Thermal Performance and Reliability of Bonded Interfaces

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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

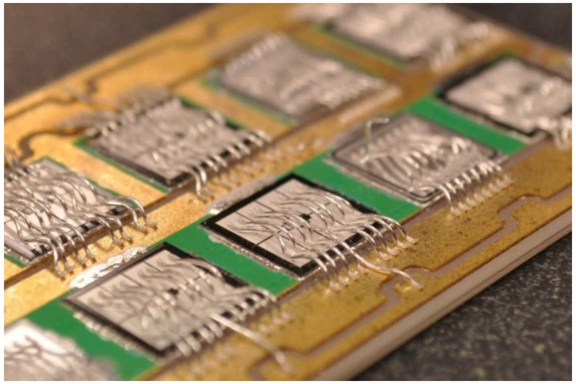
Funding for FY12: $425K

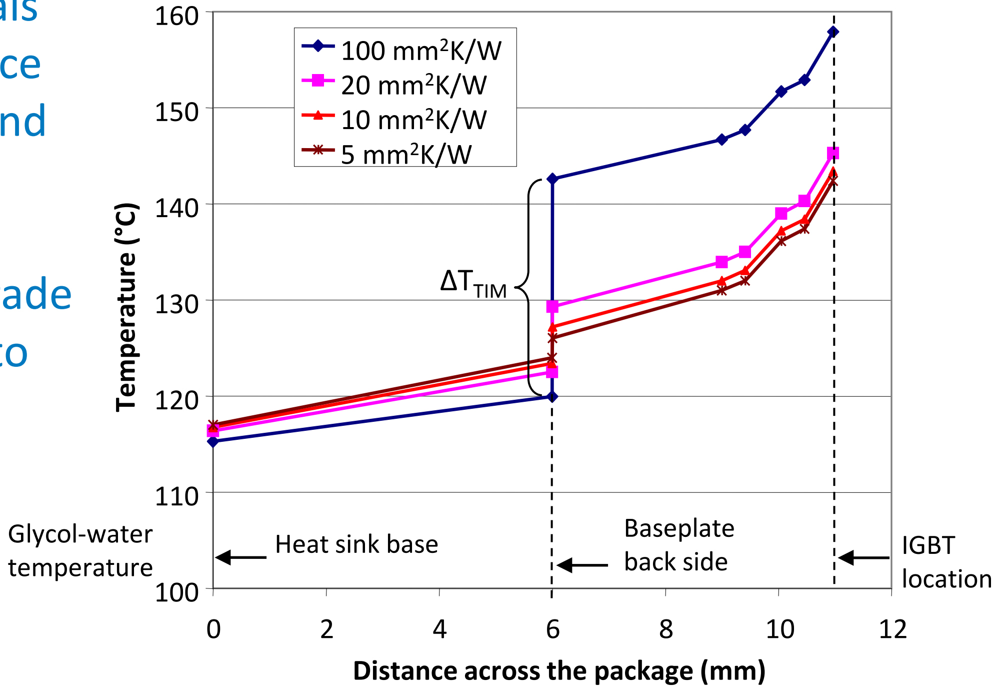
Partners

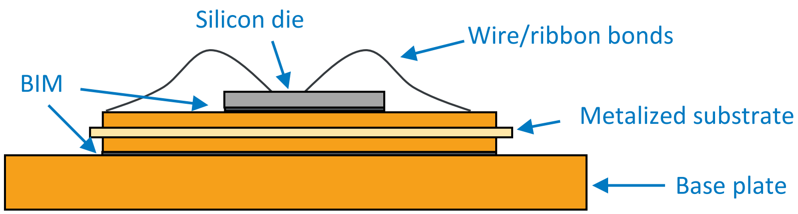
- Interactions / Collaborations
  - General Motors, Btech, Semikron, Heraeus, Kyocera, Virginia Tech, Oak Ridge National Laboratory (ORNL)
- Project lead: NREL

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 mm^2K/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:
    - Compact, light-weight, low-cost packaging
    - 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

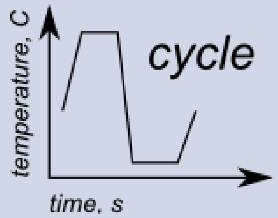
Date	Milestone or Go/No-Go Decision
June 2011	Evaluated bond quality of initial samples using nondestructive acoustic imagery (C-SAM). Aluminum nitride (AlN) delamination failures on many samples initiated change to silicon nitride (Si_3N_4) substrates.
October 2011	Completed initial finite element analysis (FEA) modeling to determine plastic work/strain energy density in lead-based solder BIM while under cycling.
December 2011	Received new Si_3N_4 substrates and tested for delamination under accelerated temperature cycling profile. New substrates meet reliability requirements for BIM testing.
January 2012	Synthesized second set of samples using revised substrates. Btech HM-2 bonded at NREL and sintered silver bonded at Semikron.
May 2012	Complete double lap shear testing of lead-based solder samples and use stress/strain data to revise viscoplastic properties needed for FEA.
September 2012	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.

Approach/Strategy

Sample Synthesis

Synthesis of samples using stencil printer and hot press

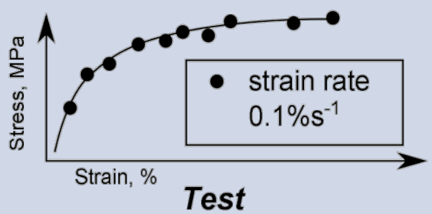
Thermal Testing/ Characterization



Cycling of samples in a thermal shock chamber

Characterization of samples via steady-state thermal resistance tester, hipot tester, C-SAM, and X-ray imaging

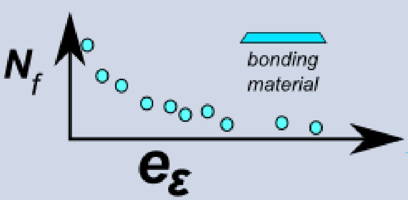
BIM Mechanical Characterization



Shear tests to extract mechanical characteristics of BIMs

Extraction of viscoplastic parameters

Reliability Calculation



Strain energy density per cycle

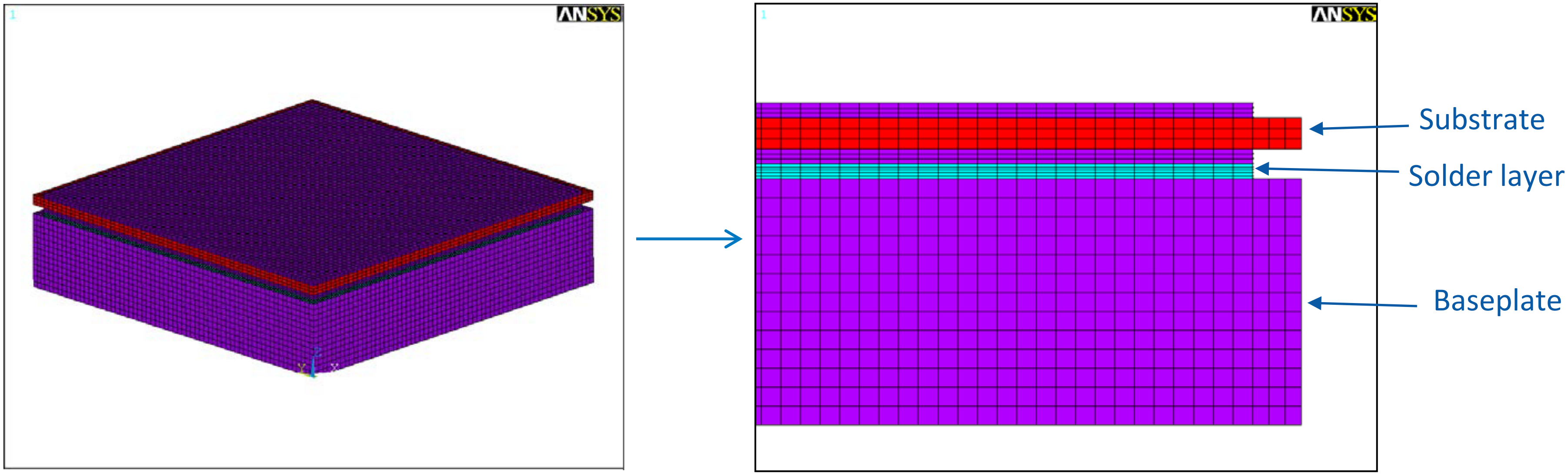
Number of cycles to crack initiation/ delamination

Fatigue life prediction

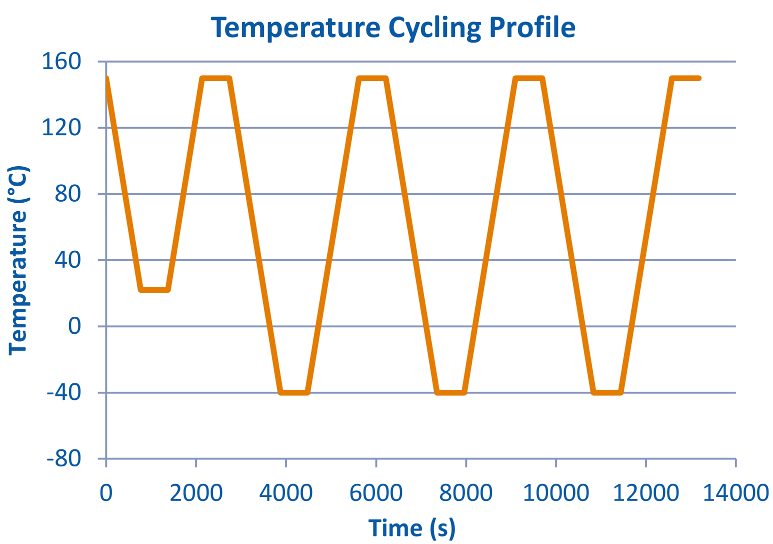
Experimental Approach

Numerical Approach - FEA/Calculations

BIM Finite Element Modeling

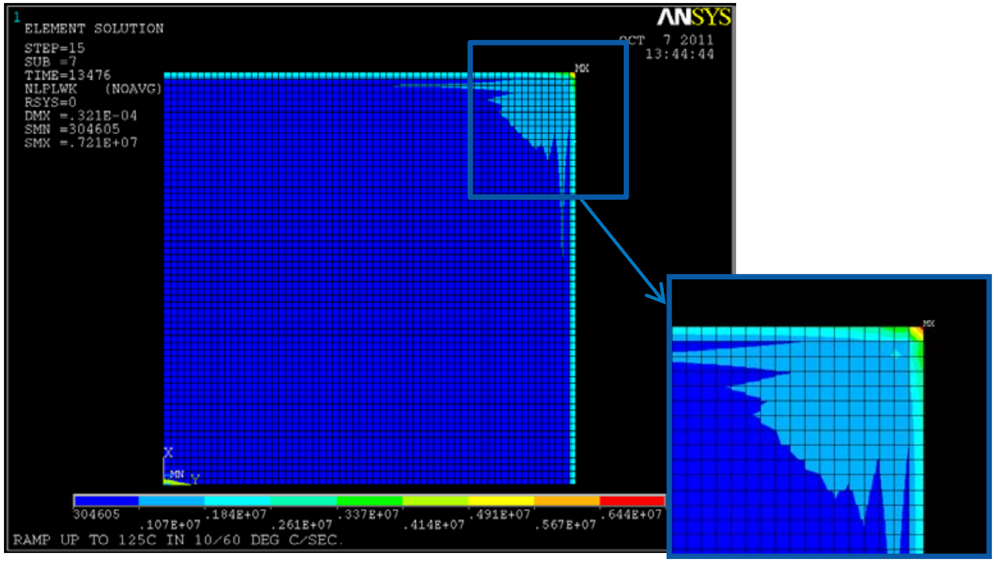


Quarter Symmetry Model

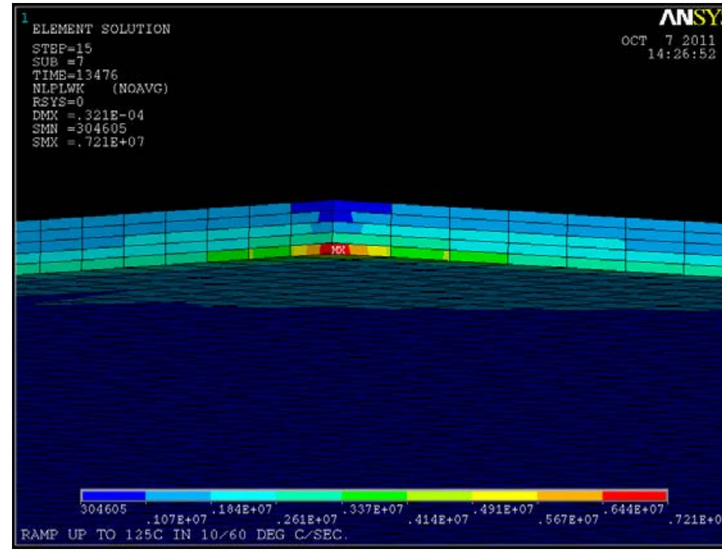


- Temperature cycling parameters:
  - Maximum temperature = 150°C
  - Minimum temperature = -40°C
  - Ramp rate = 10°C/minute
  - Dwell time = 10 minutes
- Viscoplastic material model applied to solder layer
- Temperature-dependent elastic material properties incorporated for baseplate and substrate

BIM Finite Element Modeling

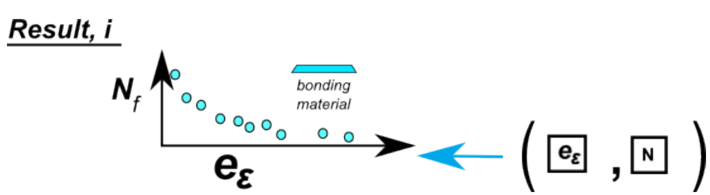


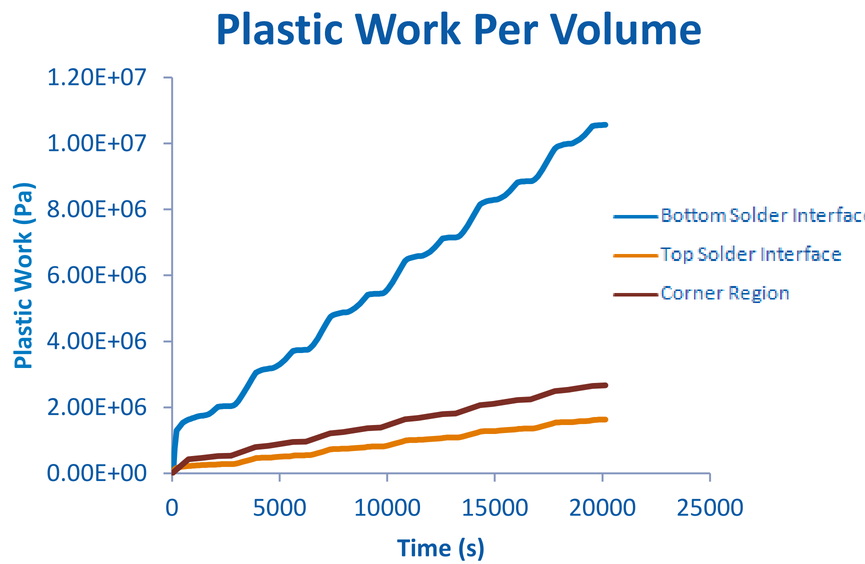
Solder Layer Bottom Surface (Quarter Symmetry Model)



Solder Layer Corner View

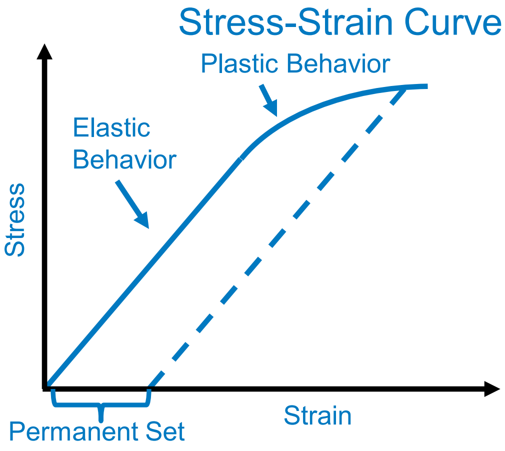
- Accumulated plastic work per volume distribution in the bonded joint region (63Sn-37Pb solder)
- Plastic work higher in the corner regions—location where failures are likely to originate
- Plastic work/strain energy density versus cycles-to-failure correlation to be obtained for lead-based and lead-free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

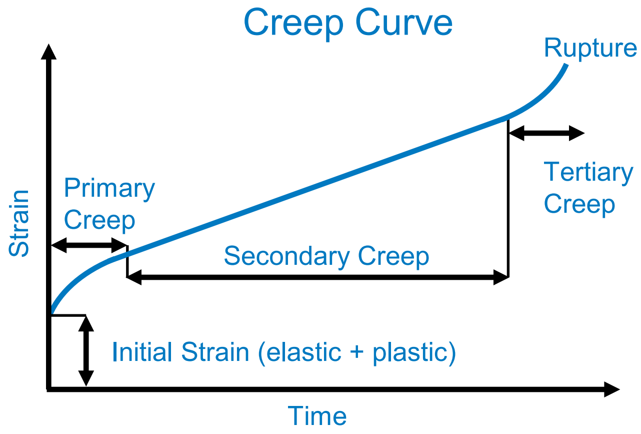




BIM Mechanical Characterization

- 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





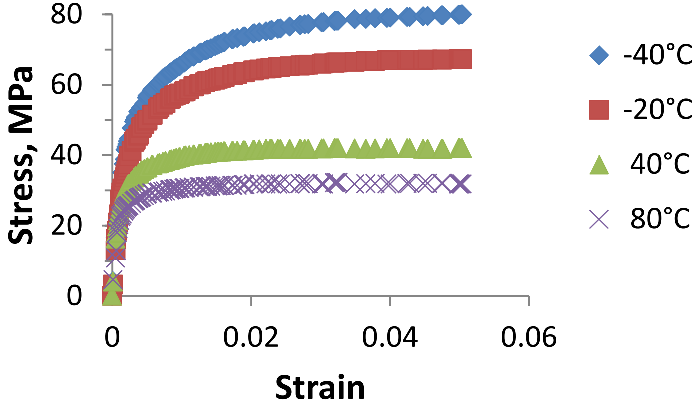
BIM Mechanical Characterization

- 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

Double-Lap Shear Fixture and Sample

Credit: Douglas DeVoto, NREL

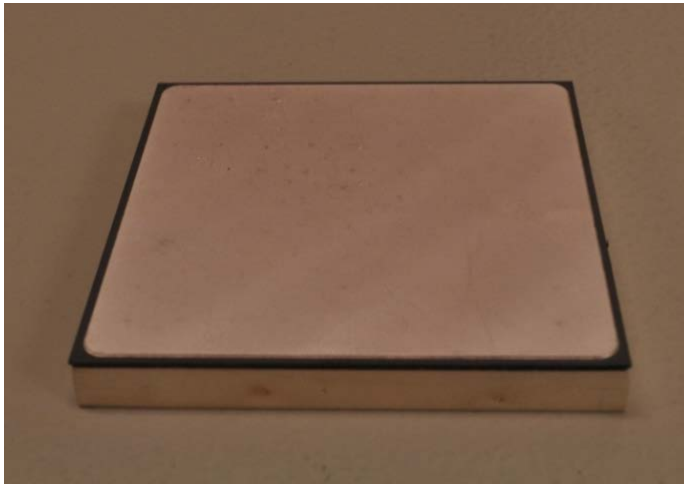
Example Stress/Strain Data at Constant Strain Rate ($0.02 s^{-1}$)



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 Si_3N_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

Sample Assembly

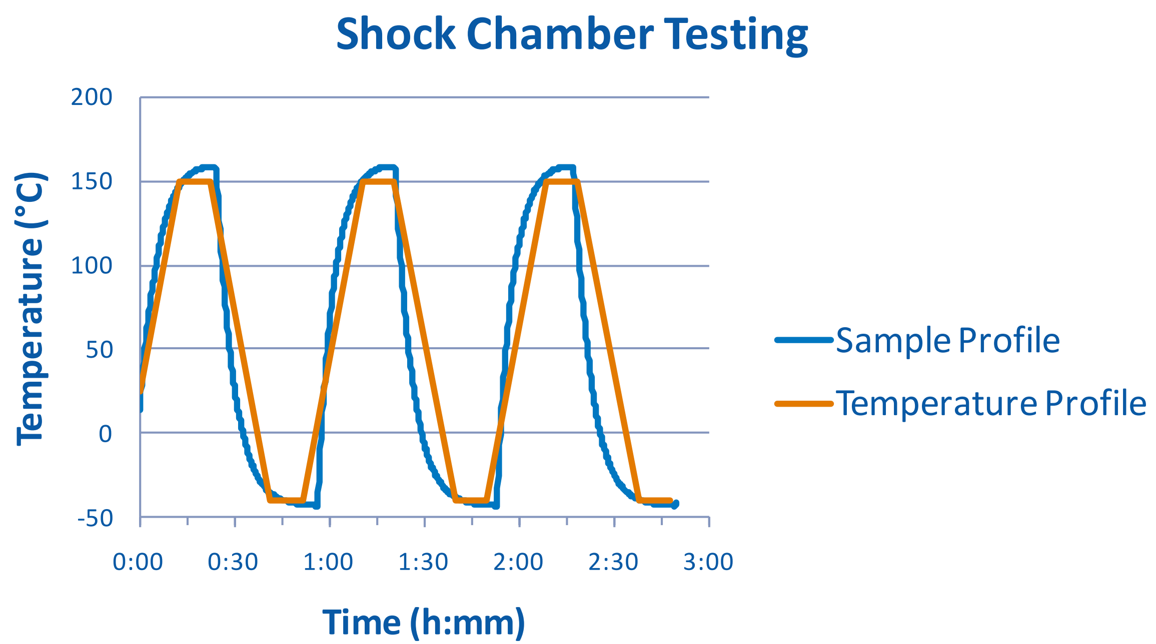


Credit: Douglas DeVoto, NREL

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

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



Shock Chamber

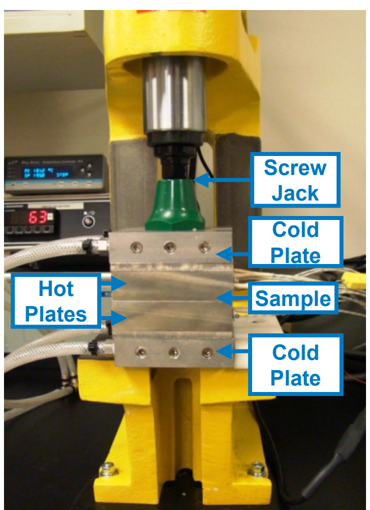
Credit: Douglas DeVoto, NREL

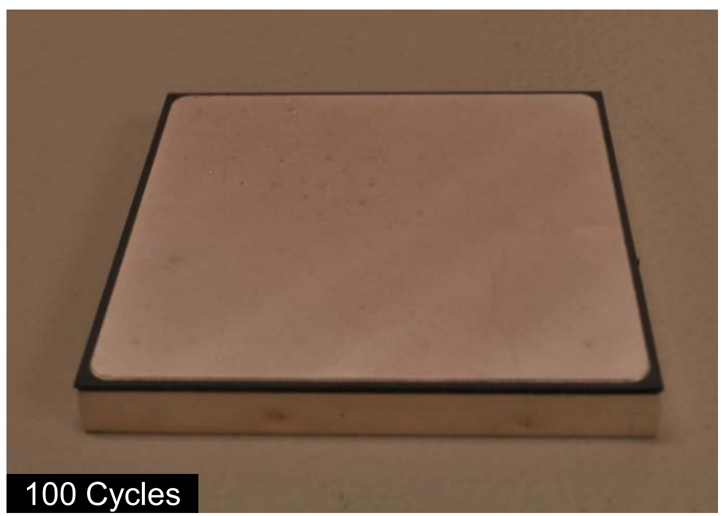
* JEDEC: Joint Electron Device Engineering Council

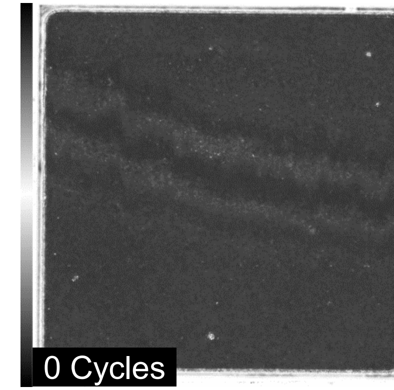
Thermally Conductive Adhesive Film

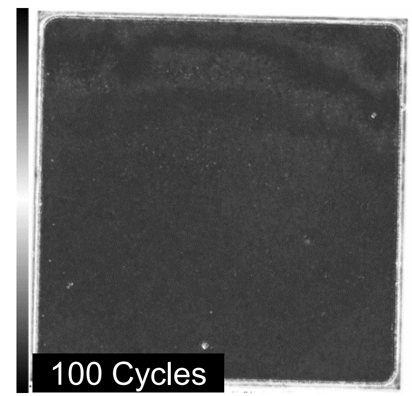
- Btech HM-2 (Carbon Fibers within Polymer Matrix)
  - Bonding
    - HM-2 was cut to the base plate dimensions. The sample assembly was placed in the hot press and raised to 195°C, then ~1 MPa (150 psi) of pressure was applied.
  - Reliability Results
    - C-SAM images show less contrast with thermoplastics,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

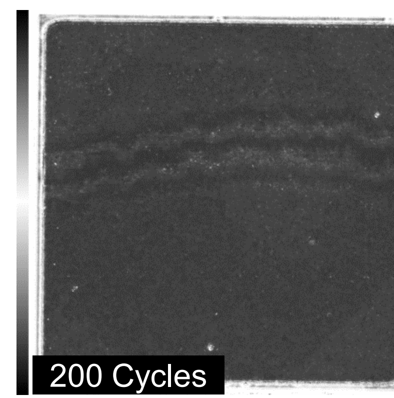
Hot Press







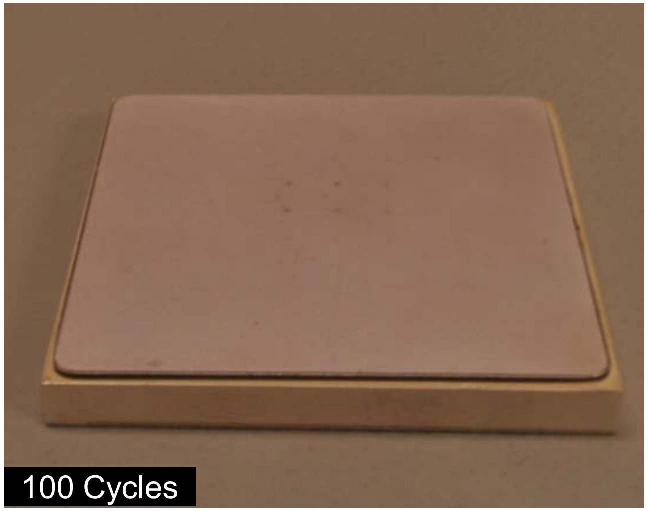


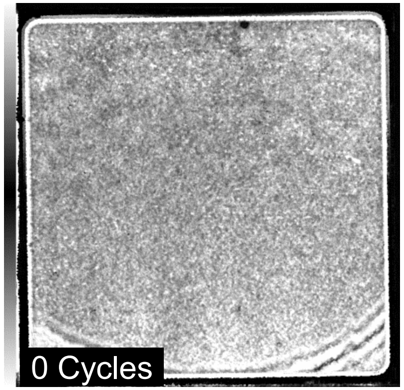


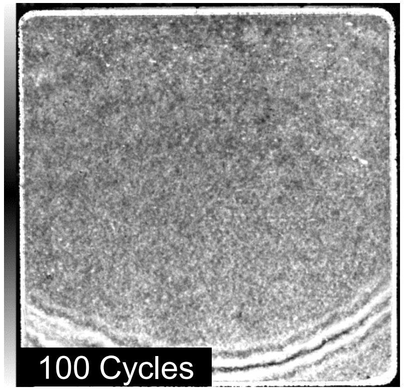
Credit: Douglas DeVoto, NREL (all photos)

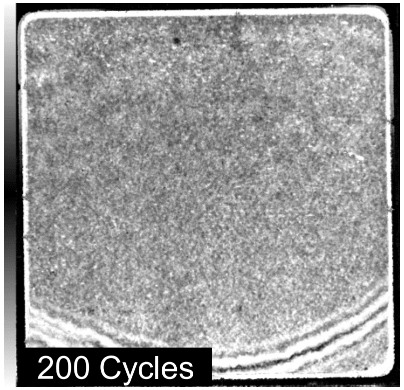
Silver Sinter

- Semikron Silver Sinter
  - Bonding
    - Corners of the Si_3N_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.
    - Independent compression testing of substrates at ORNL showed cracking of substrates required between 30 MPa to 50 MPa of pressure.
  - Reliability Results
    - Uniform bonds were obtained.
    - After 200 cycles, the bonded interface remained defect-free.









Credit: Douglas DeVoto, NREL (all photos)

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_3N_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_3N_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_3N_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 Si_3N_4 based substrates
  - Report on reliability of each BIM under specified accelerated test conditions

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