Thermal Performance and Reliability of Bonded Interfaces

2011 DOE Vehicle Technologies Program Review

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Project ID: APE028
Overview

Timeline

• Project start date: FY10
• Project end date: FY12
• Percent complete: 50%

Barriers Addressed

• Cost
• Weight
• Performance and Lifetime

Targets Addressed

• Cost
• Specific Power
• Power Density

Budget

• Total project funding
  – DOE share: $1M
• FY10 Funding: $400K
• FY11 Funding: $600K

Partners

• Interactions & Collaborations
  - General Motors, Delphi, Btech®, Virginia Tech, University of Maryland, Oak Ridge National Laboratory (ORNL), National Institute of Standards and Technology (NIST), Advanced Engineering Solutions (AES)
• Project lead: NREL
Relevance/Objectives (1/2)

- Excessive temperature (>150°C for 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 – 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.

![Diagram showing thermal interface materials and their performance](image)
Relevance/Objectives (2/2)

• Overall Objective
  – Investigate thermal performance and reliability of novel bonded interface materials (such as sintered silver, thermoplastics with embedded carbon fibers) for power electronics applications to meet the following specific objectives
    o Thermal resistance of 5 mm²K/W.
    o Maintain thermal resistance of 5 mm²K/W after 2,000 thermal cycles from -40 to 150°C.

• Addresses Targets
  – High-performance, reliable, low-cost bonded interfaces enable compact, light-weight, low-cost packaging.
  – Also enables high-temperature coolant and/or air cooling.

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

<table>
<thead>
<tr>
<th>Month/ Year</th>
<th>Milestone or Go/ No-Go Decision Point</th>
</tr>
</thead>
</table>
| December 2010    | • Established thermal shock chamber, high-potential (Hipot) tester, hot press, and modified ASTM thermal resistance measurement setup at NREL.  
                   • Synthesized a number of bonded interface samples (DBC/copper baseplate with 50.8 mm x 50.8 mm footprint) across a range of BIMs. |
| May 2011         | • Complete characterization of thermal resistance and quality (Hipot, acoustic microscopy) of the bonded interfaces at time t=0 (prior to thermal cycling).  
                   • Initiate thermal cycling of bonded interface samples.  
                   • Initiate mechanical tests to infer stress-strain constitutive relations for novel bonded interface materials to be input into finite element analysis (FEA).  
                   • Initiate FEA modeling of bonded interface samples to compute strain-energy density. |
| October 2011     | • Complete thermal cycling and characterization on samples with different types of bonded interfaces.  
                   • In conjunction with FEA, establish strain energy density versus cycles-to-failure curves for various bonded interface technologies (lead-based, lead-free solder, sintered silver, and thermoplastics). |
**Approach (1/2)**

- **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, Hipot Tester, Scanning Acoustic Microscopy (C-SAM), and X-ray imaging

- **BIM Mechanical Characterization**
  - Shear tests to extract mechanical characteristics of BIMs
  - Extraction of Anand Model Parameters

- **Reliability Calculation**
  - Strain Energy Density per Cycle
  - Fatigue Life Prediction
  - Number of Cycles to Crack Initiation/Delamination

**Experimental approach**

**Numerical approach - FEA/Calculations**
Accomplishments – Acquisition of DBC, Baseplate, BIMs

- Acquired silver sintered materials, silver-based adhesives, thermoplastics with embedded carbon fibers, and solders (both lead-based and lead-free as baseline)
  - Interface between 50.8 mm x 50.8 mm footprint DBC/copper baseplate assembly (DBC based on aluminum nitride (AlN) substrate).

<table>
<thead>
<tr>
<th>Bond Material Type</th>
<th>Name</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder</td>
<td>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>Solder</td>
<td>SAC305</td>
<td>Lead-free solder</td>
</tr>
<tr>
<td>Sintered silver</td>
<td>NanoTach</td>
<td>Based on nanoscale silver particles</td>
</tr>
<tr>
<td>Sintered silver</td>
<td>Heraeus C8829A</td>
<td>Based on micron-size silver particles</td>
</tr>
<tr>
<td>Sintered paste</td>
<td>Silver-Indium</td>
<td>Based on micron-size particles</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Dow Corning DA-6534</td>
<td>Silver-filled, heat-curable silicone adhesive</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Btech HM-2</td>
<td>Thermoplastic (polyamide) film with embedded carbon fibers</td>
</tr>
<tr>
<td>Adhesive</td>
<td>Henkel Hysol® CF3350</td>
<td>Thermally conductive silver-filled film</td>
</tr>
</tbody>
</table>

Credit: Doug DeVoto, NREL
Accomplishments – Bonded Interface Synthesis and Imaging

- Five samples of each BIM (between DBC/copper baseplate) were synthesized for testing
  - Silver coating on DBC and baseplate.
- Samples followed manufacturer-specified reflow profiles, and bonds were inspected for quality.
- X-ray imaging indicated some voiding in Sn-Ag-Cu (SAC) solder samples.
Accomplishments – Modified ASTM Setup for Thermal Resistance Testing

- New blocks fabricated to enable thermal resistance measurement on 50.8 mm X 50.8 mm footprint samples.
- ASTM results for new blocks (50.8 mm x 50.8 mm) can be directly compared to results from previous blocks (31.8 mm diameter).
- Similar thermal resistance results for Dow TC-5022 grease obtained from both block configurations – gives confidence in the use of new blocks (50.8 mm x 50.8 mm).

![Diagram of Thermal Resistance Variation by Meter Block Geometry](Credit: Doug DeVoto, NREL)
Accomplishments – Thermal Resistance Results for Select Samples Prior to Cycling

- Thermal resistance results obtained for select samples prior to thermal cycling
  - Resistance is for the DBC/BIM/Baseplate stackup.

![Graph showing thermal resistance results for different materials](image)

- **Lead-based solder** - Sn63Pb37
- **Lead-free solder** - SAC 305
- **Sintered nanosilver**
- **Adhesive - Btech HM2**
Accomplishments – Thermal Cycling Chamber Performance Characterization

- Quantification of cycling chamber performance was completed
  - Thermal cycling from -40°C to 150°C.
  - Ramp rate of 10°C/minute, dwell/soak time of 10 minutes.
  - Follows JEDEC Standard 22-A104D for temperature cycling.

- Hipot Tester was constructed and is fully operational.

![Shock Chamber](image1)

![Hipot Tester](image2)

![Sample delamination after 10 cycles](image3)

**Shock Chamber Testing**

<table>
<thead>
<tr>
<th>Time (h:mm)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00</td>
<td>0</td>
</tr>
<tr>
<td>0:30</td>
<td>-50</td>
</tr>
<tr>
<td>1:00</td>
<td>0</td>
</tr>
<tr>
<td>1:30</td>
<td>50</td>
</tr>
<tr>
<td>2:00</td>
<td>150</td>
</tr>
<tr>
<td>2:30</td>
<td>200</td>
</tr>
<tr>
<td>3:00</td>
<td>0</td>
</tr>
</tbody>
</table>

- Sample Profile
- Temperature Profile

Credit: Doug DeVoto, NREL (all photos)
Accomplishments – BIM Mechanical Characterization

• Shear testing fixture was designed for BIM specimens. Fixture will allow for sample testing at various strain rates and temperatures.

• Script developed to derive Anand parameters from strain rate test data. This will allow the behavior of new solder and sinter materials to be modeled in FEA simulations.

• Template established for performing FEA simulations of the sample geometry to determine the strain energy density per thermal cycle. This will be used as a fatigue-life indicator.
Accomplishments – FEA Modeling: Trial Simulation for Cool Down from 125°C to 22°C

- Parameters
  - Reflow temperature = 125°C
  - Room temperature = 22°C
  - Ramp rate = 10°C/minute
- Anand’s viscoelastic material model for the solder/sintered material
- Temperature-dependent material properties for copper and AlN

Courtesy: Andreas Vlahinos, AES (all graphics)
Accomplishments – FEA Modeling: Stress Distribution (Cool Down from 125°C to 22°C)

- Equivalent stress distribution in the upper/top and middle layer of the bonded joint.
- Stresses are higher in the layer adjoining the DBC and higher in the corner regions.

Courtesy: Andreas Vlahinos, AES (all graphics)
Accomplishments – FEA Modeling: Plastic Work Density Distribution (Cool Down from 125°C to 22°C)

- Plastic work density distribution in the bonded joint region.
- Work density higher in the corner regions – failures likely to originate here.
- Plastic work density/strain energy density versus cycles-to-failure correlation is the new contribution of this effort.

Courtesy: Andreas Vlahinos, AES (all graphics)
## Collaborations

<table>
<thead>
<tr>
<th>Collaborator</th>
<th>Nature of Interaction / Collaboration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical &amp; Electronics Technical Team, GM, Delphi</td>
<td>• Technical guidance</td>
</tr>
<tr>
<td>ORNL</td>
<td>• Packaging</td>
</tr>
<tr>
<td>NIST</td>
<td>• Electrothermal modeling of power modules</td>
</tr>
<tr>
<td>Virginia Tech</td>
<td>• Synthesis of soldered and sintered joints</td>
</tr>
<tr>
<td></td>
<td>• X-ray imaging</td>
</tr>
<tr>
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<td>• Provider of nanosilver paste</td>
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<td>University of Maryland</td>
<td>• Provider of silver-indium paste</td>
</tr>
<tr>
<td>AES</td>
<td>• Finite element modeling support</td>
</tr>
</tbody>
</table>
Future Work (1/2)

• Remainder of FY11
  – Perform thermal resistance test and quality characterization (C-SAM, X-ray, Hipot) on bonded samples prior to cycling.
  – Perform mechanical tests to characterize stress-strain constitutive relationship (to go into FEA modeling).
  – Perform thermal cycling on bonded samples.
  – Perform periodic (after 100 cycles) thermal resistance and quality characterization.
  – Perform FEA modeling to compute strain energy density for DBC/baseplate bonded configuration (for different bonded materials).
  – **Key output will be strain energy density versus cycles-to-failure for different BIM technologies.**
Future Work (2/2)

• **FY12**
  - Perform synthesis, characterization and modeling of thermal performance and reliability of a select few bonded interfaces between DBA/aluminum baseplate.
  - Study impact of different coatings on substrate and/or baseplate.
Summary (1/2)

- **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 DBA/DBC and baseplate (Cu/Al), thermal shock/temperature cycling, thermal resistance measurements, high-potential test and joint inspection (X-ray, C-SAM), and strain energy density versus cycles-to-failure models.

- **Accomplishments**
  - Synthesized a number of bonded interfaces between DBC/copper baseplate based on different BIM technologies
    - Lead-based and lead-free solder, sintered silver (micron-size and nanosilver), thermoplastic, silver adhesive/epoxy.
  - Initiated FEA for bonded interface geometries.
  - Initiated thermal resistance measurement and quality characterization for the different bonded interfaces prior to thermal shock/cycling.
Summary (2/2)

• Future Work
  – For bonded interface between DBC/copper baseplate:
    o Perform thermal cycling of bonded samples.
    o Characterize thermal resistance and quality of bond.
    o Characterize BIM to obtain stress-versus-strain mechanical constitutive relationships.
    o Perform FEA modeling to infer strain energy density.
    o Correlate strain energy density to cycles-to-failure.
  – Investigate thermal performance and reliability of bonded interfaces between DBA/aluminum – work plan similar to that for bonded interfaces between DBC/copper baseplate.
  – Investigate impact of coatings on thermal performance and reliability.

• Collaborations
  – Electrical & Electronics Technical Team, GM, Delphi
  – ORNL
  – NIST
  – Virginia Tech
  – Btech
  – University of Maryland
  – AES
Acknowledgements:

Susan Rogers, U.S. Department of Energy

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