Bonded Interfaces for High-Temperature Power Electronics

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National Renewable Energy Laboratory, Colorado
ASME InterPACK Conference
October 27, 2021

Agenda

- NREL Overview
- Background & Approach
- Bonded Interfaces Reliability
  - 150°C
  - 200°C
- Thermomechanical Modeling
  - Parametric study of a power module
  - Demonstration using ANSYS
- Challenges and Opportunities
- Summary

Department of Energy Laboratories

Office of Science Laboratories

① **Ames Laboratory**
Ames, Iowa

② **Argonne National Laboratory**
Argonne, Illinois

③ **Brookhaven National Laboratory**
Upton, New York

④ **Fermi National Accelerator Laboratory**
Batavia, Illinois

⑤ **Lawrence Berkeley National Laboratory**
Berkeley, California

⑥ **Oak Ridge National Laboratory**
Oak Ridge, Tennessee

⑦ **Pacific Northwest National Laboratory**
Richland, Washington

⑧ **Princeton Plasma Physics Laboratory**
Princeton, New Jersey

⑨ **SLAC National Accelerator Laboratory**
Menlo Park, California

⑩ **Thomas Jefferson National Accelerator Facility**
Newport News, Virginia

Other DOE Laboratories

① **Idaho National Laboratory**
Idaho Falls, Idaho

② **National Energy Technology Laboratory**
Morgantown, West Virginia
Pittsburgh, Pennsylvania
Albany, Oregon

③ **National Renewable Energy Laboratory**
Golden, Colorado

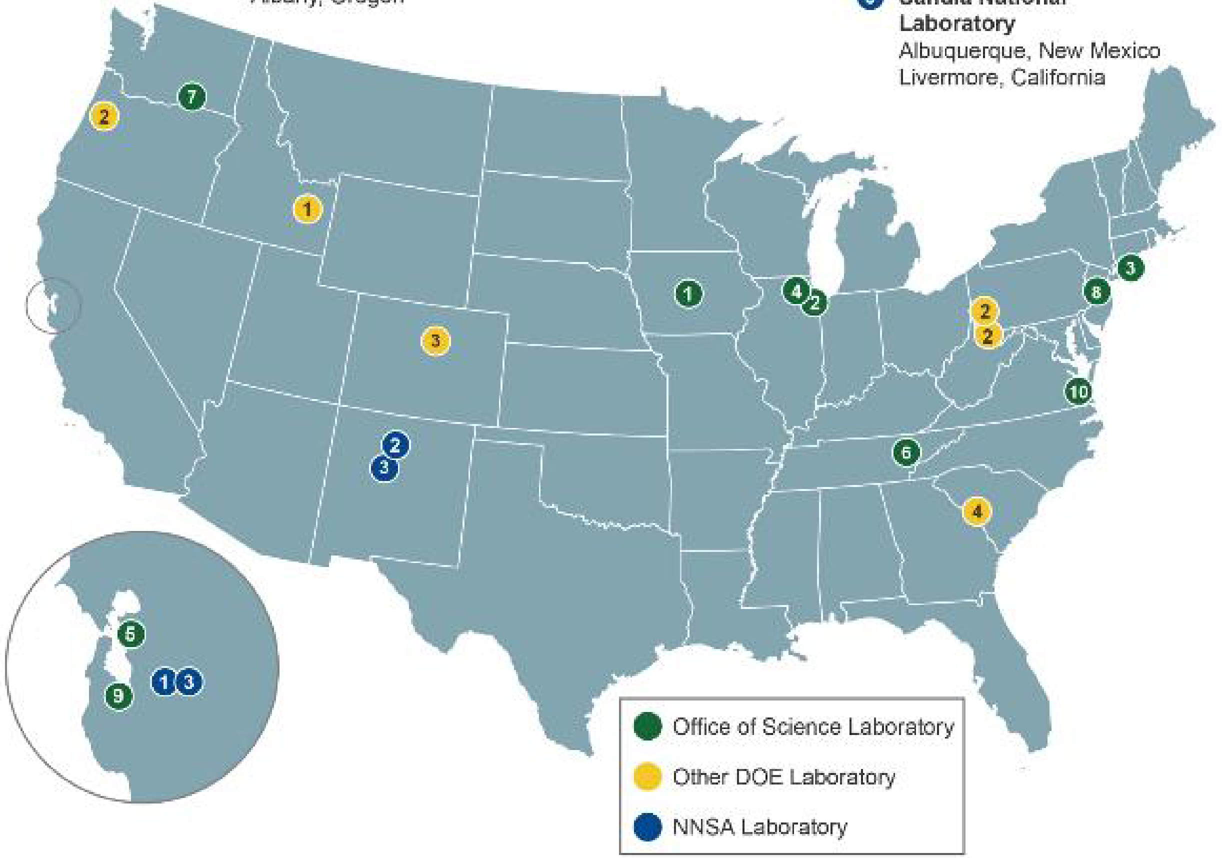
④ **Savannah River National Laboratory**
Aiken, South Carolina

NNSA Laboratories

① **Lawrence Livermore National Laboratory**
Livermore, California

② **Los Alamos National Laboratory**
Los Alamos, New Mexico

③ **Sandia National Laboratory**
Albuquerque, New Mexico
Livermore, California



National Renewable Energy Laboratory

Leading clean-energy innovation for 44 years

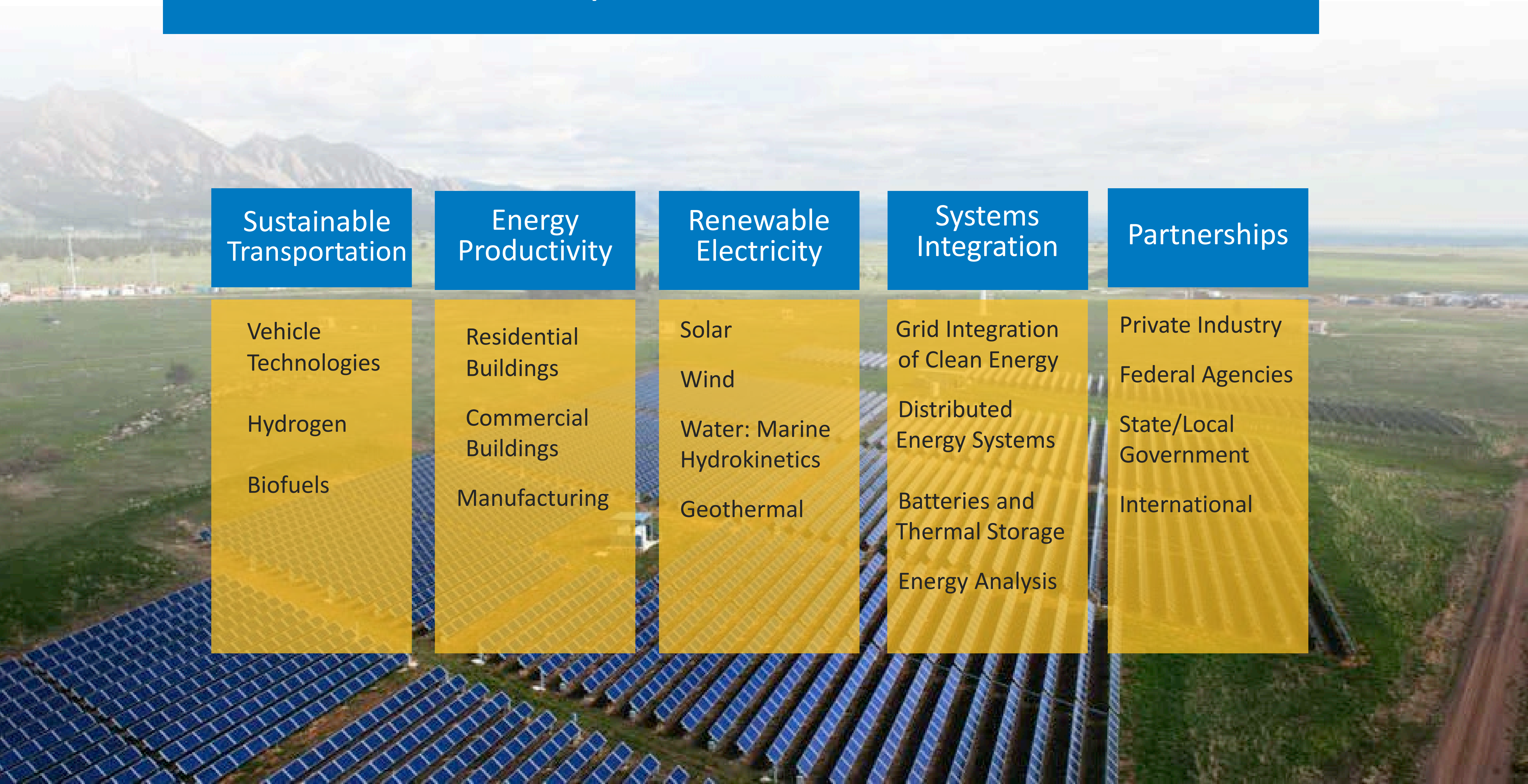
2,500 employees with world-class facilities

Campus is a living model of sustainable energy

Owned by the Department of Energy (DOE)

Operated by the Alliance for Sustainable Energy

Scope of NREL Mission



Sustainable Transportation

- Vehicle Technologies
- Hydrogen
- Biofuels

Energy Productivity

- Residential Buildings
- Commercial Buildings
- Manufacturing

Renewable Electricity

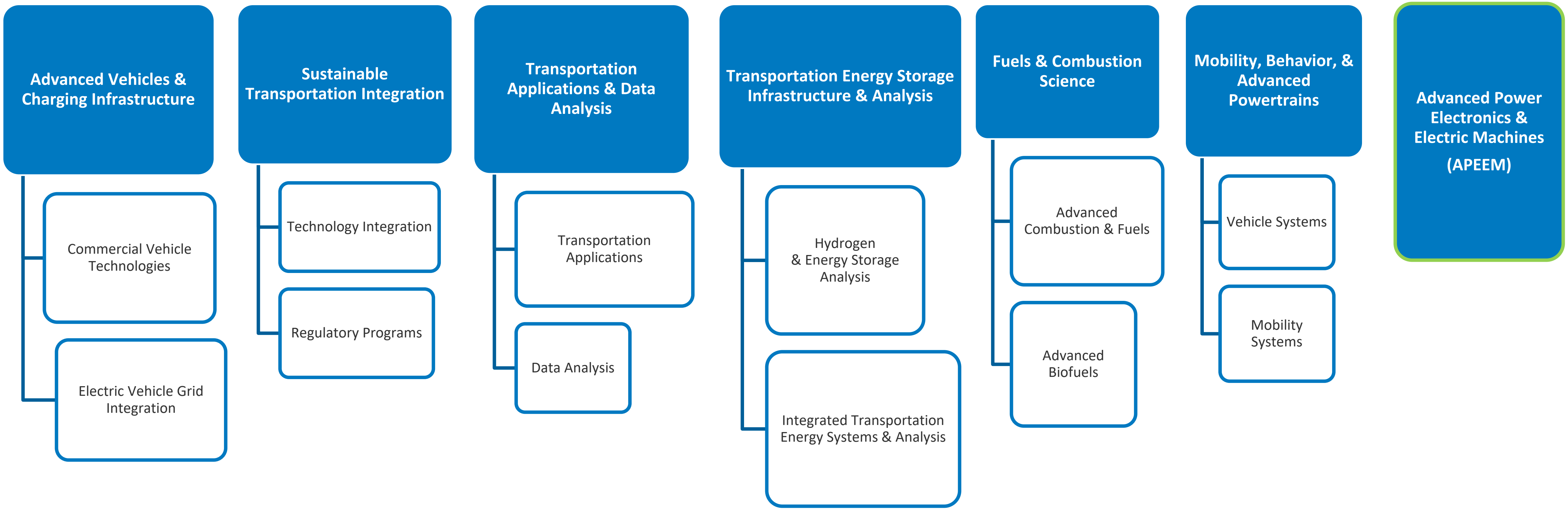
- Solar
- Wind
- Water: Marine Hydrokinetics
- Geothermal

Systems Integration

- Grid Integration of Clean Energy
- Distributed Energy Systems
- Batteries and Thermal Storage
- Energy Analysis

Partnerships

- Private Industry
- Federal Agencies
- State/Local Government
- International



Advanced Vehicles & Charging Infrastructure
- Commercial Vehicle Technologies
- Electric Vehicle Grid Integration

Sustainable Transportation Integration
- Technology Integration
- Regulatory Programs

Transportation Applications & Data Analysis
- Transportation Applications
- Data Analysis

Transportation Energy Storage Infrastructure & Analysis
- Hydrogen & Energy Storage Analysis
- Integrated Transportation Energy Systems & Analysis

Fuels & Combustion Science
- Advanced Combustion & Fuels
- Advanced Biofuels

Mobility, Behavior, & Advanced Powertrains
- Vehicle Systems
- Mobility Systems

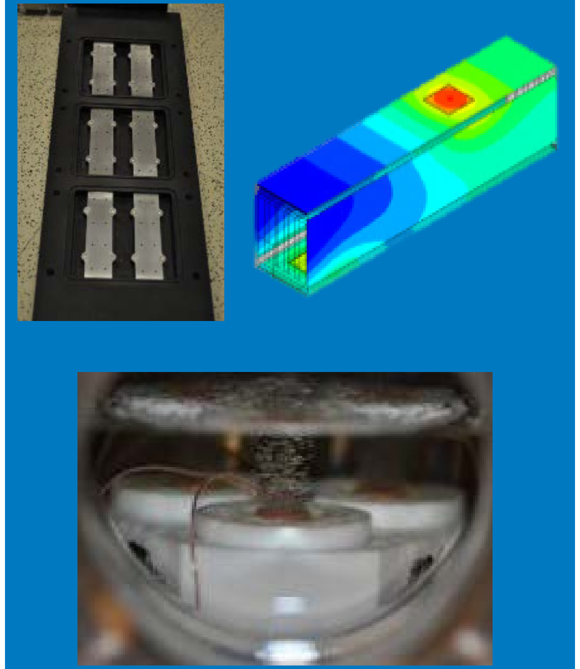
Advanced Power Electronics & Electric Machines (APEEM)

Center for Integrated Mobility Sciences (CIMS)

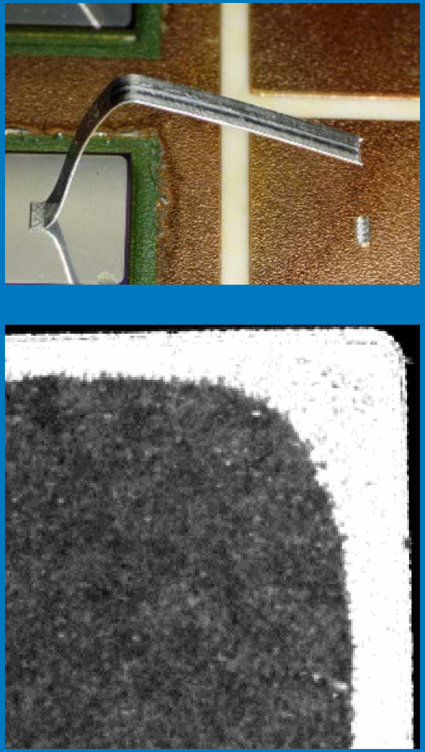
APEEM Group: Twelve (12) staff members involved in thermal, electro-thermal, thermomechanical, and reliability research activities.

APEEM Group Focus Areas

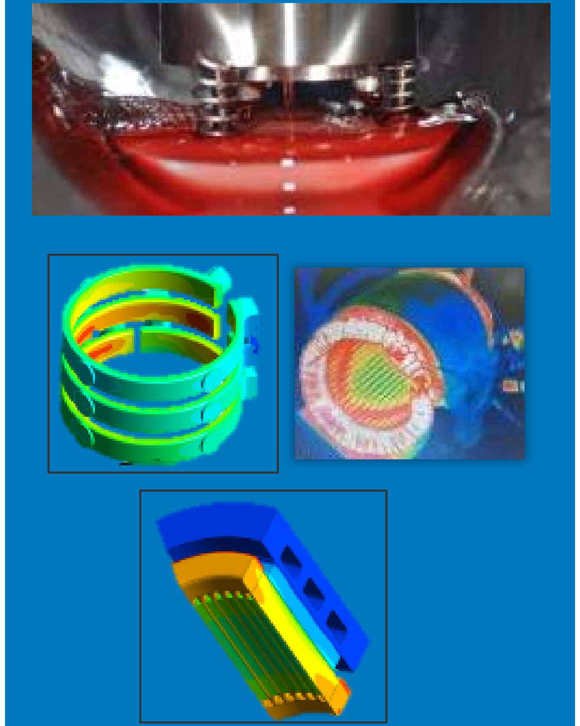
Power Electronics Thermal Management



Advanced Packaging Designs and Reliability

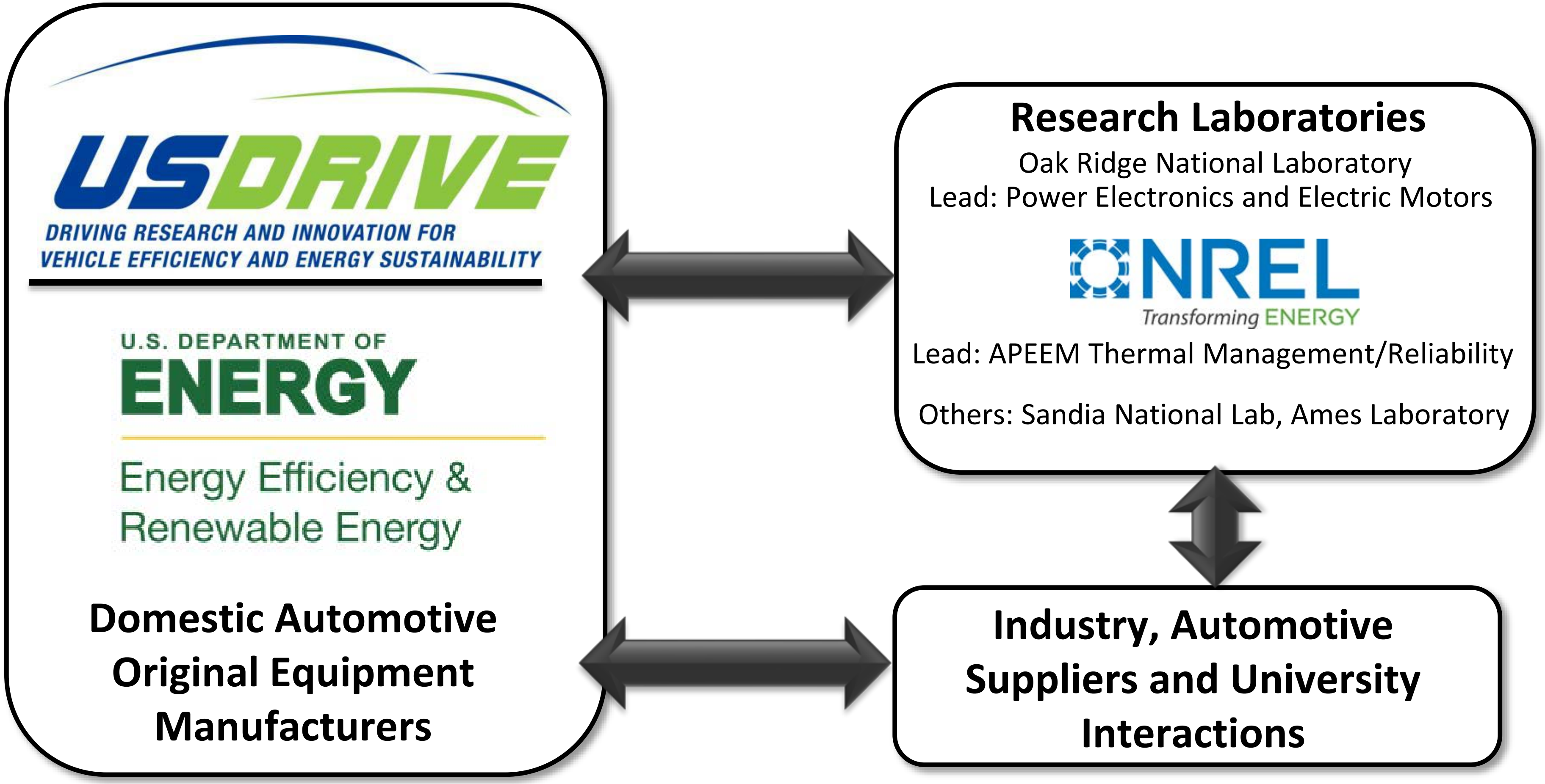


Electric Motor Thermal Management



APEEM: advanced power electronics and electric machines

DOE Electric Drive Technologies (EDT) Program



USDRIVE
DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

U.S. DEPARTMENT OF
ENERGY
Energy Efficiency &
Renewable Energy

Domestic Automotive Original Equipment Manufacturers

Research Laboratories

Oak Ridge National Laboratory
Lead: Power Electronics and Electric Motors

NREL
Transforming ENERGY
Lead: APEEM Thermal Management/Reliability

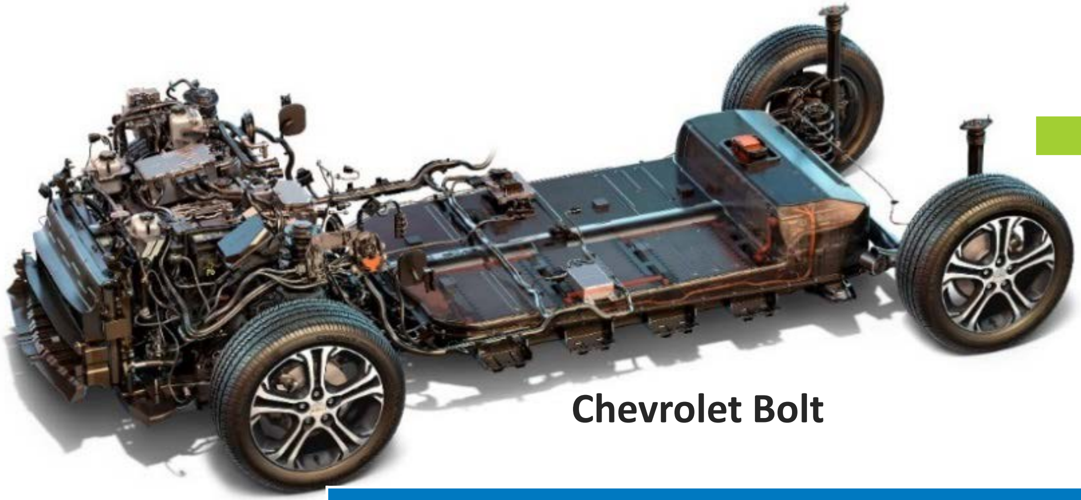
Others: Sandia National Lab, Ames Laboratory

Industry, Automotive Suppliers and University Interactions

Background & Approach

Research Pathway for Electric-Drive Vehicle Electrification

Roadmap defines the pathway to 2025 targets



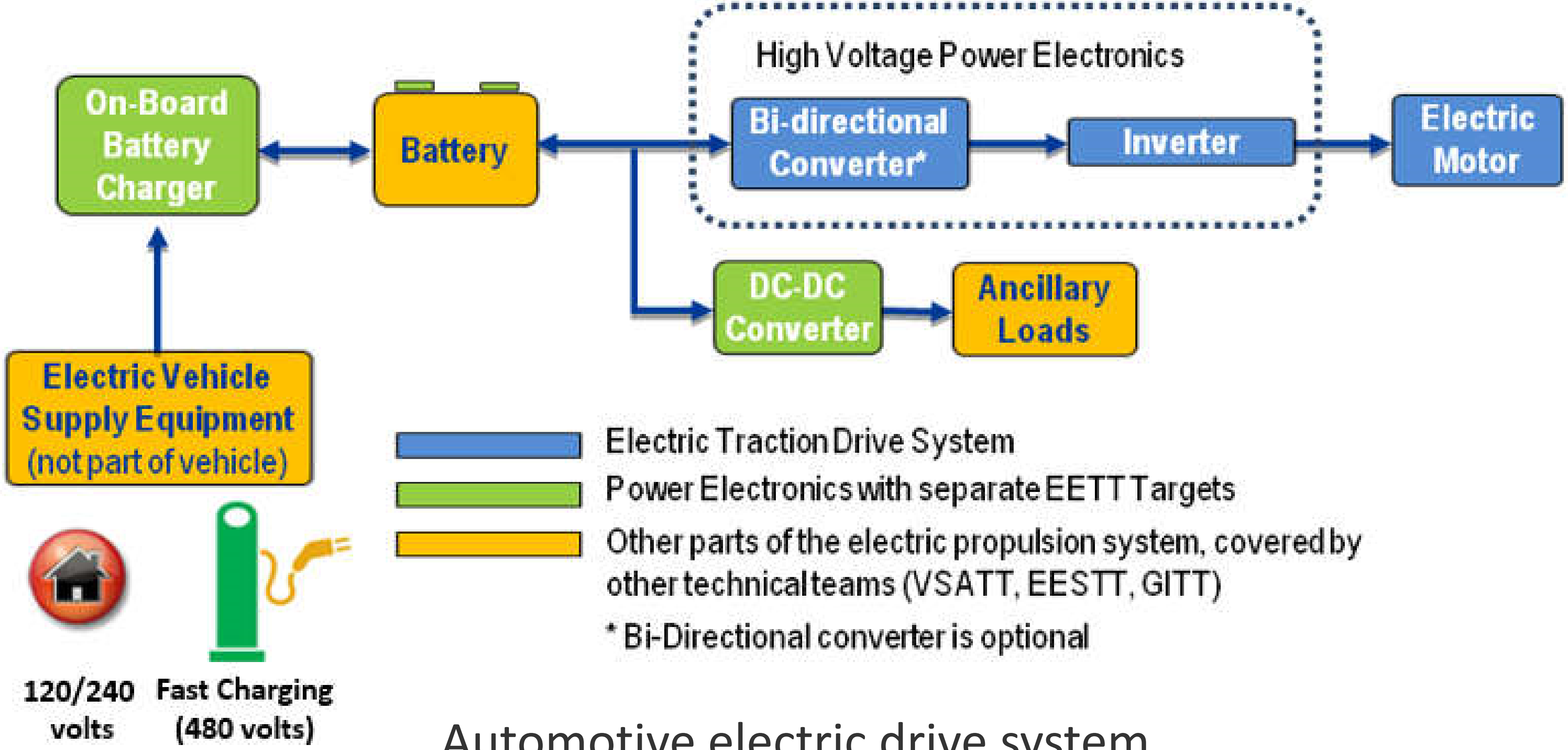
Chevrolet Bolt

Future Mobility Design Concept

2025 Targets	
Cost	$6/kW (50% reduction)
Power Density	33 kW/L (850% increase)
Power Level	100 kW
Reliability/Lifetime	300,000 miles (100% increase)

Source: Electrical and Electronics Technical Team Roadmap, https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf.

Electric Drive System



High Voltage Power Electronics

On-Board Battery Charger

Battery

Bi-directional Converter*

Inverter

Electric Motor

DC-DC Converter

Ancillary Loads

Electric Vehicle Supply Equipment (not part of vehicle)

120/240 volts

Fast Charging (480 volts)

🟦 Electric Traction Drive System

🟩 Power Electronics with separate EETT Targets

🟨 Other parts of the electric propulsion system, covered by other technical teams (VSATT, EESTT, GITT)

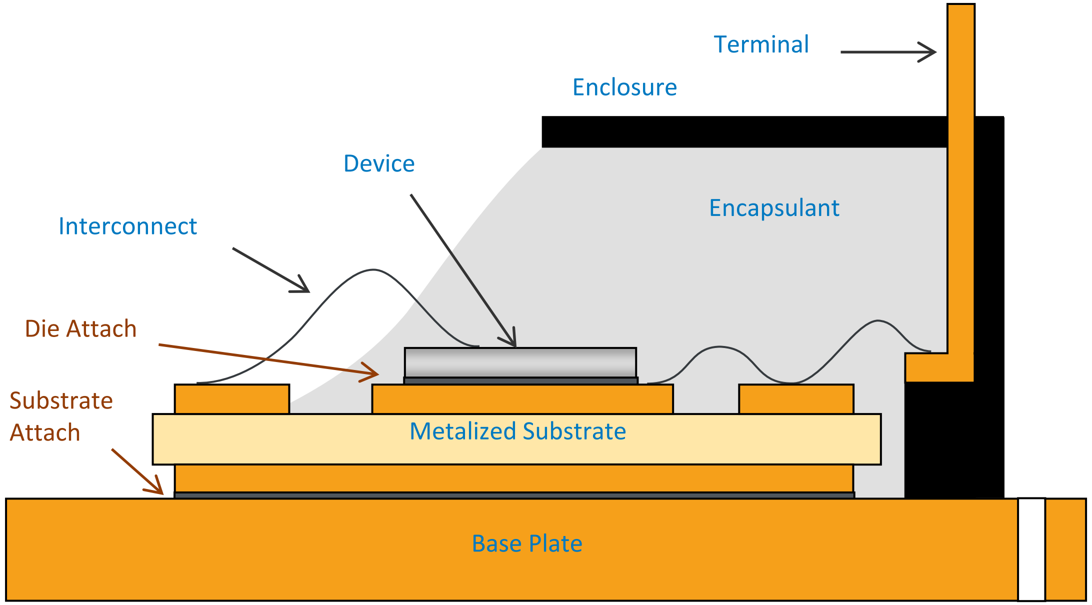
* Bi-Directional converter is optional

Automotive electric drive system

- Cost
- Power density
- Reliability

Schematic from 2017 Electrical and Electronics Technical Team (EETT) Roadmap
VSATT – Vehicle Systems Analysis Tech Team
EESTT – Electrochemical Energy Storage Tech Team
GITT – Grid Interaction Tech Team

Power Electronics Package



Traditional Power Electronics Package


Image Credit: Gilbert Moreno

Cree Wide Bandgap Device Package

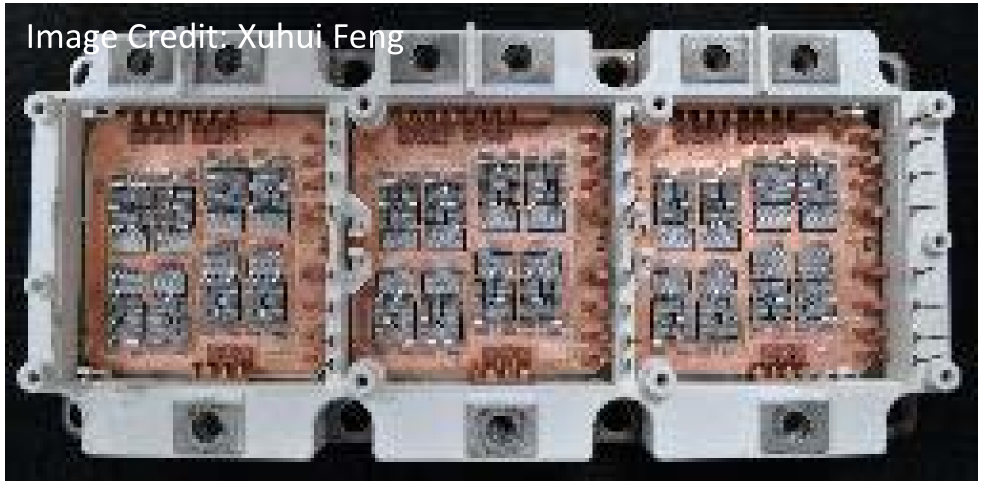


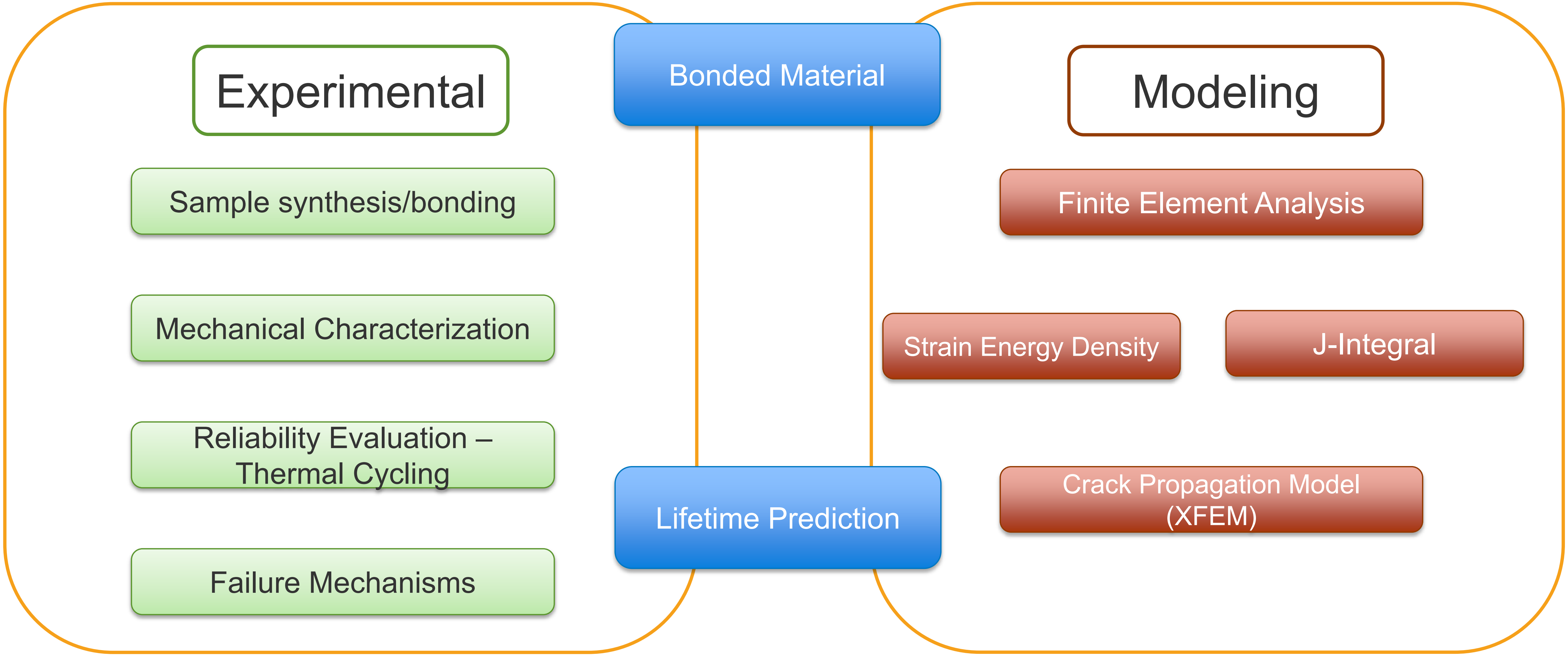
Image Credit: Xuhui Feng

2015 BMW i-3


Image Credit: Scot Waye

2012 Nissan Leaf

General Approach



Experimental

Sample synthesis/bonding

Mechanical Characterization

Reliability Evaluation – Thermal Cycling

Failure Mechanisms

Bonded Material

Lifetime Prediction

Modeling

Finite Element Analysis

Strain Energy Density

J-Integral

Crack Propagation Model (XFEM)

Bonded Material – Die Attach, Substrate Attach
XFEM – Extended Finite Element Method

Bonded Interfaces at 150°C

Bonded Materials

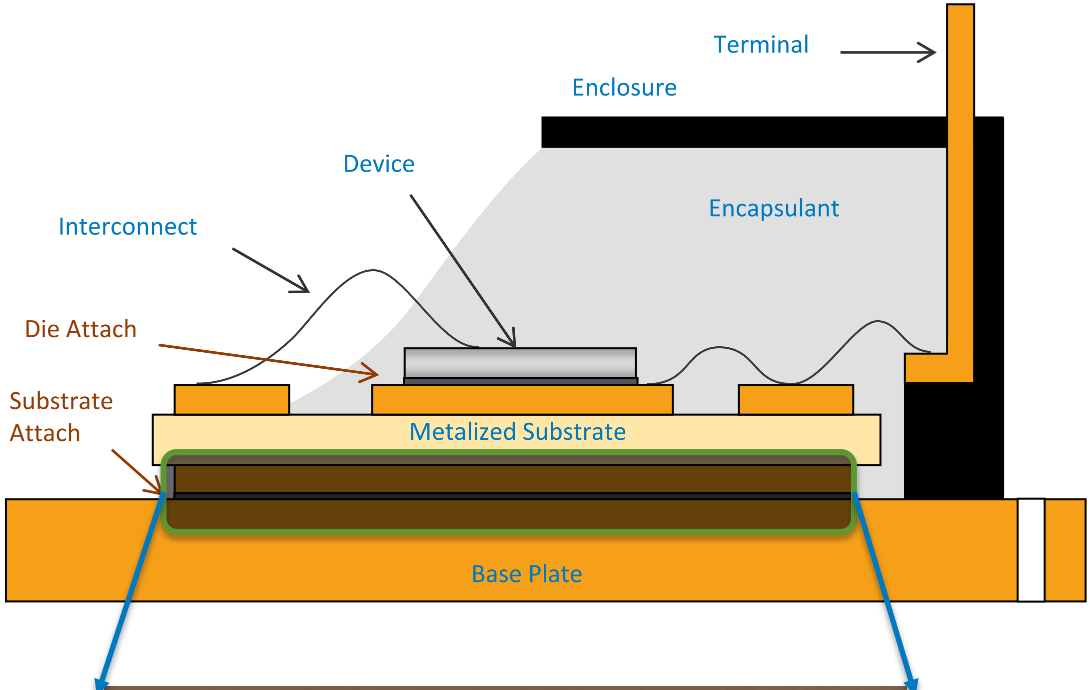
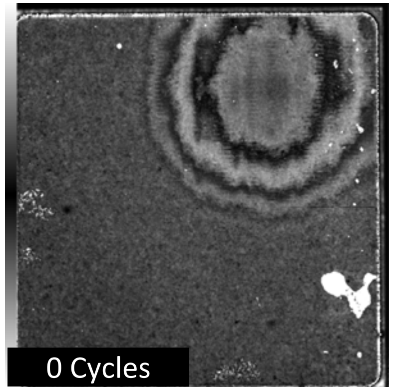


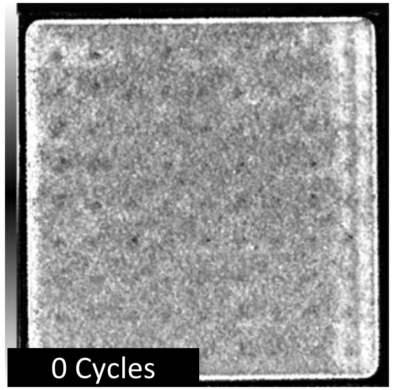

Image Credit: Douglas DeVoto

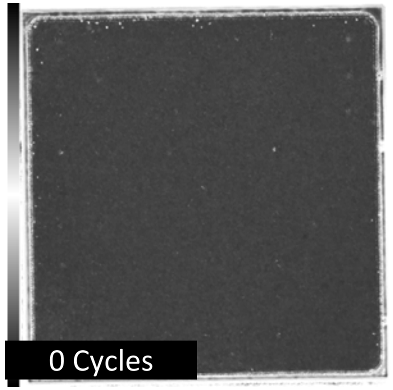
- Five samples of each bonded material were synthesized for characterization and included:
  - Silver plating on the substrate and base plate.
  - Substrate based on a Si_3N_4 active metal bonding process.
  - An interface between 50.8-mm x 50.8-mm footprint.

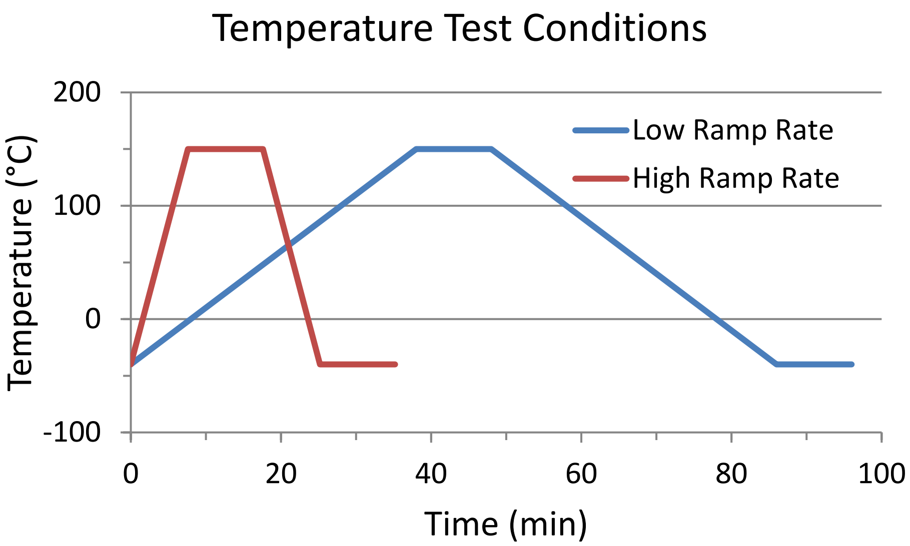
Bond Material Type	Name	Comments
Solder	Kester Sn63Pb37	Baseline (lead-based solder)
Sintered Silver	Semikron	Based on Semikron synthesis process
Adhesive	Btech HM-2	Thermoplastic (polyamide) film with embedded carbon fibers

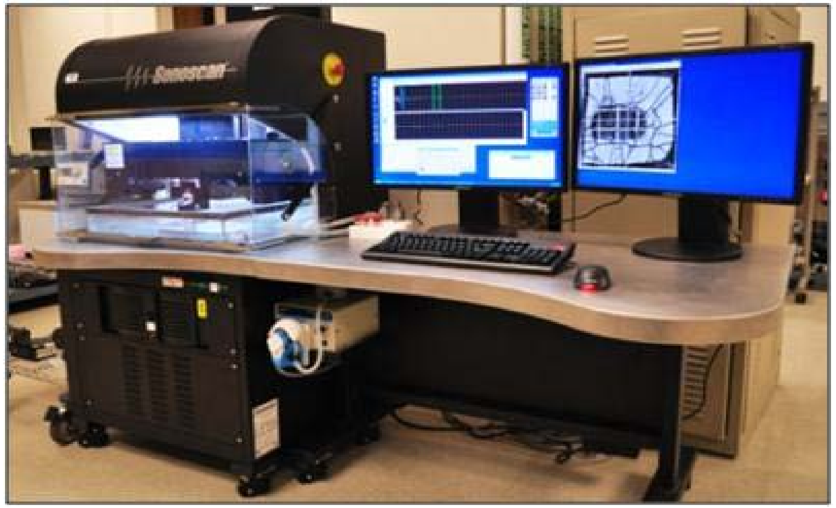
Material Evaluation



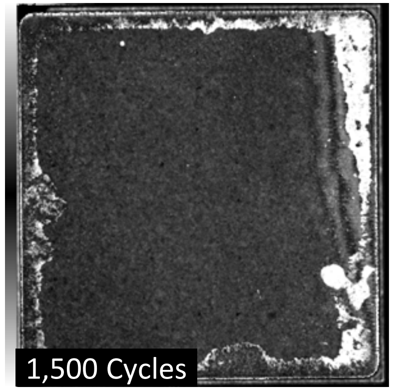




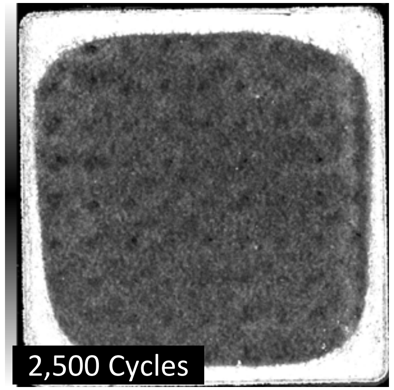




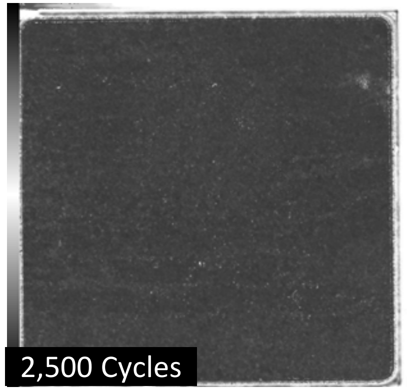
Scanning Acoustic Microscope



63Sn37Pb

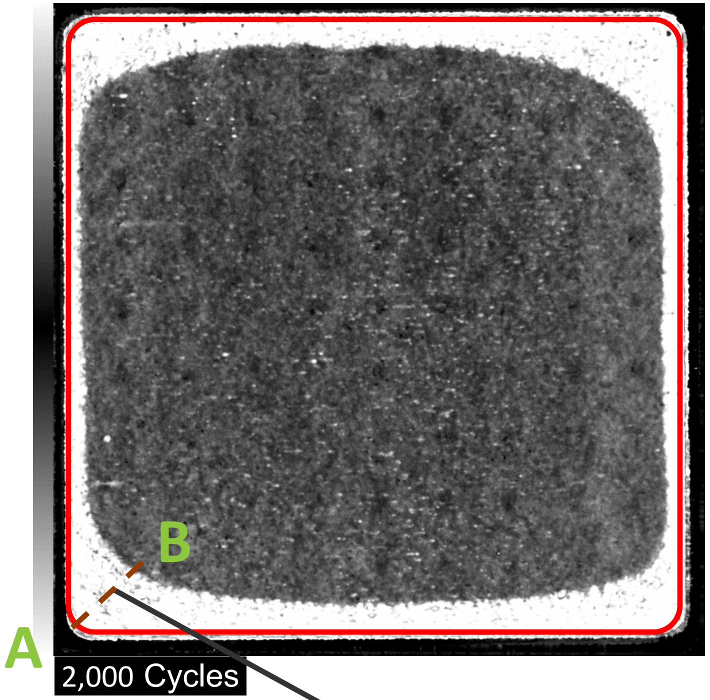


Sintered silver

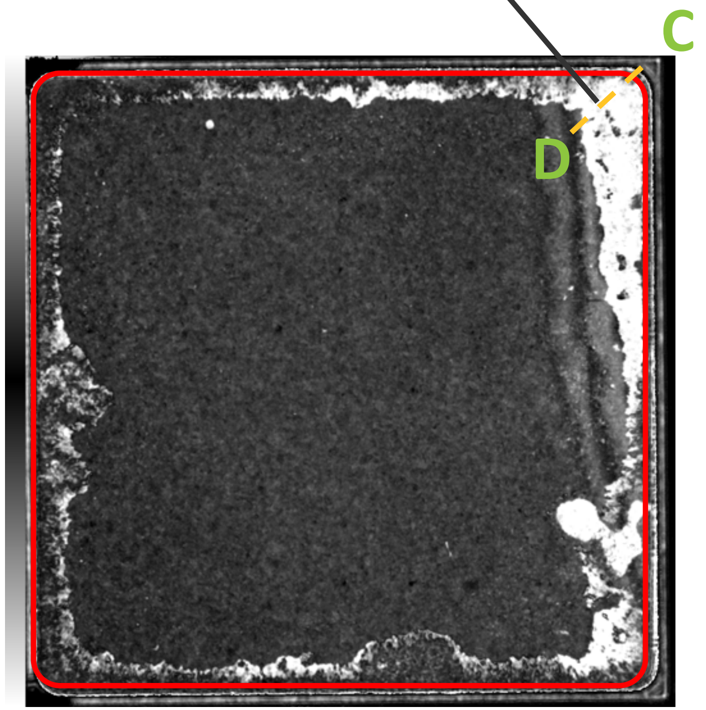


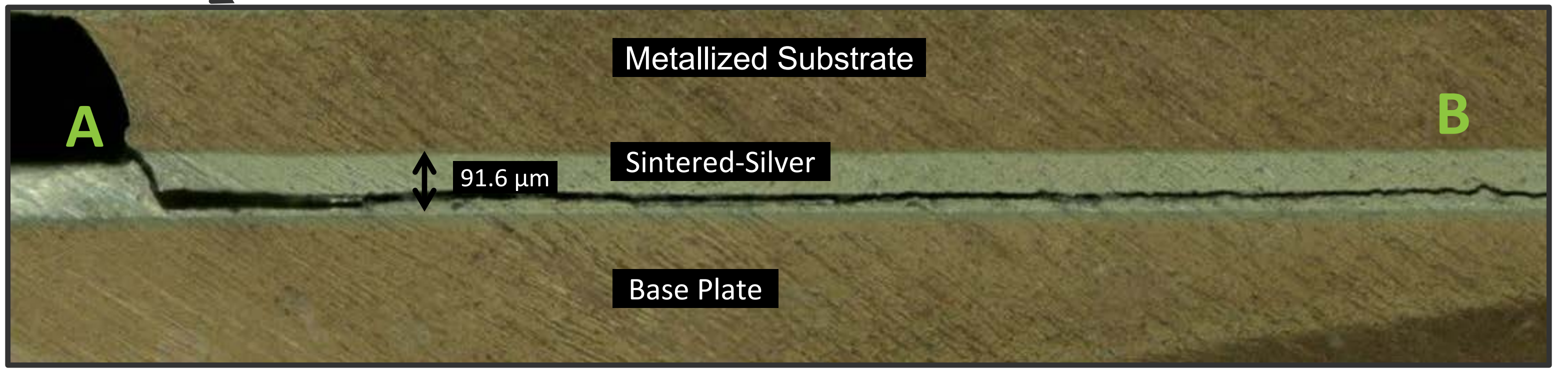
Btech HM-2

Failure Mechanisms

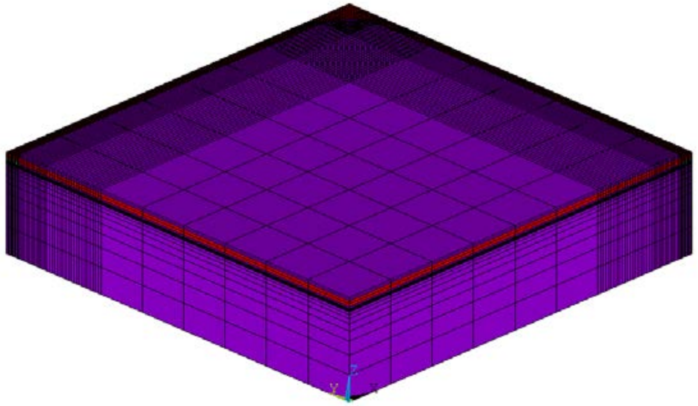


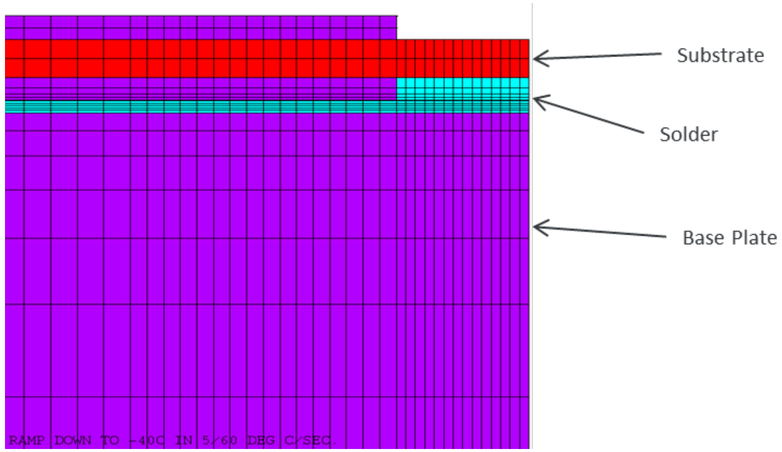
- Cohesive fracture observed in both solder and sintered silver.
- Failure criterion is 20% of crack growth by area.



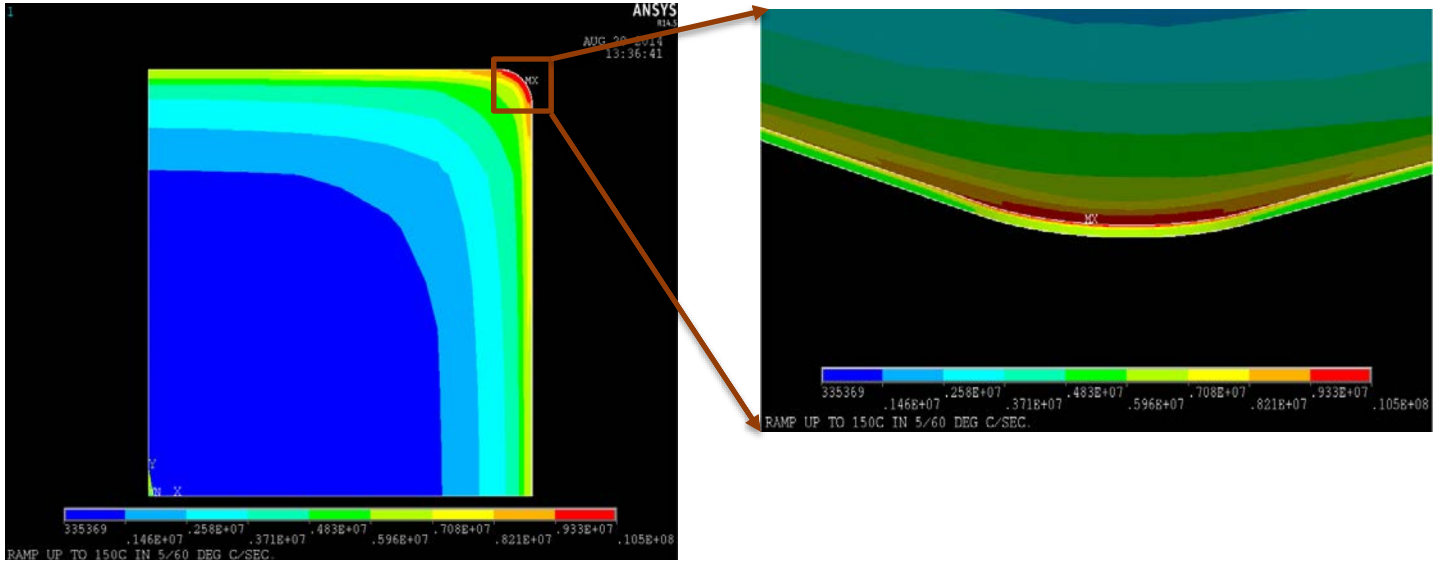


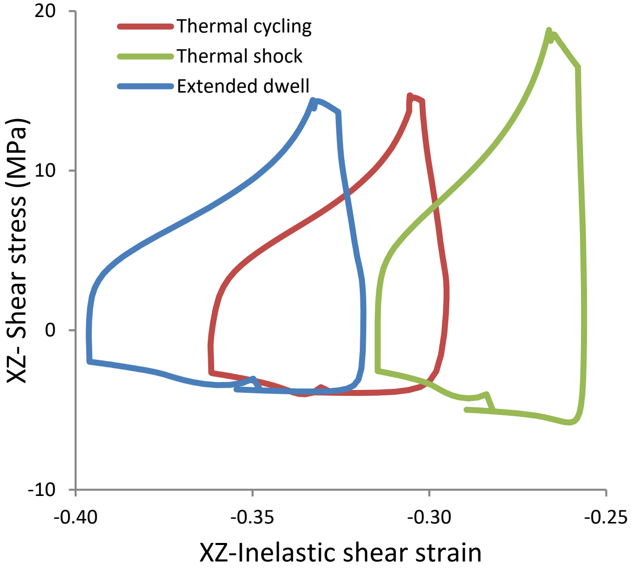
Thermomechanical Modeling

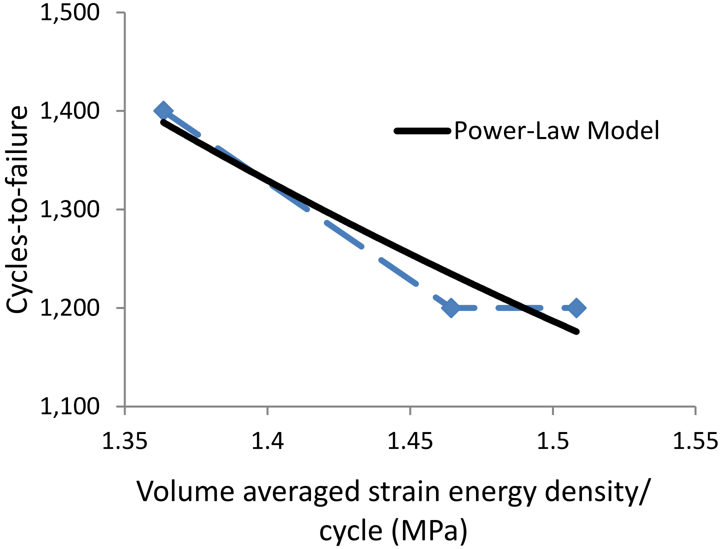




- Anand viscoplasticity model applied to the solder layer.
- Thermal cycling load is the boundary condition.







Bonded Interfaces at 200°C

High-Temperature Materials

- High-Temperature Bonded Material
  - Georgia Tech
    - Cu/Al, Cu/Sn
  - Virginia Tech
    - Sintered Silver
      - Pressureless
      - Low Pressure-Assisted
        - 3 MPa
        - 10 MPa
  - NREL
    - Sintered Silver (industry)
      - Pressureless

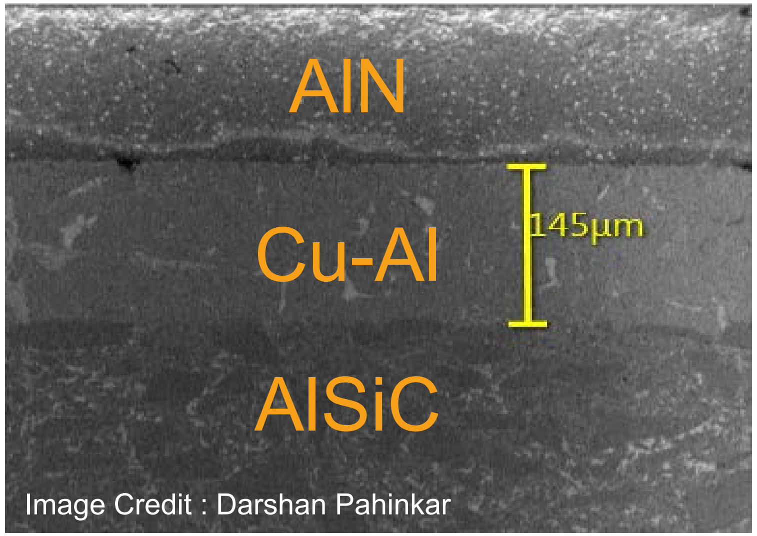


Image Credit : Darshan Pahinkar

Cu-Al bond – SEM image

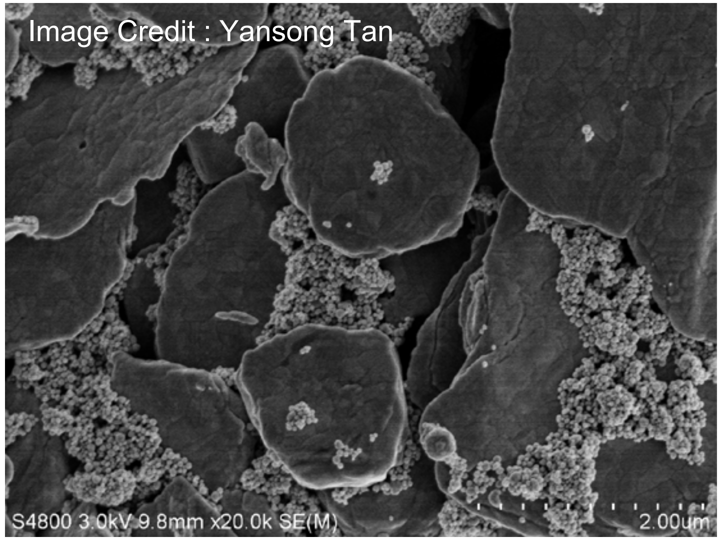


Image Credit : Yansong Tan

Hybrid-silver – SEM image

Cu: Copper
Al: Aluminum
Sn: Tin
AlN: Aluminum Nitride
AlSiC: Aluminum Silicon-Carbide

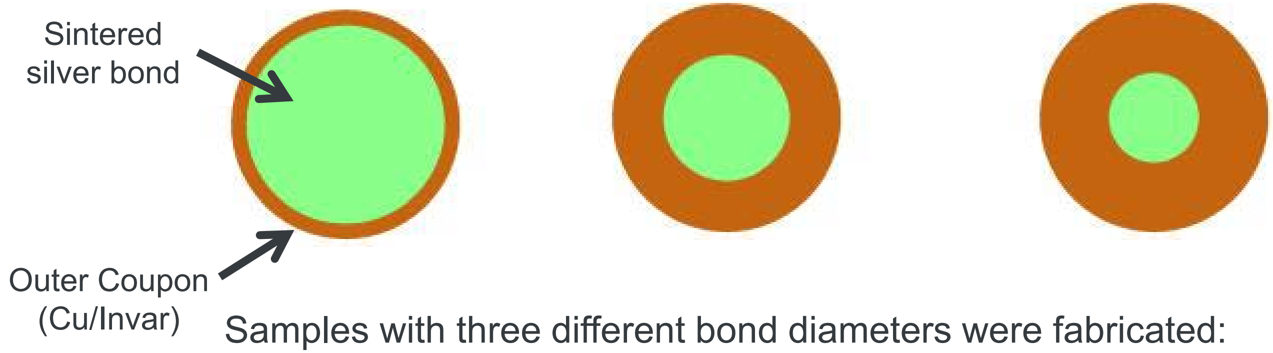
SEM – Scanning Electron Microscope

Approach – Reliability Evaluation


Image Credit: Douglas DeVoto

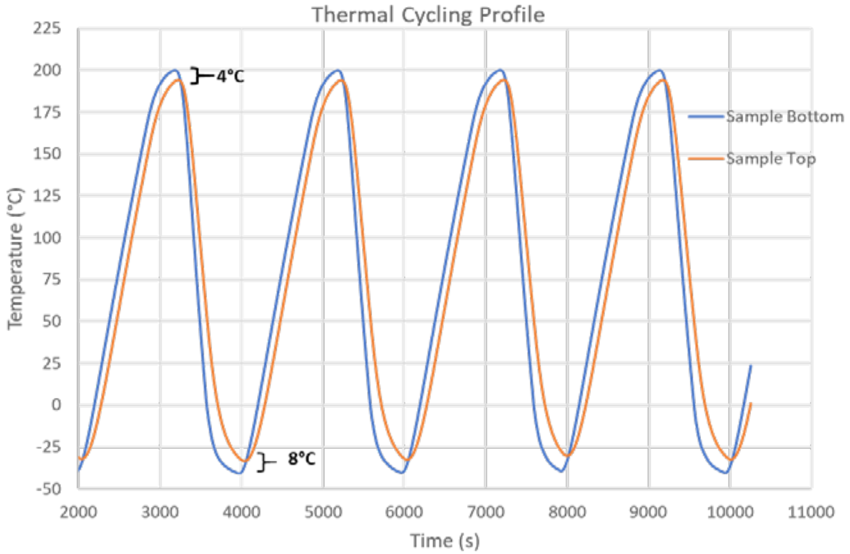
ϕ1-inch Copper and Invar Coupons: non-plated (top), plated with 5-µm-thick silver (bottom)

Sample Structure



Samples with three different bond diameters were fabricated: 22 mm (left), 16 mm (center), and 10 mm (right)

Accelerated Thermal Cycling



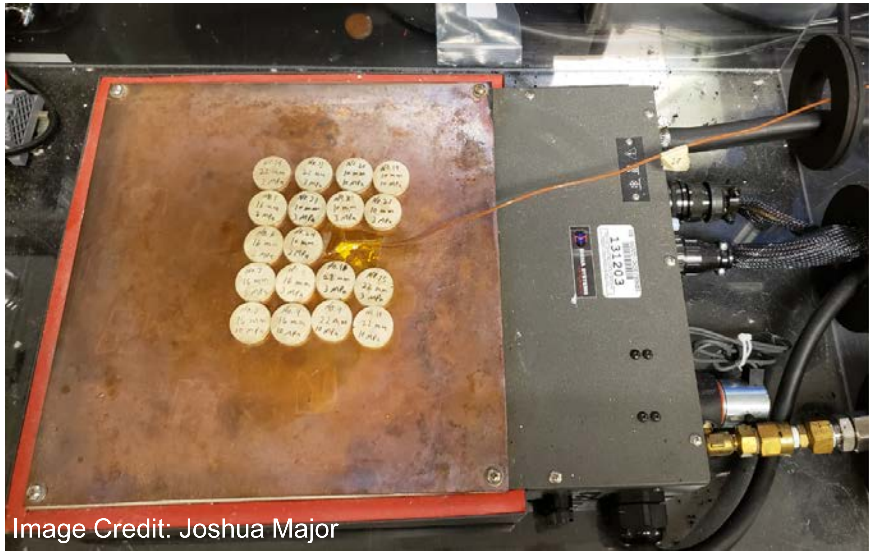
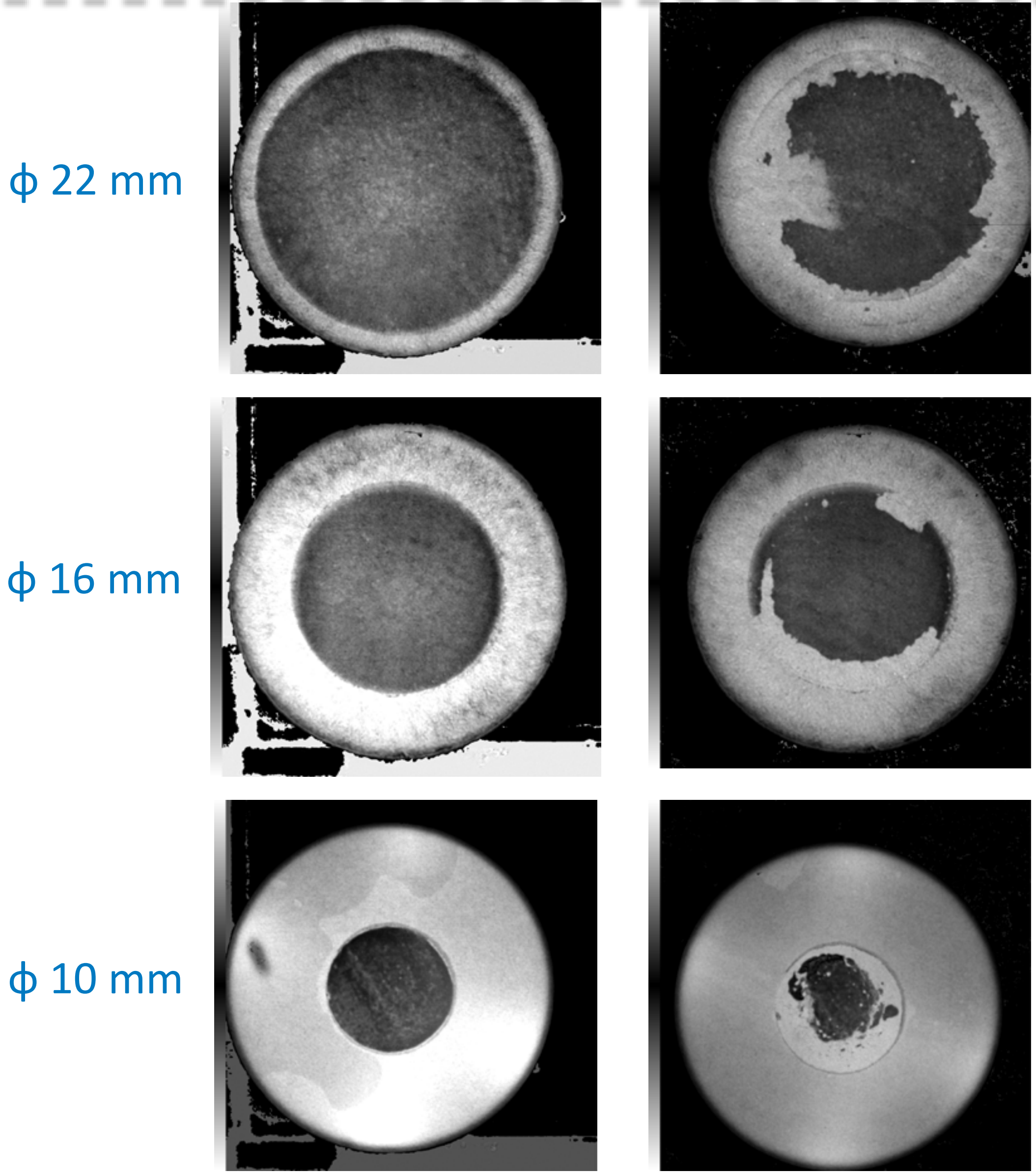


Image Credit: Joshua Major

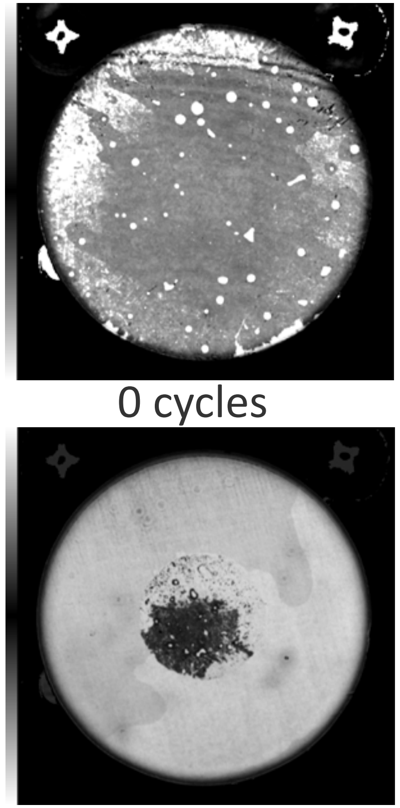
Samples placed on thermal platform for thermal cycling, C-SAM images of these samples are taken periodically

C-SAM – C-Mode Scanning Acoustic Microscope
ϕ - Diameter

Reliability Comparison – Sintered Silver and Solder



0 cycles 50 cycles

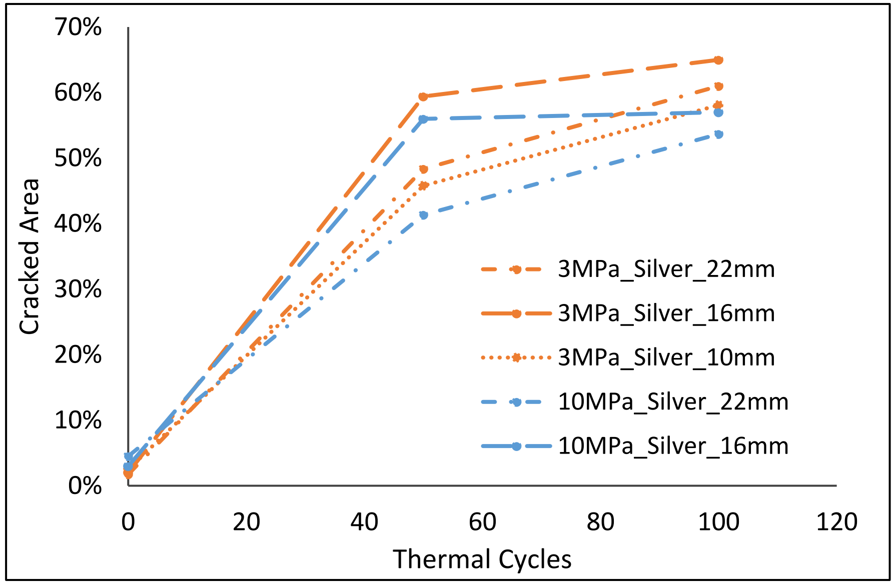


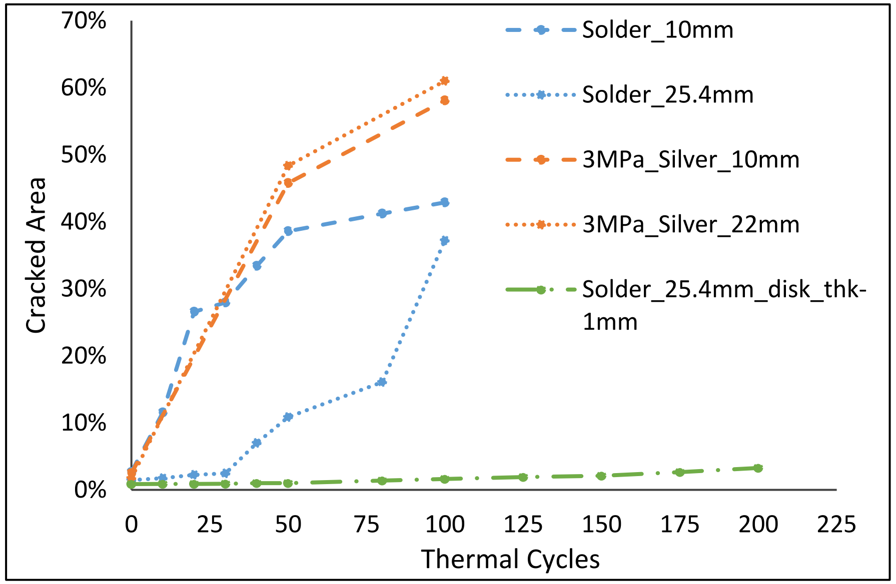
0 cycles

50 cycles

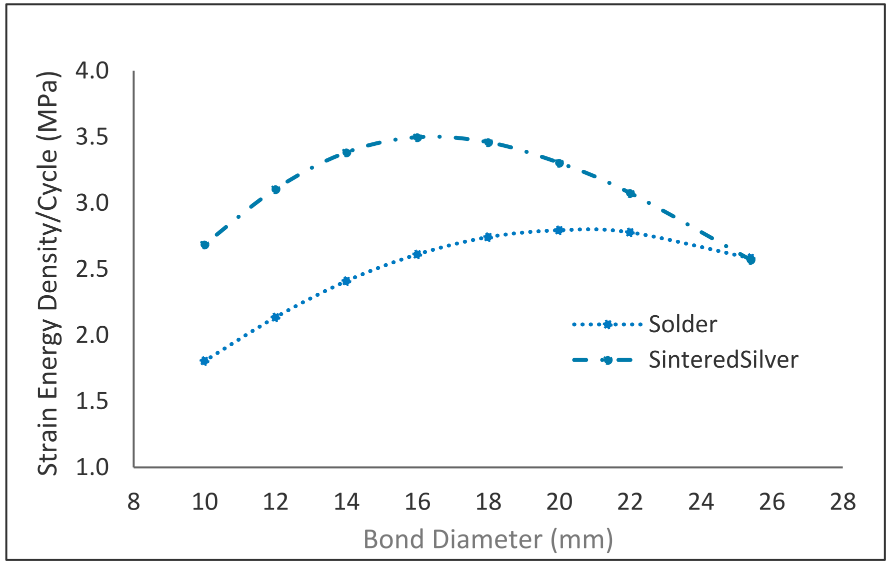
95Pb5Sn

Sintered silver

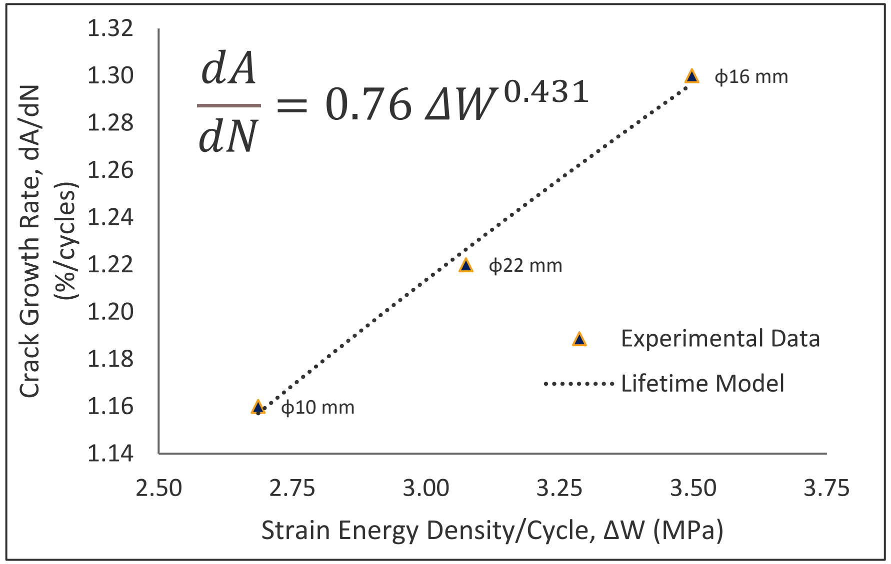




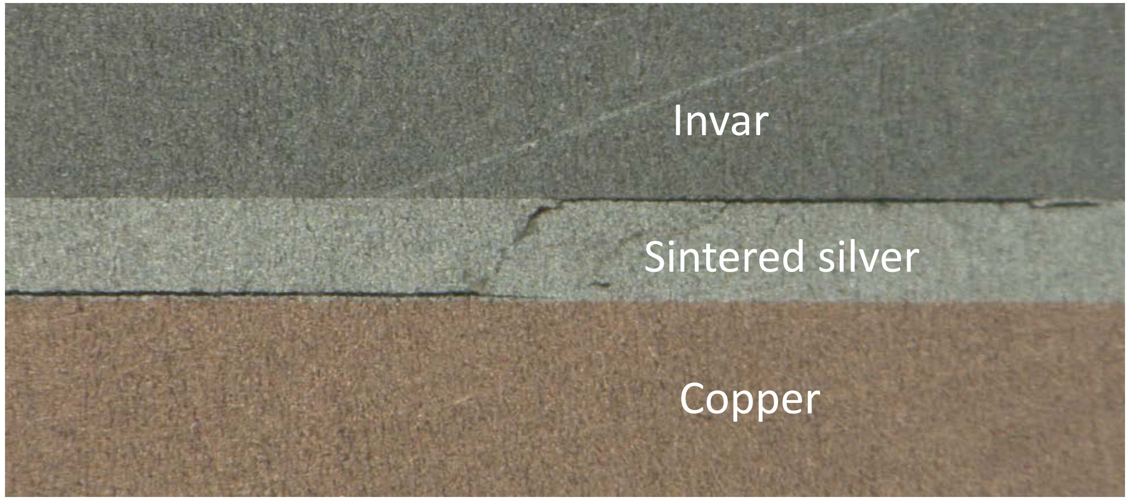
Lifetime Prediction Model



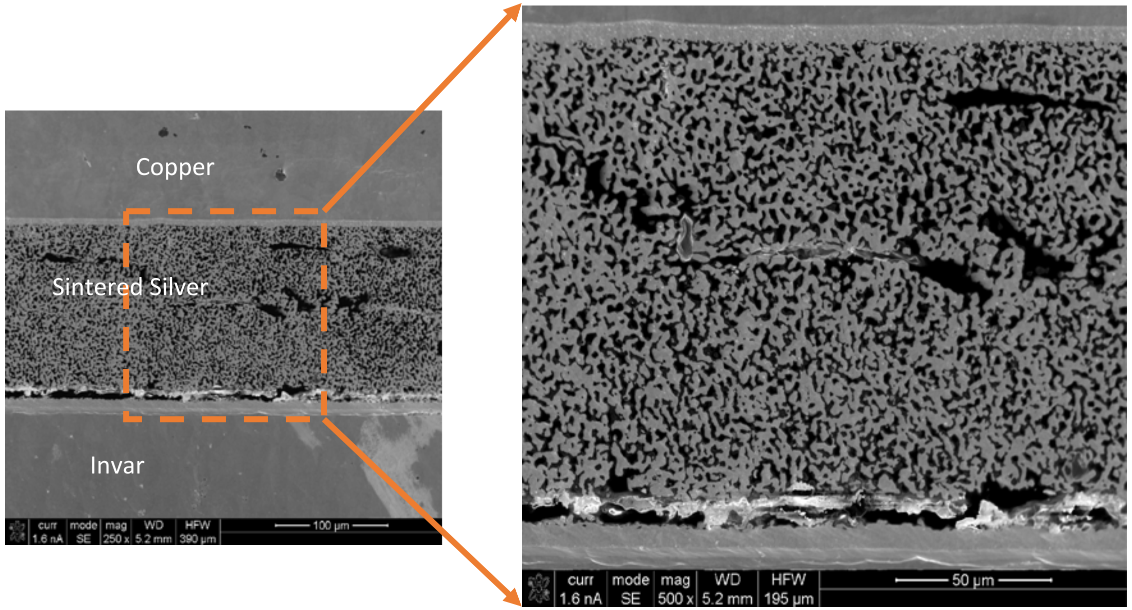
Modeling Results



Lifetime Prediction Model



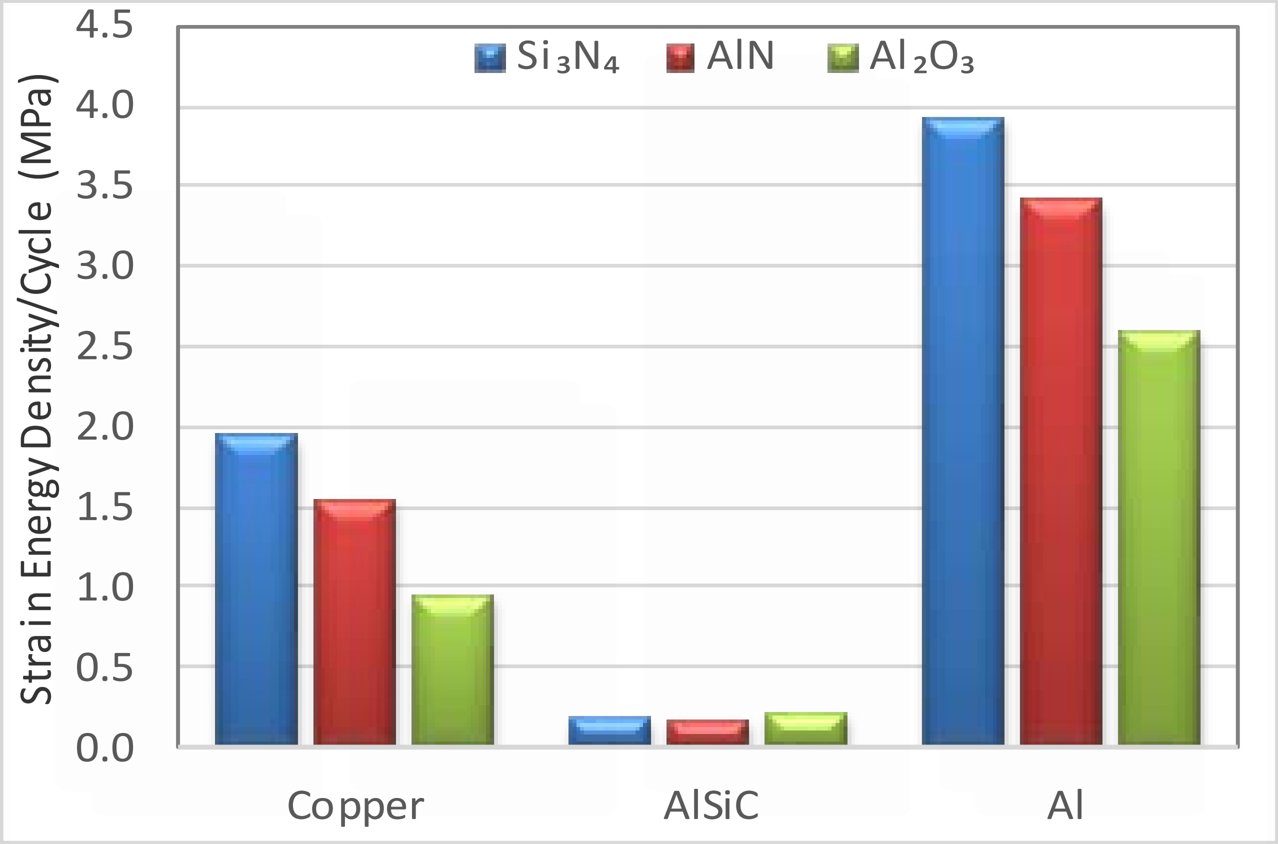
Optical Microscope Image



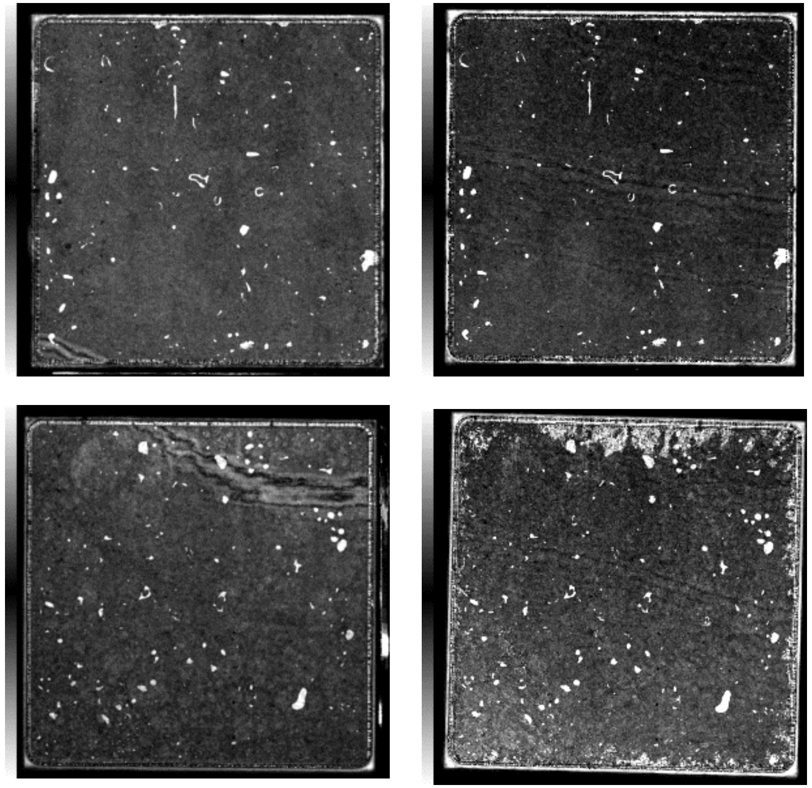
Scanning Electron Microscrope Image

Thermomechanical Modeling – Parametric Study

Impact of Baseplate & Ceramic Material



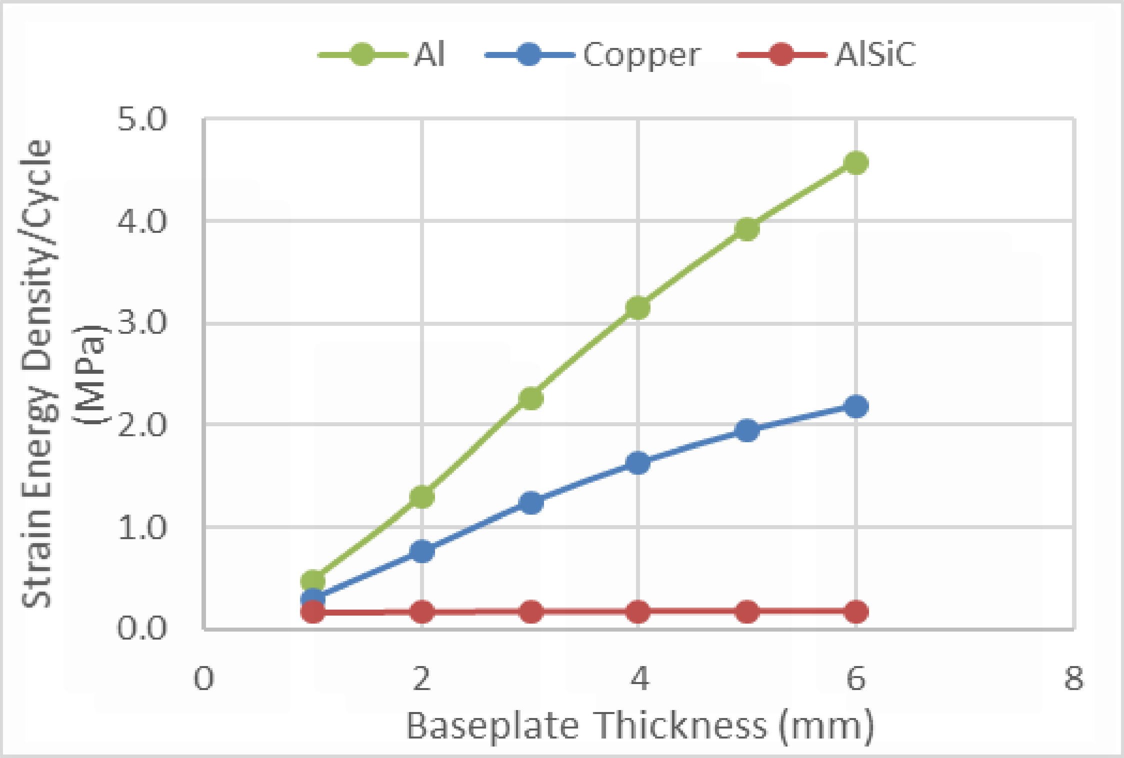
Thickness of baseplate – 5 mm; ceramic – 0.32 mm, metallization – 0.2 mm



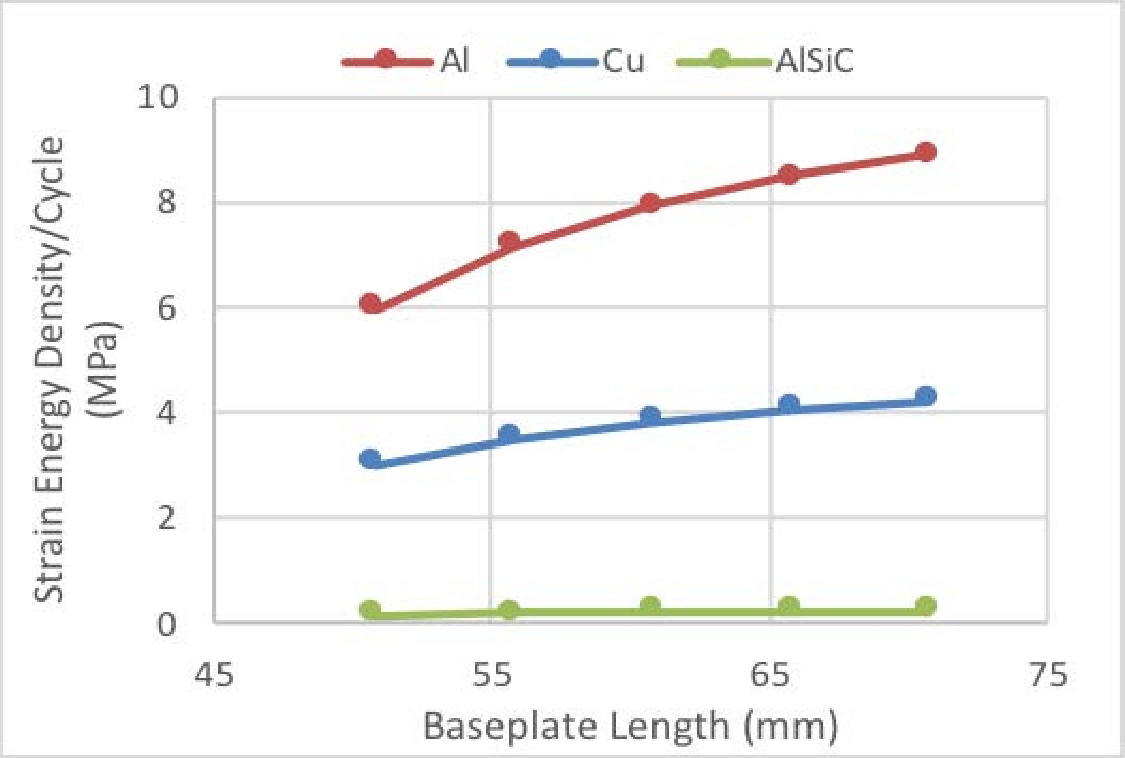
C-SAM Images of SAC305 solder with AlSiC (top) and Cu (bottom) baseplates. Images on the left and right were taken at 0 cycles and 500 cycles, respectively.

- AlSiC baseplate offers superior reliability than its Cu or Al counterparts, mainly due to the low coefficient of thermal expansion mismatch with the ceramic material.

Impact of Baseplate Thickness & Footprint



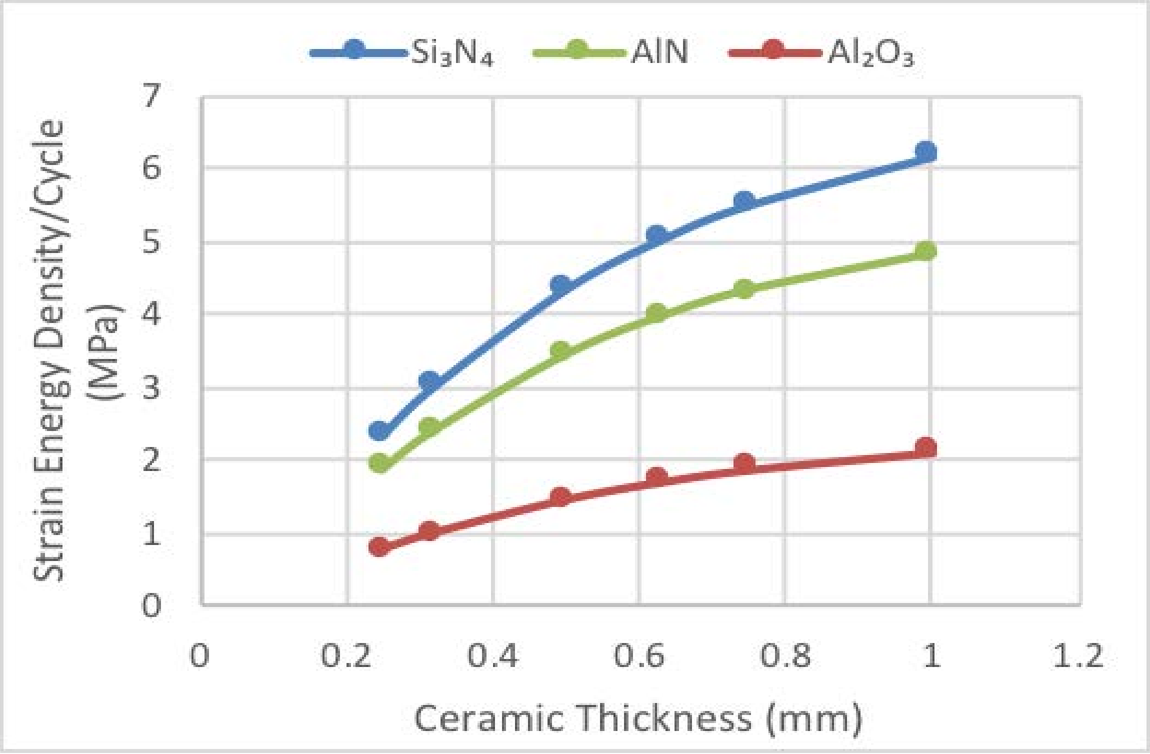
Ceramic (Si_3N_4) thickness – 0.32 mm; metallization – 0.2 mm



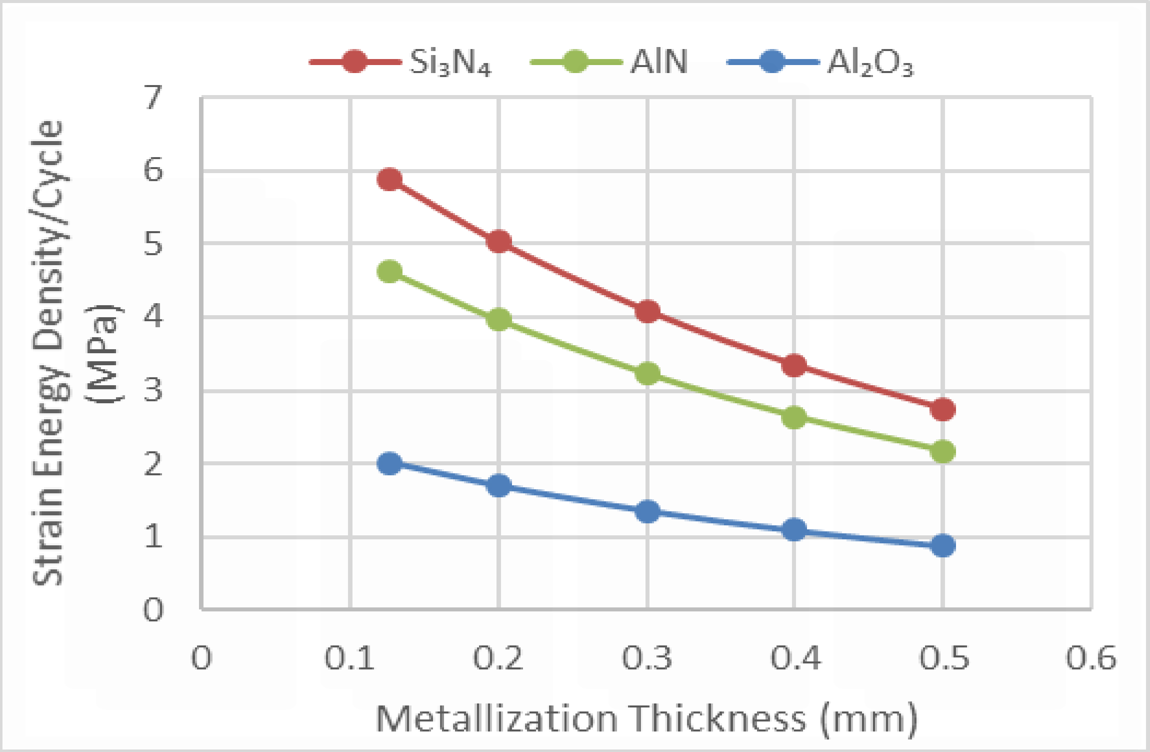
Baseplate thickness – 5mm; ceramic (Si_3N_4) – 0.32 mm; metallization – 0.2 mm.
Thermal cycling profile - -40°C - 200°C

- Thickness variation has a larger impact on solder joint reliability than footprint/size variation.

Impact of Ceramic and Metallization Thickness



Baseplate (Cu) thickness – 5 mm; metallization – 0.2 mm



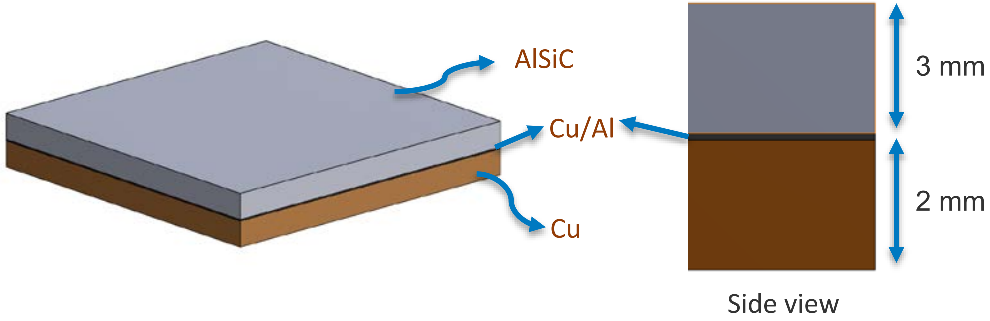
Baseplate (Cu) thickness – 5 mm; ceramic – 0.63 mm

- Higher the coefficient of thermal expansion mismatch, higher the impact of stiffness variation is.

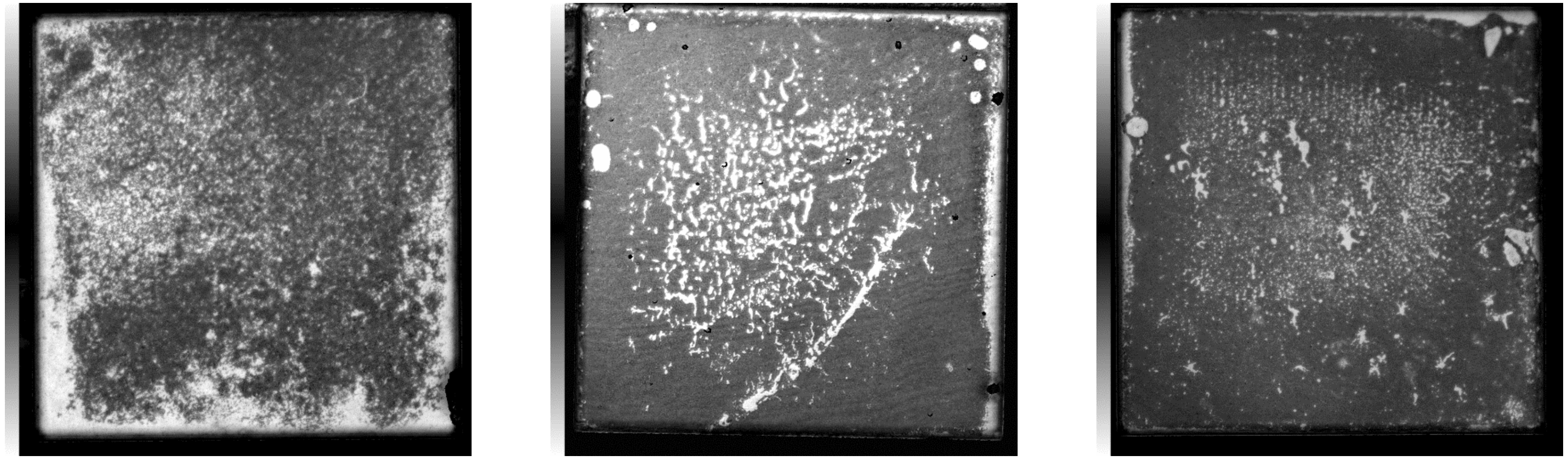
Other Work

Transient Liquid Phase Cu-Al Bonds

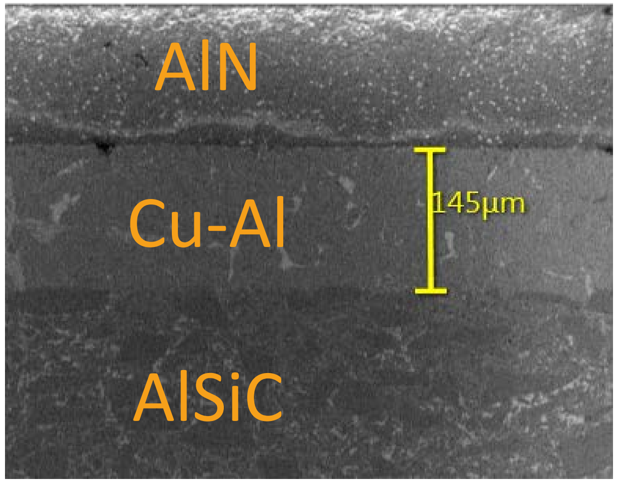
- Reliability Evaluation
  - Selected sample configuration: Cu bonded to AlSiC coupons using Cu-Al alloy, footprint is 1-inch x 1-inch.
  - Samples synthesized at Georgia Tech and sent to NREL for thermal cycling experiments.
  - Thermal cycling currently underway; scanning acoustic microscope images and thermal resistance measurements are indicators of thermomechanical performance.



Sample design for reliability evaluation



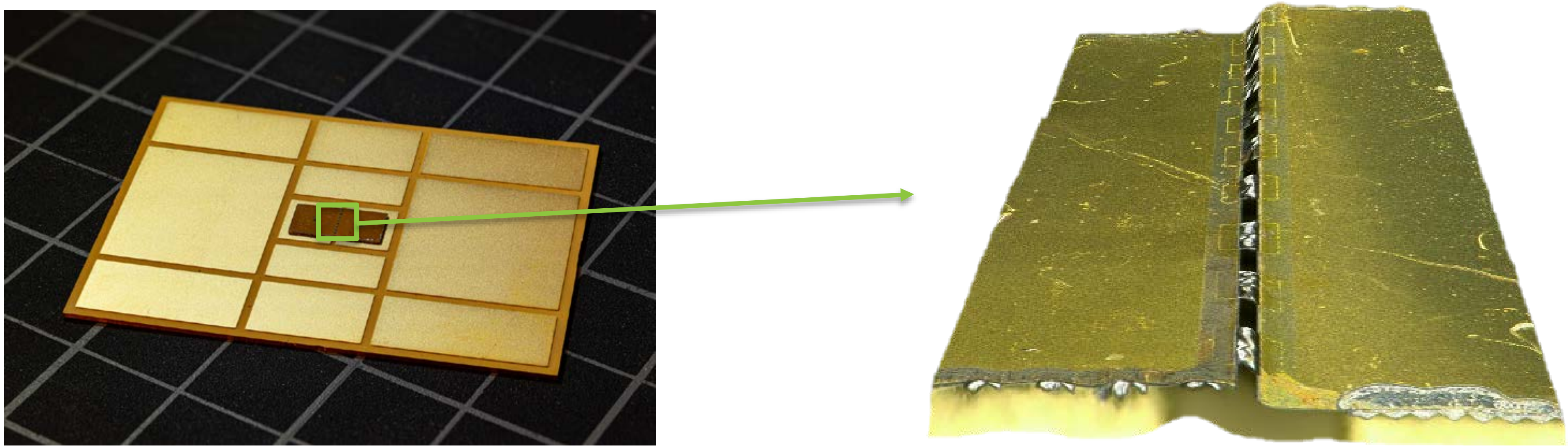
C-SAM images of AlN-AlSiC sample with Cu-Al bond



Cross-sectional SEM image of Cu-Al bond

Organic DBC and Quilt Packaging

- Alternative interconnect designs are required as devices are reduced in size and spacing between devices is minimized
- **Traditional wire interconnects or etched substrates for topside electrical connections will be replaced with direct chip-to-chip connection**
- Devices are joined with quilt packaging, eliminating the need for wire bonds or other external electrical connection technology
  - Experimental samples have been designed in collaboration with IIC and ORNL
  - Reliability evaluation will be completed at NREL



Challenges and Opportunities

- Material development
  - Reliable, cost-effective, thermally and electrically high-performing
  - Data-driven techniques to identify material compositions
  - Functionally graded materials
  - Constitutive models.

- Faster characterization techniques
  - Time-independent evaluation of material/package
  - Combining different physics-based characterization for co-designed packages

- Circular economy design principles
  - Recycling of non-failed components.

Reference Material

- Top causes of failure in power semiconductors - https://chargedevs.com/features/top-causes-of-failure-in-power-semiconductors/
- Here’s why Tesla transitioned to a semi-custom power module design in Model 3 inverter - https://chargedevs.com/features/heres-why-tesla-transitioned-to-a-semi-custom-power-module-design-in-model-3-inverter/
- Reliability challenges of automotive power electronics – U. Scheuermann
  - https://doi.org/10.1016/j.microrel.2009.06.045
- Power Electronics Reliability: State of the Art and Outlook – H. Wang
  - https://doi.org/10.1109/JESTPE.2020.3037161

Summary

- Reliability evaluation of bonded materials is a critical research area for enabling low-cost, lightweight, and reliable power electronic packages that can operate at high temperatures.
- Synthesis of high-temperature bond materials, mechanical characterization, reliability evaluation, thermomechanical modeling, and lifetime prediction models.
- Collaborations – Virginia Tech, Georgia Tech, Oak Ridge National Laboratory, Ames National Laboratory, Sandia National Laboratory.
- Publications:
  - Paul Paret, Joshua Major, Douglas DeVoto, Sreekant Narumanchi, Chao Ding, and Guo-Quan Lu, "Reliability and Lifetime Prediction Model of Sintered Silver under High-Temperature Cycling", IEEE Journal of Emerging and Selected Topics in Power Electronics, DOI 10.1109/JESTPE.2021.3121195.
  - P. P. Paret, D. J. DeVoto, and S. Narumanchi, "Reliability of Emerging Bonded Interface Materials for Large-Area Attachments," *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 6, no. 1, pp. 40–49, Jan. 2016, doi: 10.1109/TCPMT.2015.2499767.
  - P. Paret, D. DeVoto, J. Major and S. Narumanchi, "Parametric Design Study of a Power Electronics Package for Improving Solder Joint Reliability," *2020 19th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm)*, 2020, pp. 1065-1072, doi: 10.1109/ITherm45881.2020.9190318.

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Thank You

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