Thermal Performance and Reliability of Bonded Interfaces

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May 15, 2012

Project ID: APE028

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Overview

Timeline
Project Start Date: FY10
Project End Date: FY12
Percent Complete: 80%

Barriers and Targets
• Cost
• Weight
• Performance and Lifetime

Budget
Total Project Funding: DOE Share: $1.4M
Funding Received in FY11: $600K
Funding for FY12: $425K

Partners
• Interactions / Collaborations
  • General Motors, Btech, Semikron, Heraeus, Kyocera, Virginia Tech, Oak Ridge National Laboratory (ORNL)
• Project lead: NREL
Relevance/Objectives

- Excessive temperature (>150°C for silicon [Si] devices) can degrade the performance, life, and reliability of power electronics components
- Interfaces in the package can pose a major bottleneck to heat removal
- Conventional thermal interface materials (TIMs) do not meet thermal performance and reliability targets—the industry trend is towards bonded interface materials (BIMs)
- Bonded interfaces, such as solder, degrade at higher temperatures and are prone to thermomechanical failure under large temperature cycling

Credit: Douglas DeVoto, NREL
Relevance/Objectives

• **Overall Objective**
  – Investigate the reliability of emerging BIMs (such as silver sinters, lead-free solders, and thermoplastics with embedded carbon fibers) for power electronics applications to meet the thermal performance target of 5 mm²K/W
  – Identify failure modes in emerging BIMs, experimentally characterize their life under known conditions, and develop lifetime estimation models

• **Address Targets**
  – High-performance, reliable, low-cost bonded interfaces enable:
    o Compact, light-weight, low-cost packaging
    o High-temperature coolant and/or air cooling

• **Uniqueness and Impacts**
  – Thermal performance and reliability of emerging sintered materials and thermoplastics in large-area attach will be characterized.
## Milestones

<table>
<thead>
<tr>
<th>Date</th>
<th>Milestone or Go/No-Go Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2011</td>
<td>Evaluated bond quality of initial samples using nondestructive acoustic imagery (C-SAM). Aluminum nitride (AlN) delamination failures on many samples initiated change to silicon nitride (Si$_3$N$_4$) substrates.</td>
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<tr>
<td>October 2011</td>
<td>Completed initial finite element analysis (FEA) modeling to determine plastic work/strain energy density in lead-based solder BIM while under cycling.</td>
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<tr>
<td>December 2011</td>
<td>Received new Si$_3$N$_4$ substrates and tested for delamination under accelerated temperature cycling profile. New substrates meet reliability requirements for BIM testing.</td>
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<tr>
<td>January 2012</td>
<td>Synthesized second set of samples using revised substrates. Btech HM-2 bonded at NREL and sintered silver bonded at Semikron.</td>
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<tr>
<td>May 2012</td>
<td>Complete double lap shear testing of lead-based solder samples and use stress/strain data to revise viscoplastic properties needed for FEA.</td>
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<tr>
<td>September 2012</td>
<td>Complete experimental temperature cycling of samples to 2,000 cycles or until failure. Develop strain energy density versus cycles-to-failure models for lead-based and lead-free solders.</td>
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</table>
**Approach/Strategy**

**Sample Synthesis**
- Synthesis of samples using stencil printer and hot press.

**Thermal Testing/Characterization**
- Cycling of samples in a thermal shock chamber.
- Characterization of samples via steady-state thermal resistance tester, hi-pot tester, C-SAM, and X-ray imaging.

**BIM Mechanical Characterization**
- Shear tests to extract mechanical characteristics of BIMs.
- Extraction of viscoplastic parameters.

**Reliability Calculation**
- Strain energy density per cycle.
- Number of cycles to crack initiation/delamination.
- Fatigue life prediction.

**Experimental Approach**

**Numerical Approach - FEA/Calculations**

**Experimental Approach**

**Numerical Approach - FEA/Calculations**
• Temperature cycling parameters:
  – Maximum temperature = 150°C
  – Minimum temperature = -40°C
  – Ramp rate = 10°C/minute
  – Dwell time = 10 minutes
• Viscoplastic material model applied to solder layer
• Temperature-dependent elastic material properties incorporated for baseplate and substrate
BIM Finite Element Modeling

- Accumulated plastic work per volume distribution in the bonded joint region (63Sn-37Pb solder)
- Plastic work higher in the corner regions—location where failures are likely to originate
- Plastic work/strain energy density versus cycles-to-failure correlation to be obtained for lead-based and lead-free solders

Plastic Work Per Volume

\[
\text{Result, } i = N_f e_{\varepsilon} \quad \begin{pmatrix} \varepsilon_b & \varepsilon_N \end{pmatrix}
\]
• Strain prediction of solder material is dependent on stress, temperature, and time
  – A high enough stress will cause the material to plastically deform
  – Solder has a tendency to creep at room temperature; this increases as operating (absolute) temperature approaches the melting temperature
  – Creep, or time-dependent plasticity, occurs when a material’s absolute temperature is greater than one-half of its melting temperature
• Viscoplasticity models combine plasticity and creep deformations into one equation to properly define solder in FEA
BIM Mechanical Characterization

• A double-lap shear testing fixture was designed for solder BIM specimens
  – Sample testing at various strain rates and temperatures generates the needed data to characterize the viscoplastic nature of solder
• A script was developed to derive viscoplastic parameters from strain rate test data
  – This will allow the behavior of new solder materials to be modeled in FEA simulations

Credit: Douglas DeVoto, NREL
Sample Assembly

- Five samples of each BIM (between substrate/copper base plate) were synthesized for testing and included:
  - Silver coating on the substrate and base plate
  - Substrate based on a $\text{Si}_3\text{N}_4$ active metal bonding process
  - An interface between 50.8-mm x 50.8-mm footprint
- Samples followed manufacturer-specified reflow profiles, and bonds were inspected for quality

<table>
<thead>
<tr>
<th>Bond Material Type</th>
<th>Name</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Solder</td>
<td>Kester Sn63Pb37</td>
<td>Baseline (lead-based solder)</td>
</tr>
<tr>
<td>Solder</td>
<td>Henkel Innolot LF318</td>
<td>Lead-free solder</td>
</tr>
<tr>
<td>Sintered Silver</td>
<td>Heraeus LTS043</td>
<td>Based on micron-size silver particles</td>
</tr>
<tr>
<td>Sintered Silver</td>
<td>nanoTach®</td>
<td>Based on nanoscale silver particles</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Btech HM-2</td>
<td>Thermoplastic (polyamide) film with embedded carbon fibers</td>
</tr>
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Thermal Cycling

- **Cycle Profile**
  - Thermal extremes from -40°C to 150°C
  - Ramp rate of 5°C/minute, with a dwell/soak time of 10 minutes
  - Adherence to JEDEC* Standard 22-A104D for temperature cycling

* JEDEC: Joint Electron Device Engineering Council
Thermally Conductive Adhesive Film

- **Btech HM-2 (Carbon Fibers within Polymer Matrix)**
  - **Bonding**
    - HM-2 was cut to the base plate dimensions. The sample assembly was placed in the hot press and raised to 195°C, then ~1 MPa (150 psi) of pressure was applied.
  - **Reliability Results**
    - C-SAM images show less contrast with thermoplastics, but uniform bonds were obtained.
    - After 200 cycles, the bonded interface remained defect-free.

Credit: Douglas DeVoto, NREL (all photos)
Silver Sinter

• Semikron Silver Sinter
  – Bonding
    o Corners of the Si$_3$N$_4$ were rounded off to match the 2-mm radius of copper layers. The sample assembly was placed in a hot press and raised to its processing temperature, then pressure was applied.
    o Independent compression testing of substrates at ORNL showed cracking of substrates required between 30 MPa to 50 MPa of pressure.
  – Reliability Results
    o Uniform bonds were obtained.
    o After 200 cycles, the bonded interface remained defect-free.
Collaboration and Coordination

• Partners
  – General Motors (Industry): technical guidance
  – Virginia Tech (Academic): collaboration on synthesis of samples using silver sintered material
  – ORNL (Federal): collaboration to determine maximum pressure that Si$_3$N$_4$ substrates could withstand
  – Btech (Industry): collaboration on optimizing thermoplastic BIM for large area attach
  – Semikron (Industry): provided bonded samples to NREL using company’s silver sintering process
  – Heraeus (Industry): collaboration on using low pressure silver sintered materials before products are commercially available
  – Kyocera (Industry): provided insight on Si$_3$N$_4$ substrate bonding process and advantages over AlN substrates
Proposed Future Work (FY12)

- Derive viscoplastic parameters for lead-based and lead-free solders from double-lap shear test experiments
- Expand strain energy density versus cycles-to-failure models to lead-free solders
- Complete 2,000 thermal cycles on all selected materials using Si$_3$N$_4$ based substrates
- Report on reliability of each BIM under specified accelerated test conditions
Summary

- **DOE Mission Support**
  - BIMs are a key enabling technology for compact, light-weight, low-cost, reliable packaging and for high-temperature coolant and air-cooling technical pathways.

- **Approach**
  - Synthesis of various joints between substrates and baseplate, thermal shock/temperature cycling, high-potential test and joint inspection (C-SAM), and strain energy density versus cycles-to-failure models.

- **Accomplishments**
  - Synthesized a number of bonded interfaces between substrate and copper baseplate based on different BIM technologies
    - Lead-based and lead-free solder, sintered silver (micron-size and nanosilver), thermoplastic.
  - Initiated FEA for solder bonded interface geometries.
Summary

• Collaborations
  – General Motors, Virginia Tech, ORNL, Btech, Semikron, Heraeus, Kyocera

• Future Work
  – Derive viscoplastic parameters for lead-based and lead-free solders from double-lap shear test experiments
  – Expand strain energy density versus cycles-to-failure models to lead-free solders
  – Complete 2,000 thermal cycles on all selected materials using Si₃N₄ based substrates
  – Report on reliability of each BIM under specified accelerated test conditions
Acknowledgments:
Susan Rogers and Steven Boyd, U.S. Department of Energy

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