Thermal Performance and Reliability of Bonded Interfaces

2011 DOE Vehicle Technologies Program Review

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Project ID: APE028

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

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

Budget

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

Barriers Addressed

- Cost
- Weight
- Performance and Lifetime

Targets Addressed

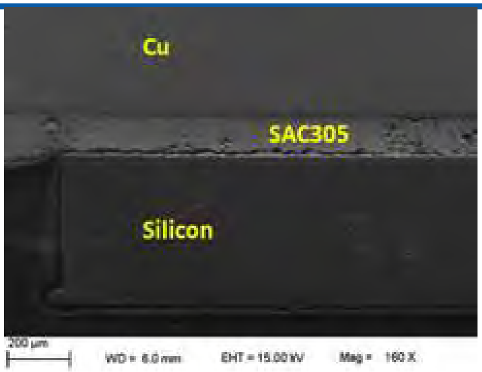
- Cost
- Specific Power
- Power Density

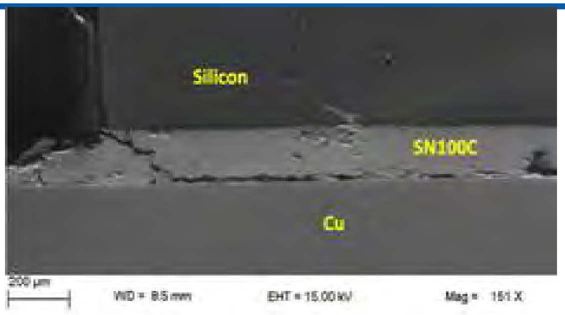
Partners

- 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

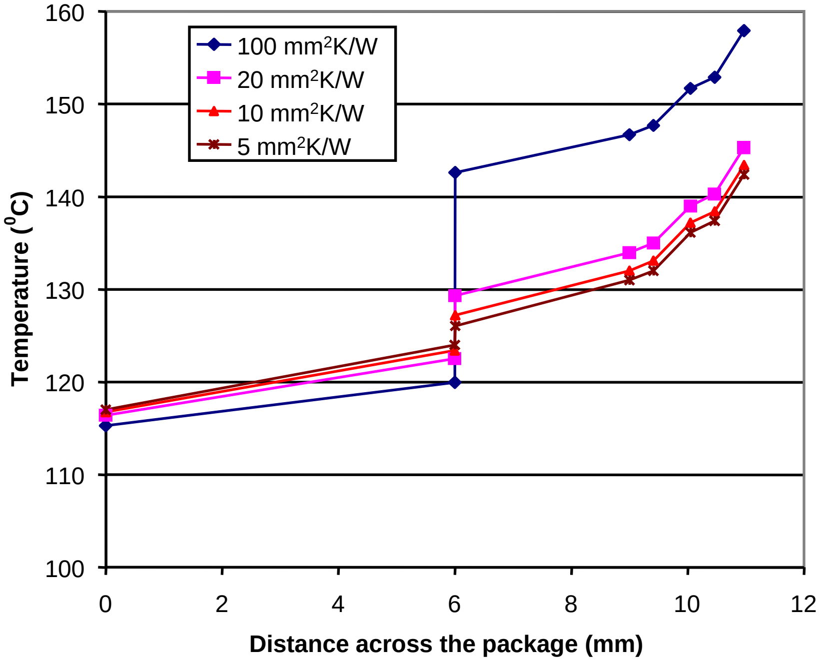
Relevance/Objectives (1/2)

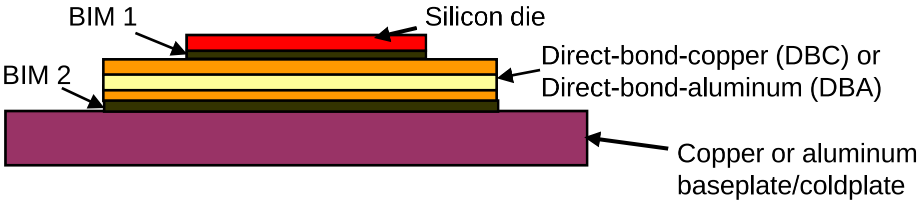
- Excessive temperature (>150°C for Si devices) can degrade the performance, life and reliability of power electronics components.
- Interfaces in the package can pose a major bottleneck to heat removal.
- Conventional thermal interface materials (TIMs) do not meet thermal performance and reliability 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.





Courtesy: G.Q. Lu, Virginia Tech





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
    - Thermal resistance of 5 mm^2K/W.
    - Maintain thermal resistance of 5 mm^2K/W after 2,000 thermal cycles from -40 to 150°C.

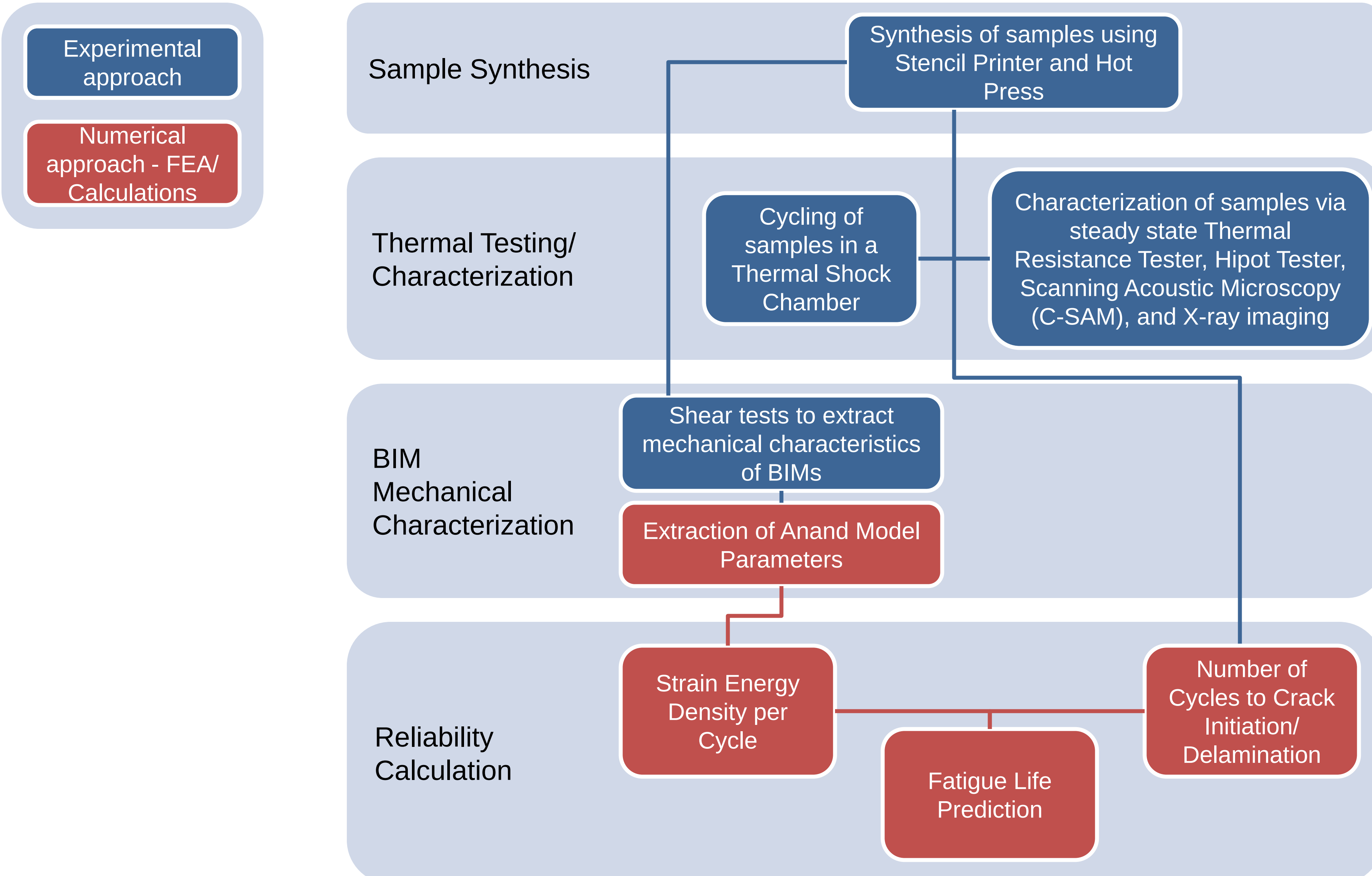
- Addresses Targets
  - High-performance, reliable, low-cost bonded interfaces enable compact, light-weight, low-cost packaging.
  - Also enables high-temperature coolant and/or air cooling.

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

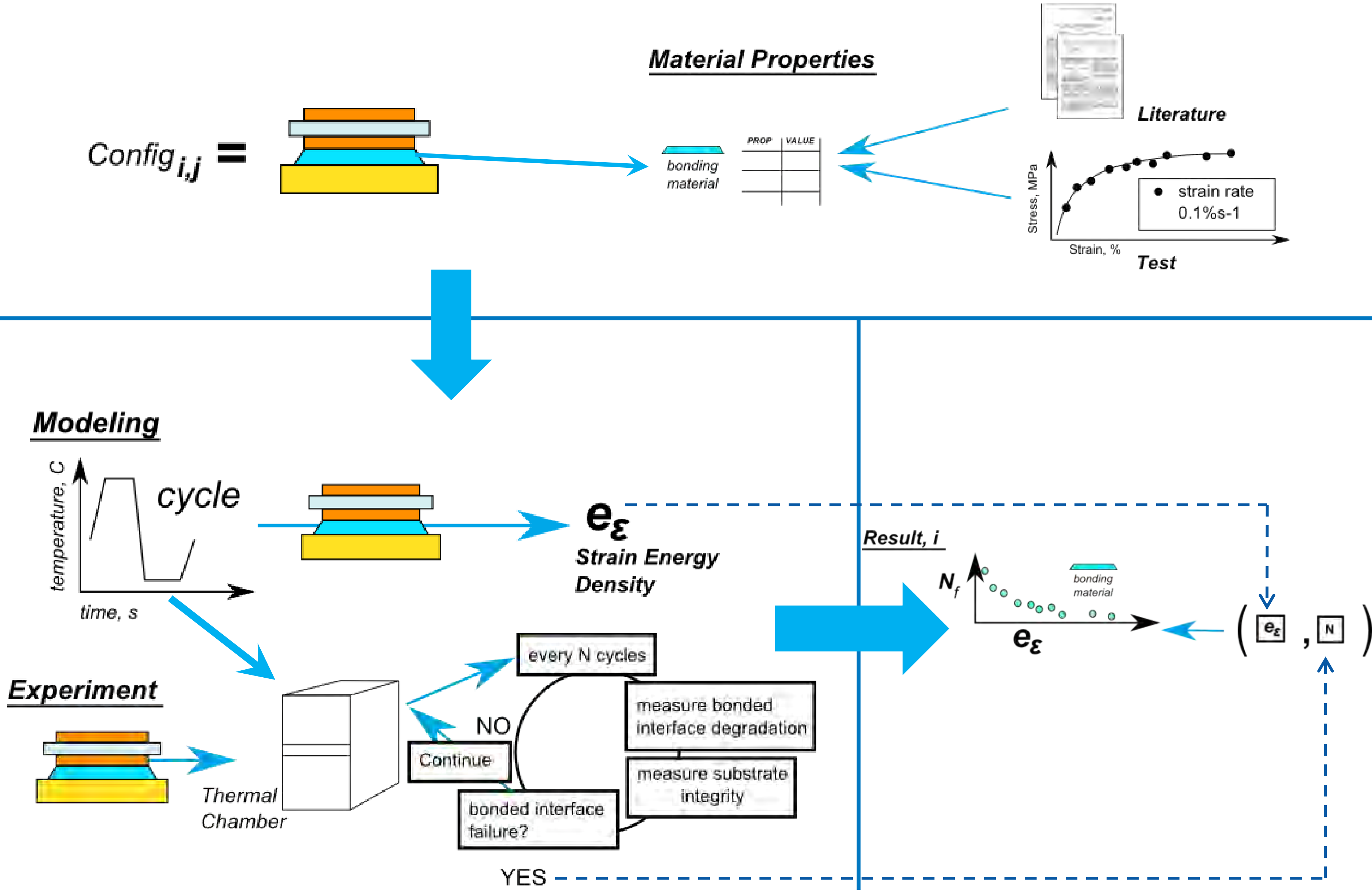
Milestones

Month/ Year	Milestone or Go/ No-Go Decision Point
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 chacterization 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)

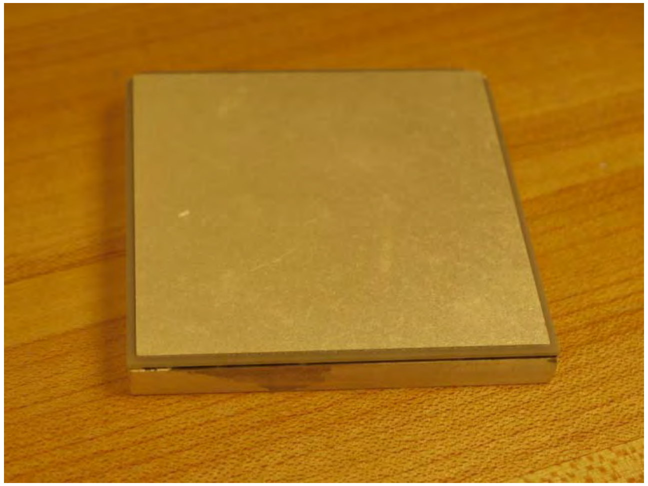

Experimental approach
Numerical approach - FEA/ Calculations
Sample Synthesis
Synthesis of samples using Stencil Printer and Hot Press
Thermal Testing/ Characterization
Cycling of samples in a Thermal Shock Chamber
Characterization of samples via steady state Thermal Resistance Tester, Hipot Tester, 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
Number of Cycles to Crack Initiation/ Delamination
Fatigue Life Prediction

Approach (2/2)


Material Properties
Config i,j =
bonding material
PROP
VALUE
Literature
Stress, MPa
Strain, %
strain rate 0.1%s-1
Test
Modeling
temperature, C
time, s
cycle
eε
Strain Energy Density
Experiment
Thermal Chamber
every N cycles
measure bonded interface degradation
measure substrate integrity
bonded interface failure?
NO
Continue
YES
Result, i
Nf
bonding material
eε
(eε , N)

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).



DBC/baseplate assembly

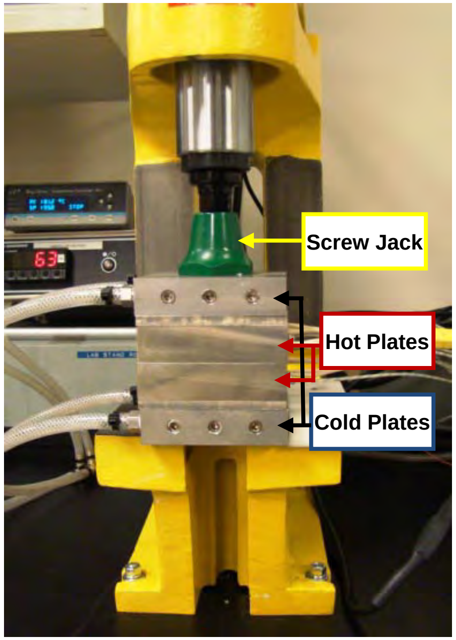
Credit: Doug DeVoto, NREL

Bond Material Type	Name	Comments
Solder	Sn63Pb37	Baseline (lead-based solder)
Solder	Henkel Innolot LF318	Lead-free solder
Solder	SAC305	Lead-free solder
Sintered silver	NanoTach	Based on nanoscale silver particles
Sintered silver	Heraeus C8829A	Based on micron-size silver particles
Sintered paste	Silver-Indium	Based on micron-size particles
Adhesive	Dow Corning DA-6534	Silver-filled, heat-curable silicone adhesive
Adhesive	Btech HM-2	Thermoplastic (polyamide) film with embedded carbon fibers
Adhesive	Henkel Hysol® CF3350	Thermally conductive silver-filled film

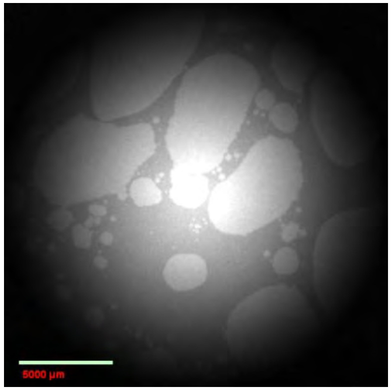
Accomplishments – Bonded Interface Synthesis and Imaging

- 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.

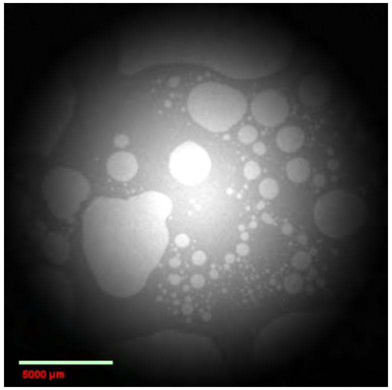
Credit: Doug DeVoto, NREL



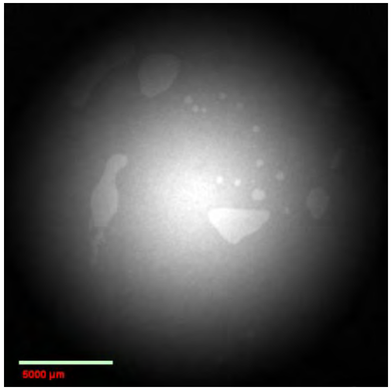
Hot Press



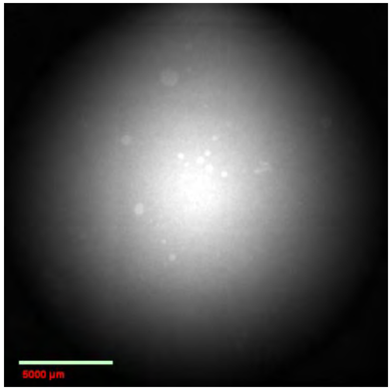
SAC solder (middle)



SAC solder (edge)



Pb-Sn solder (middle)

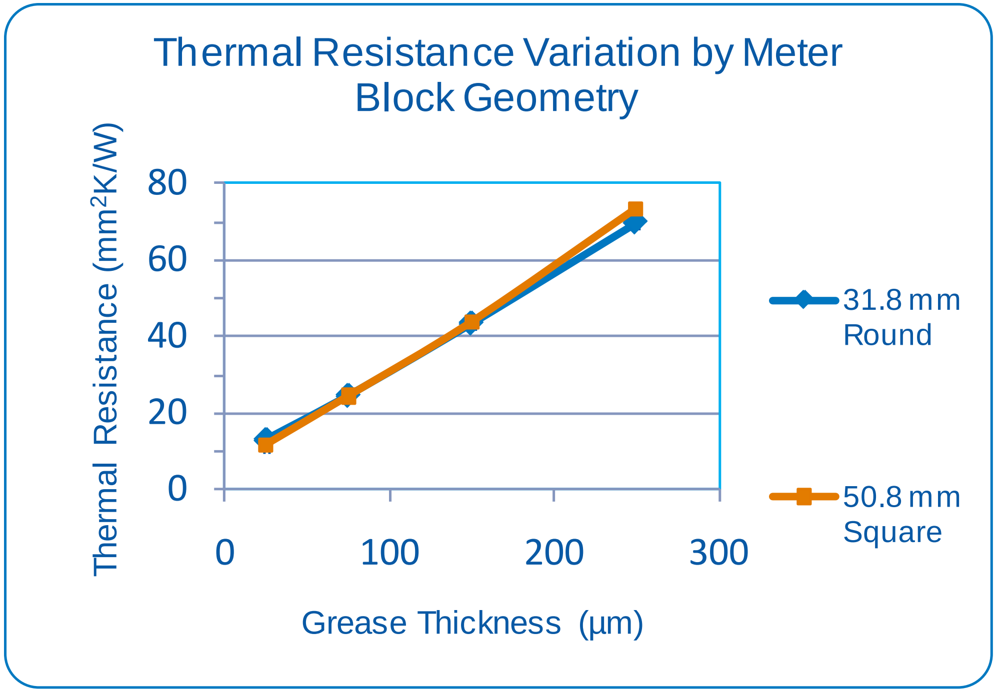


Pb-Sn solder (edge)

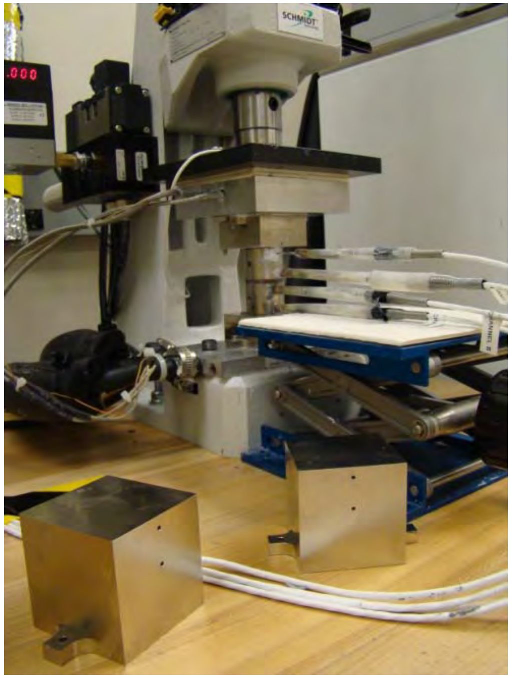
Courtesy: Jesus Calata, Virginia Tech

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).



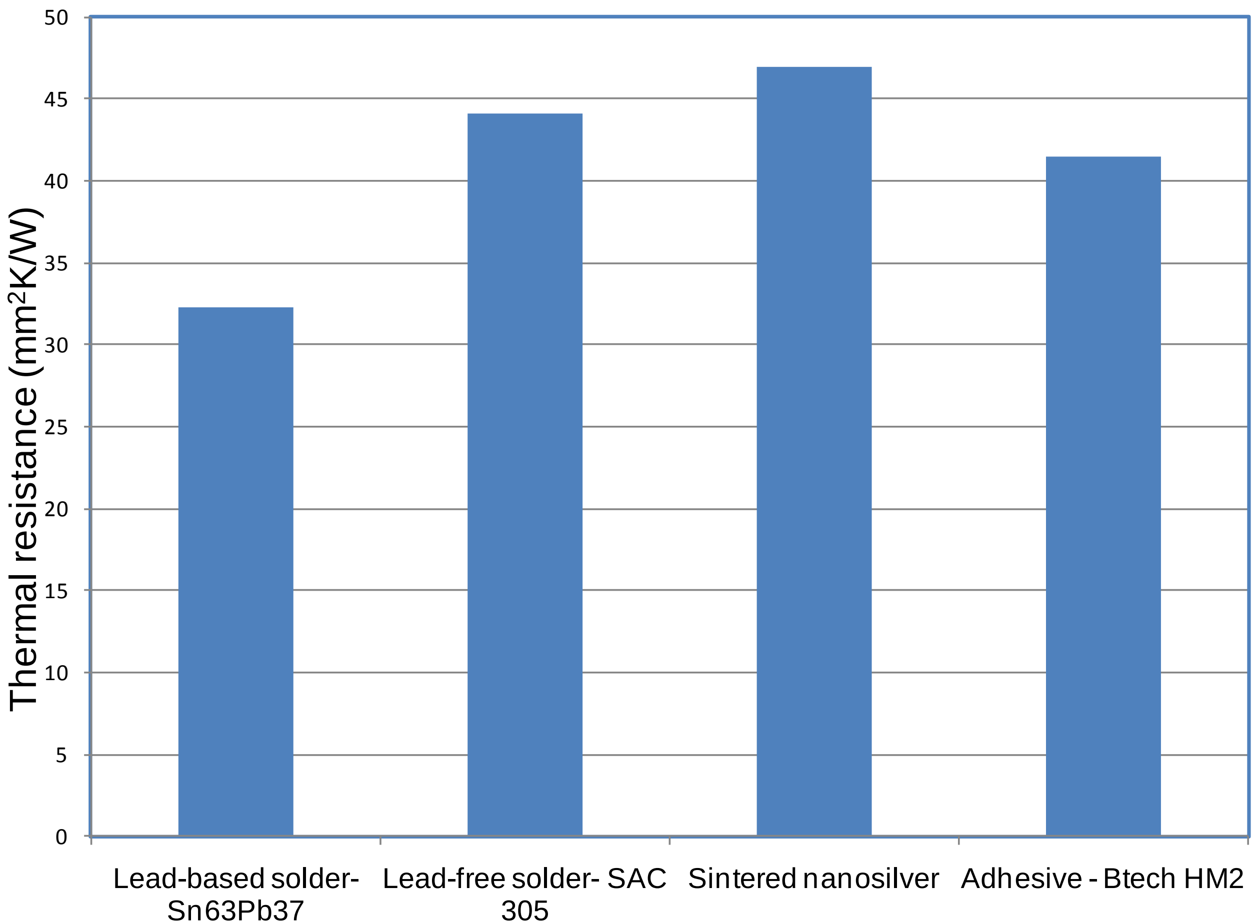
Credit: Doug DeVoto, NREL



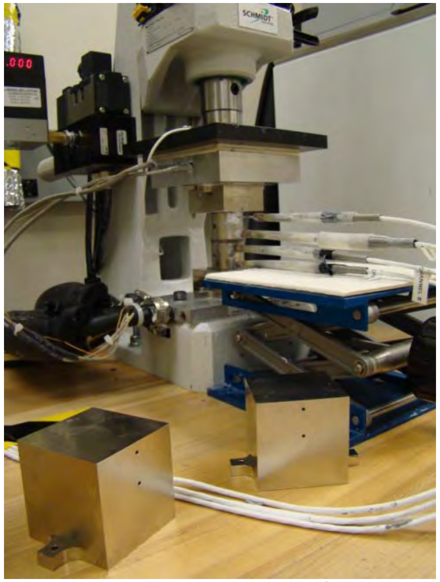
ASTM Stand

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.



Credit: Doug DeVoto, NREL



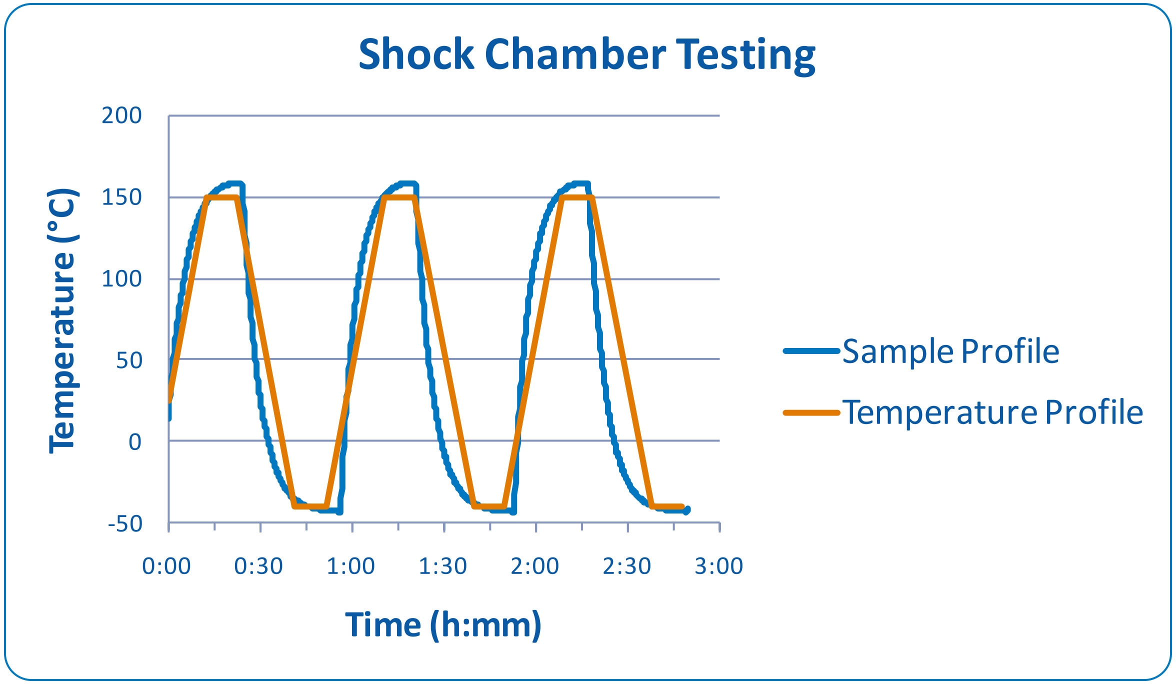
ASTM Stand

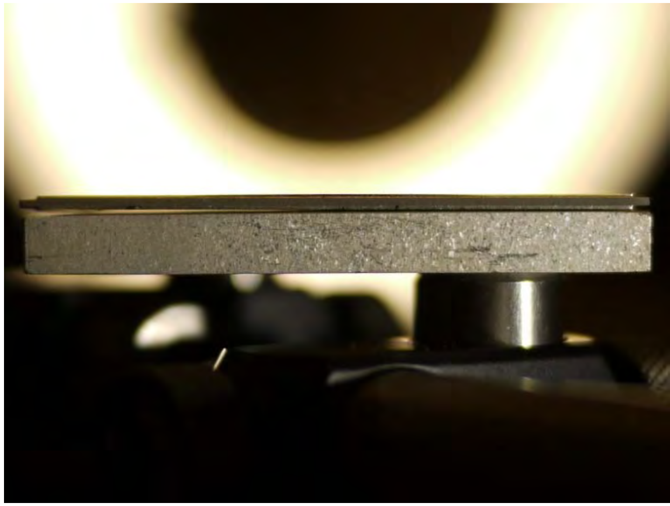
Accomplishments – Thermal Cycling Chamber Performance Characterization

- 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

Hipot Tester



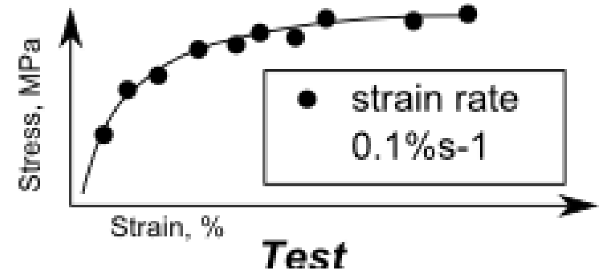


Sample delamination after 10 cycles

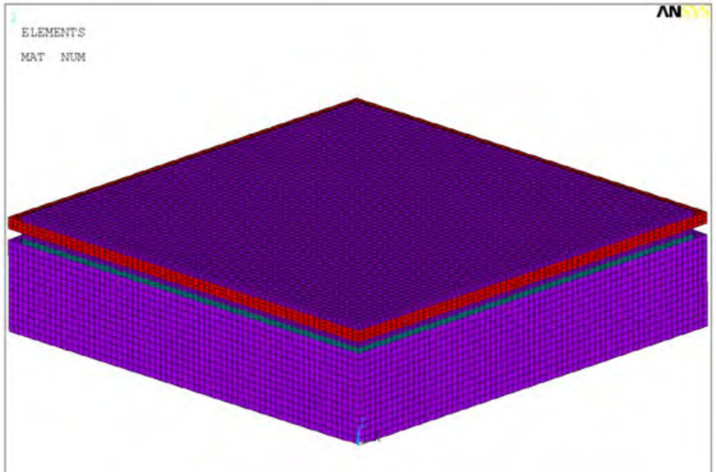
Credit: Doug DeVoto, NREL (all photos)

Accomplishments – BIM Mechanical Characterization

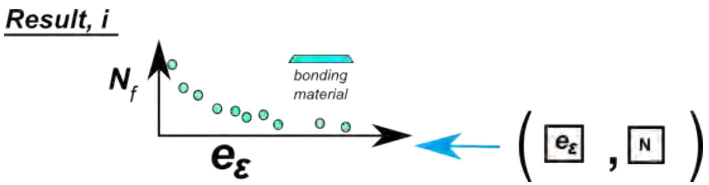
- Shear testing fixture was designed for BIM specimens. Fixture will allow for sample testing at various strain rates and temperatures.
- Script developed to derive Anand parameters from strain rate test data. This will allow the behavior of new solder and sinter materials to be modeled in FEA simulations.
- 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.



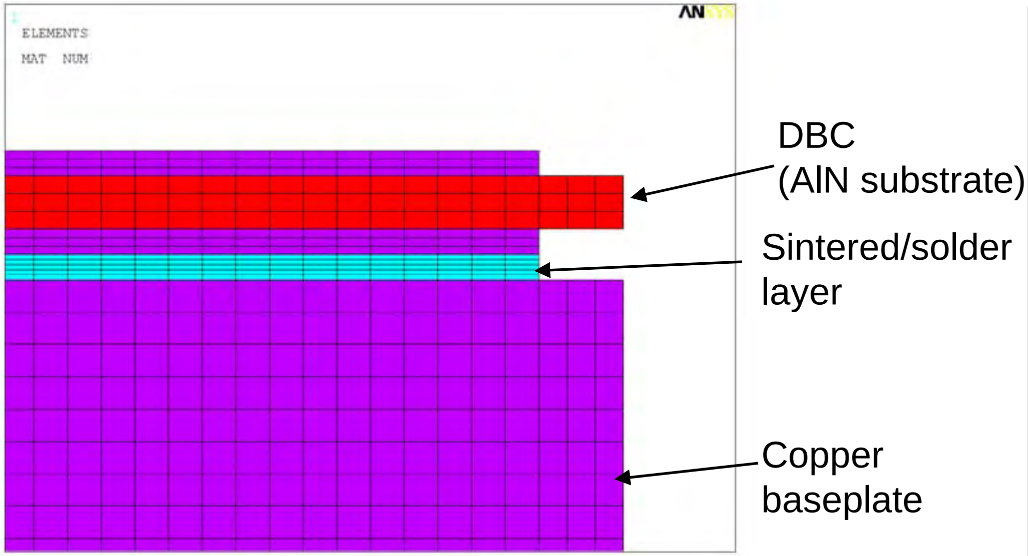
Example Stress-Strain Test Data

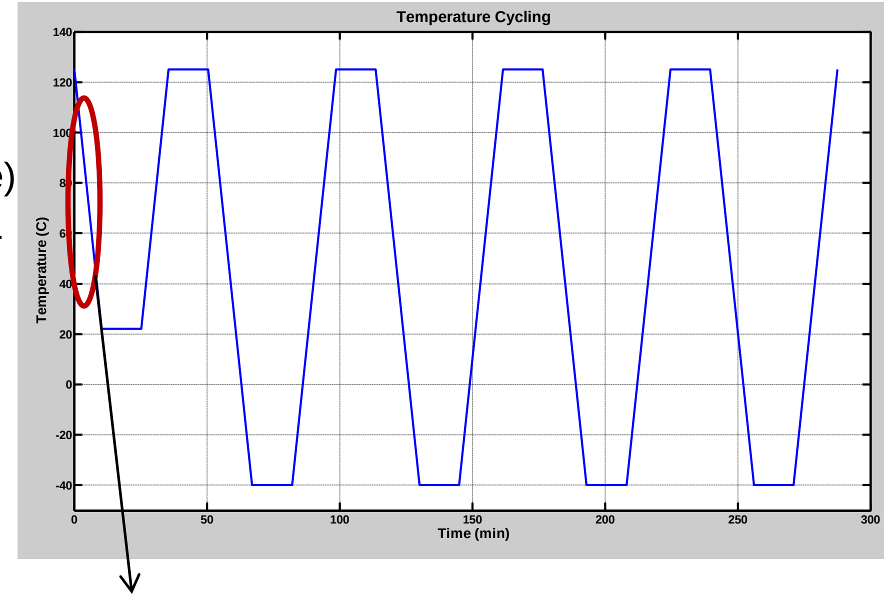


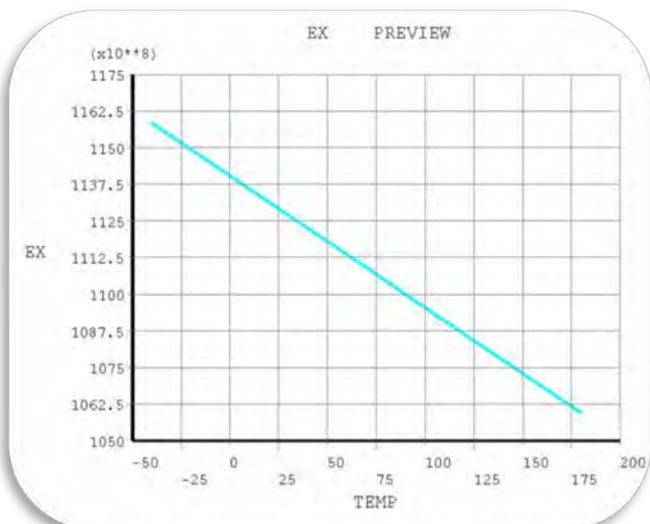
Courtesy: Andreas Vlahinos, AES

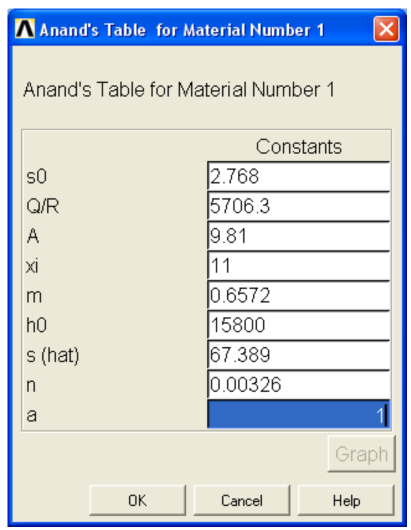


Accomplishments – FEA Modeling: Trial Simulation for Cool Down from 125°C to 22°C









Anand's Table for Material Number 1

Anand's Table for Material Number 1

	Constants
s0	2.768
Q/R	5706.3
A	9.81
xi	11
m	0.6572
h0	15800
s (hat)	67.389
n	0.00326
a	1

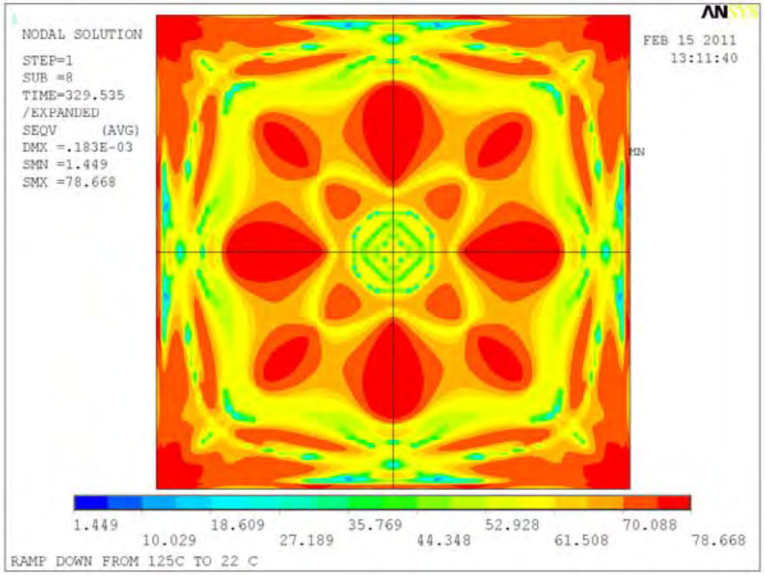
Graph

OK Cancel Help

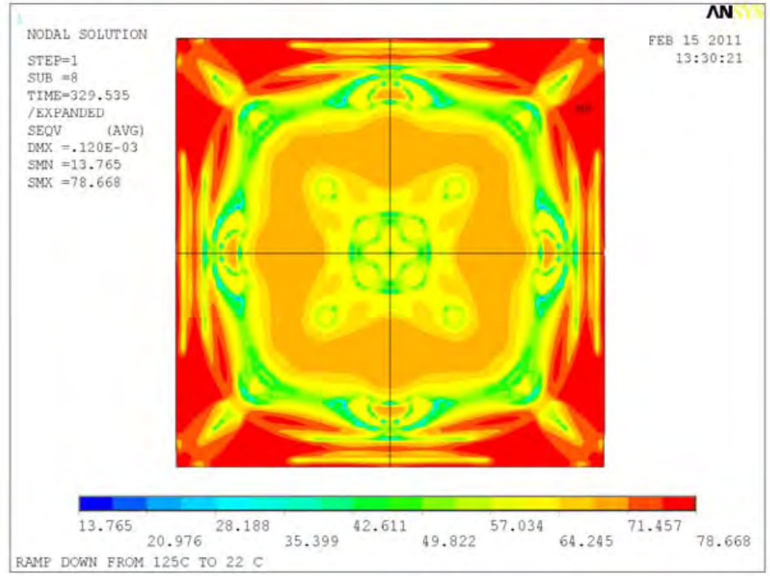
- Parameters
  - Reflow temperature = 125°C
  - Room temperature = 22°C
  - Ramp rate = 10°C/minute
- Anand's viscoplastic material model for the solder/sintered material
- Temperature-dependent material properties for copper and AlN

Courtesy: Andreas Vlahinos, AES (all graphics)

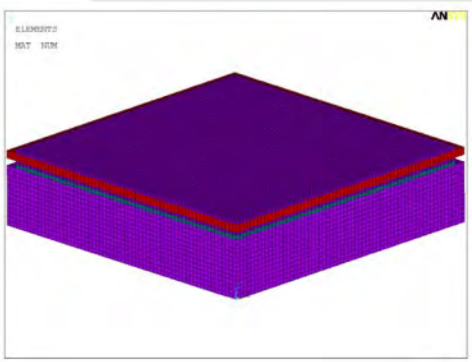
Accomplishments – FEA Modeling: Stress Distribution (Cool Down from 125°C to 22°C)



Upper/top layer of bonded joint



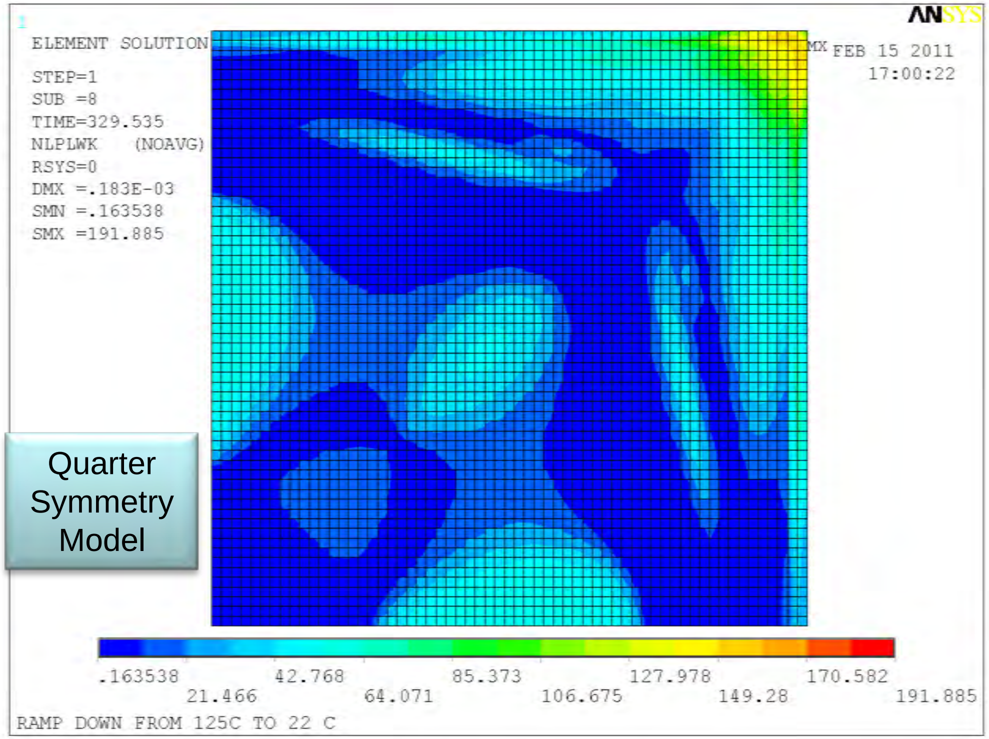
Middle layer of bonded joint



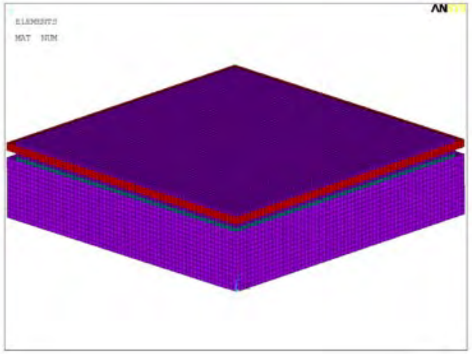
Courtesy: Andreas Vlahinos, AES (all graphics)

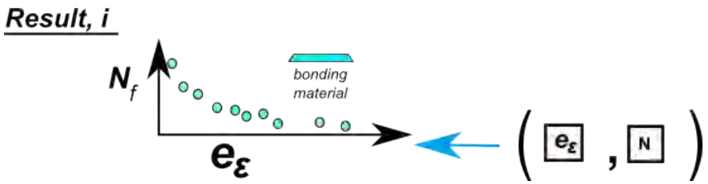
- Equivalent stress distribution in the upper/top and middle layer of the bonded joint.
- Stresses are higher in the layer adjoining the DBC and higher in the corner regions.

Accomplishments – FEA Modeling: Plastic Work Density Distribution (Cool Down from 125°C to 22°C)



Courtesy: Andreas Vlahinos, AES (all graphics)





- 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.

Collaborations

Collaborator	Nature of Interaction / Collaboration
Electrical & Electronics Technical Team, GM , Delphi	• Technical guidance
ORNL	• Packaging
NIST	• Electrothermal modeling of power modules
Virginia Tech	• Synthesis of soldered and sintered joints • X-ray imaging • Provider of nanosilver paste
Btech	• Provider of thermoplastic (polyamide) with embedded carbon fibers
University of Maryland	• Provider of silver-indium paste
AES	• Finite element modeling support

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:
    - Perform thermal cycling of bonded samples.
    - Characterize thermal resistance and quality of bond.
    - Characterize BIM to obtain stress-versus-strain mechanical constitutive relationships.
    - Perform FEA modeling to infer strain energy density.
    - 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:

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