C when TIM resistance decreases from 100 to 8 mm²K/W.
Future Work

Remainder of FY10

• Work with Btech to develop and test (via ASTM steady-state approach) improved and reliable thermoplastics with embedded carbon fibers meeting target thermal performance
  – Reduce contact resistance via ion-implantation and metal evaporation/sputtering techniques.

• In collaboration with Virginia Tech and Btech, synthesize and characterize various joints between DBA/DBC and aluminum/copper baseplate
  – Synthesis of soldered, sintered, brazed and thermoplastic joints,
  – Subject joints to thermal shock,
  – Thermal resistance measurement after select cycles,
  – CSAM after select cycles,
  – High-potential test after select cycles,
  – Modeling of the joint thermomechanical behavior (physics-of-failure) – end-of-life predictive model.

Tom Gennett, NREL
Future Work

FY11, FY12

- Detailed synthesis and characterization of thermal performance and reliability of joints based on the matrix given below
  - Synthesis of bond/joint,
  - Subject joint/bond to thermal shock,
  - Thermal resistance measurements after select cycles,
  - Joint quality characterization (CSAM) after select cycles,
  - High-potential test after select cycles,
  - Modeling of thermo-mechanical behavior of the joints,
  - Degradation/end-of-life model of the joints and the package.

<table>
<thead>
<tr>
<th>Joint Material</th>
<th>Substrate</th>
<th>Metallization</th>
<th>Coating</th>
<th>Baseplate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder Joints (Pb free &amp; Pb)</td>
<td>AlN</td>
<td>Al</td>
<td>Ag</td>
<td>Al</td>
</tr>
<tr>
<td>Brazed Joints</td>
<td>Al₂O₃</td>
<td>Cu</td>
<td>Au</td>
<td>Cu</td>
</tr>
<tr>
<td>Sintered Joints</td>
<td>Si₃N₄</td>
<td></td>
<td></td>
<td>AlSiC</td>
</tr>
<tr>
<td>Thermoplastics</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

+ PROCESS
+ REPETITIONS
Summary

- BIMs are a key enabling technology for compact, light-weight, reliable packaging, and for high temperature coolant and air cooling technical pathways.

- Approach includes – synthesis of various joints between DBA/DBC and baseplate (Cu/Al/AlSiC), thermal shock cycles, thermal resistance measurements, hi-potential test and joint inspection (CSAM), and physics-of-failure models.

- In close collaboration with industry partners (GM, Delphi), established a workplan to characterize thermal performance and reliability of a number of bonded interfaces (soldered, sintered, brazed, thermoplastic with embedded carbon fibers).

- Promising initial results for sintered interfaces (silver nanoparticles – Virginia Tech) and promising performance of thermoplastic adhesives with embedded carbon fibers (Btech).
Summary

• Thermoplastics with embedded carbon fibers
  – Ion-implantation and metal-sputtering to reduce contact resistance further.

• Thermoplastics, sintered, soldered and brazed joints
  – Various substrates/baseplates combination,
  – Synthesis (recipe),
  – Thermal shock cycles,
  – Thermal resistance measurements,
  – Hi-potential test and CSAM,
  – Physics-of-failure models.

Future work

• GM and Delphi (all bonded interfaces).
• Virginia Tech (synthesis of sintered and soldered joints).
• Btech (thermoplastics with embedded carbon fibers).
• NREL materials group (ion-implantation and metal-sputtering – thermoplastics).
• ORNL (sintered and soldered joints).

Collaborations