Performance and Reliability of Bonded Interfaces for High-Temperature Packaging

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Overview

Timeline

- **Project Start Date:** FY14
- **Project End Date:** FY16
- **Percent Complete:** 30%

Barriers and Targets

- Cost
- Weight
- Performance and Lifetime

Budget

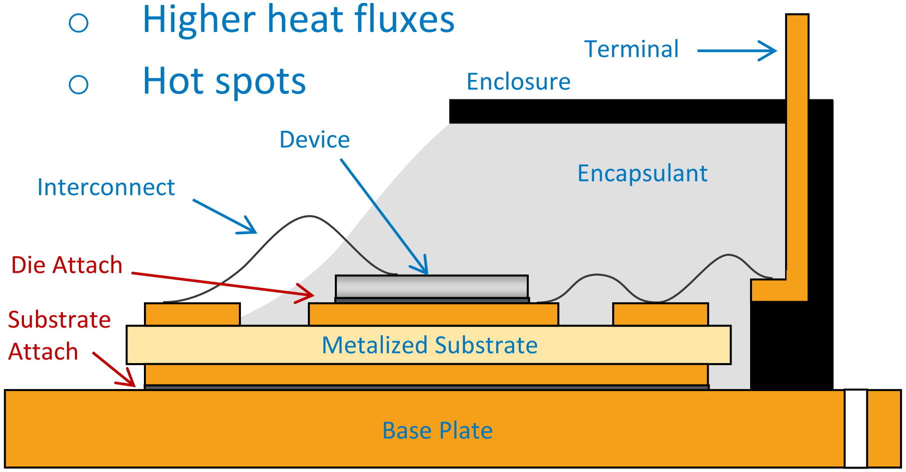
- **Total Project Funding: $900K**
  - DOE Share: $900K
- **Funding for FY14:** $400K

Partners

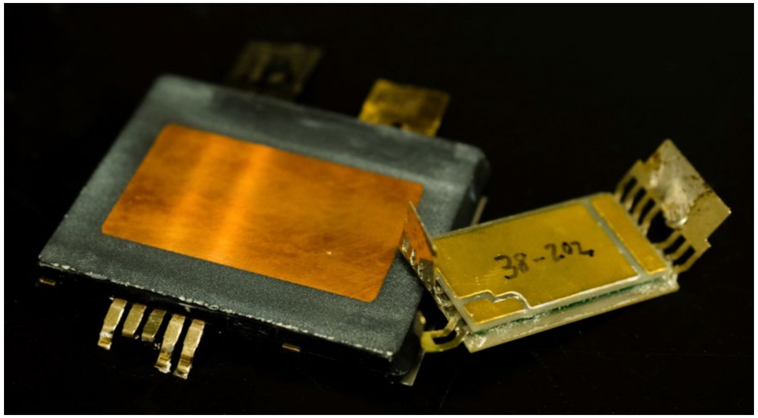
- Interactions / Collaborations
  - Heraeus, Henkel, General Motors, Fraunhofer, Oak Ridge National Laboratory (ORNL) (Andrew Wereszczak)
- Project Lead
  - National Renewable Energy Laboratory (NREL)

Relevance

- Current automotive power electronics are transitioning from silicon to wide bandgap (WBG) devices to meet cost, volume, and weight targets
- Packaging designs must improve to take advantage of WBG devices' operating parameters:
  - Higher operating temperatures
  - Higher heat fluxes
  - Hot spots



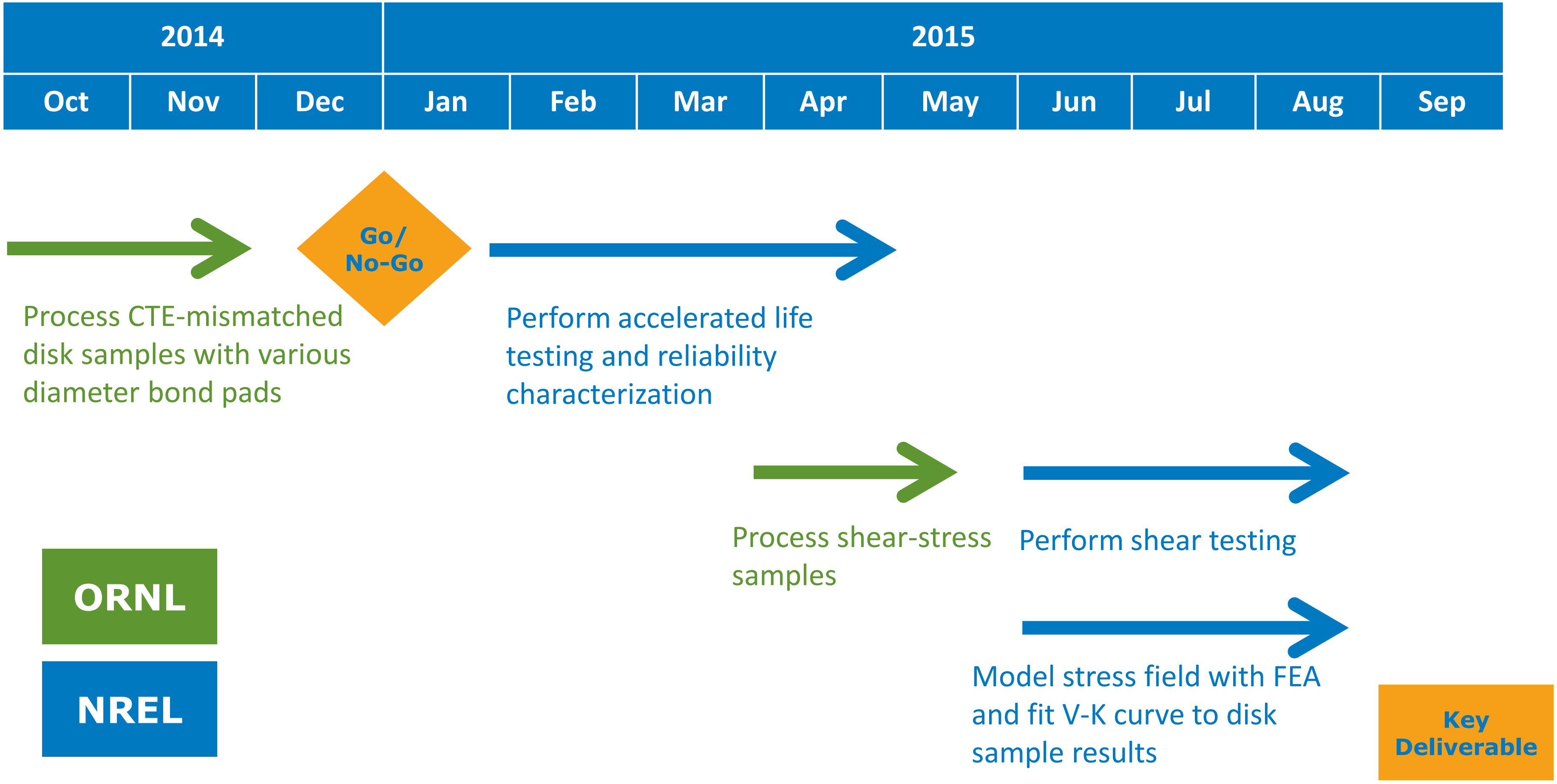
Traditional Power Electronics Package



State-of-the-Art Packages

- Sintered-silver reliability has not been documented at 200°C conditions for the substrate attach layer
  - ORNL and NREL's prior experience with sintered-silver processing will generate recommended practices for synthesis of reliable interfaces

Milestones



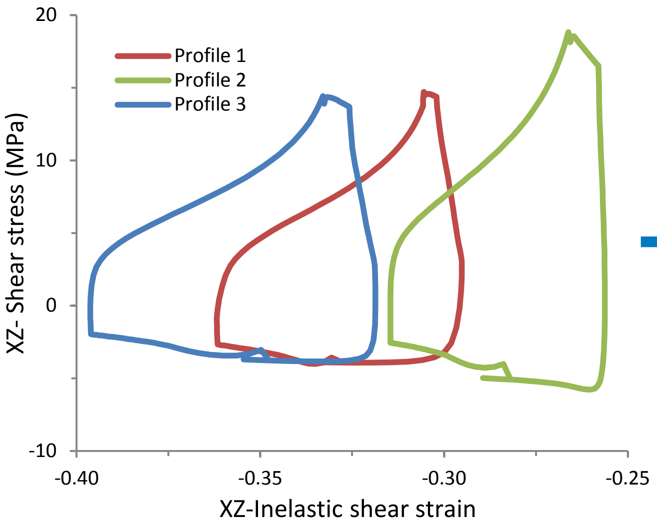
Go/No-Go: Do bonds meet minimum strength requirements?

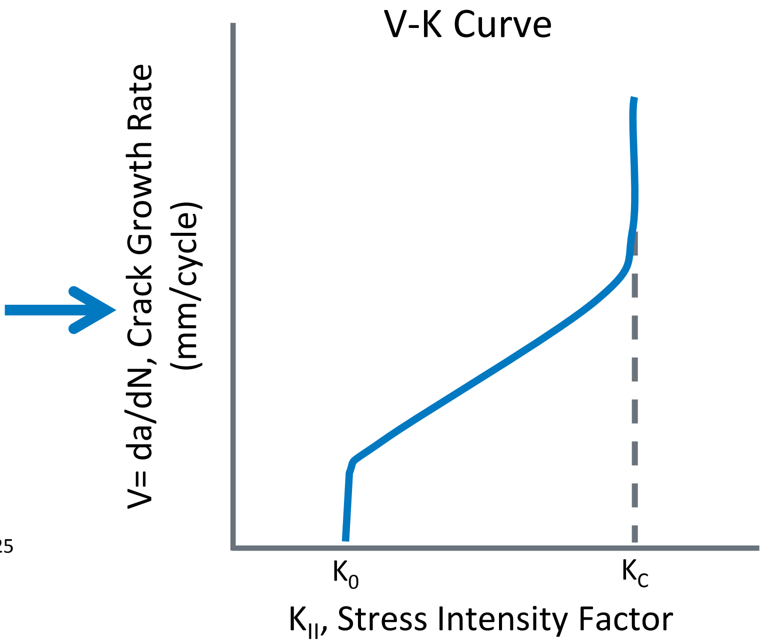
Key Deliverable: Publish V-K curve for sintered-silver

CTE = coefficient of thermal expansion
FEA = finite element analysis
V= da/dN, crack growth rate (mm/cycle)
K = stress intensity factor

Strategy

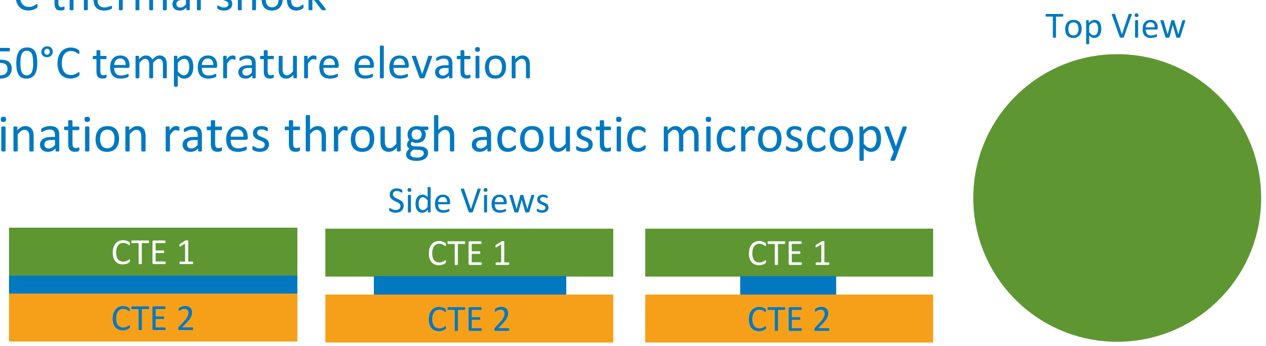
- Identify threshold at which stress field is sufficient to cause delamination initiation
    - The stress field is a function of the loading amount, deformation mode, and the region of interest relative to the crack tip deformation
    - Crack tip deformation can propagate through three modes:
        - Tension, K_I
        - Shear, K_{II}
        - Tearing, K_{III}





Strategy

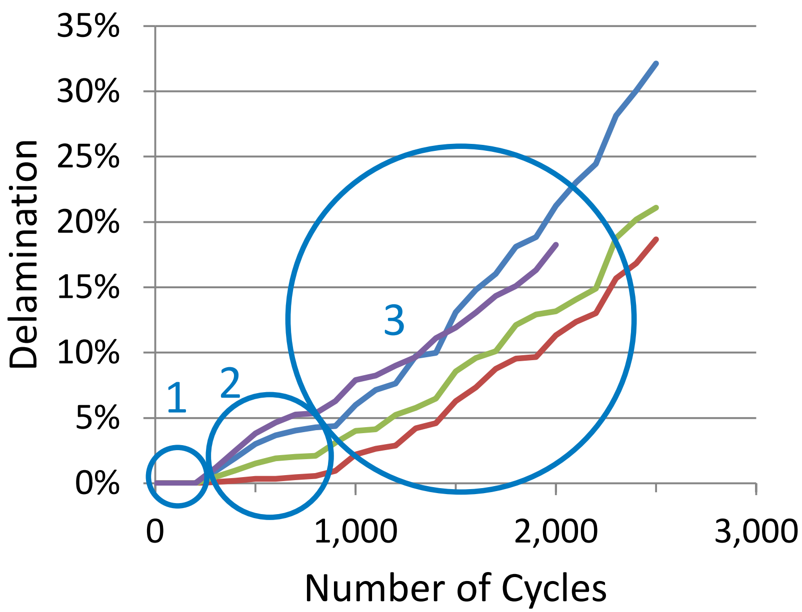
- Process CTE-mismatched disk samples with various diameter bond pads to validate stress field relationship with delamination initiation
- Subject samples to accelerated temperature testing:
  - -40°C to 175°C thermal shock
  - 175°C and 250°C temperature elevation
- Monitor delamination rates through acoustic microscopy

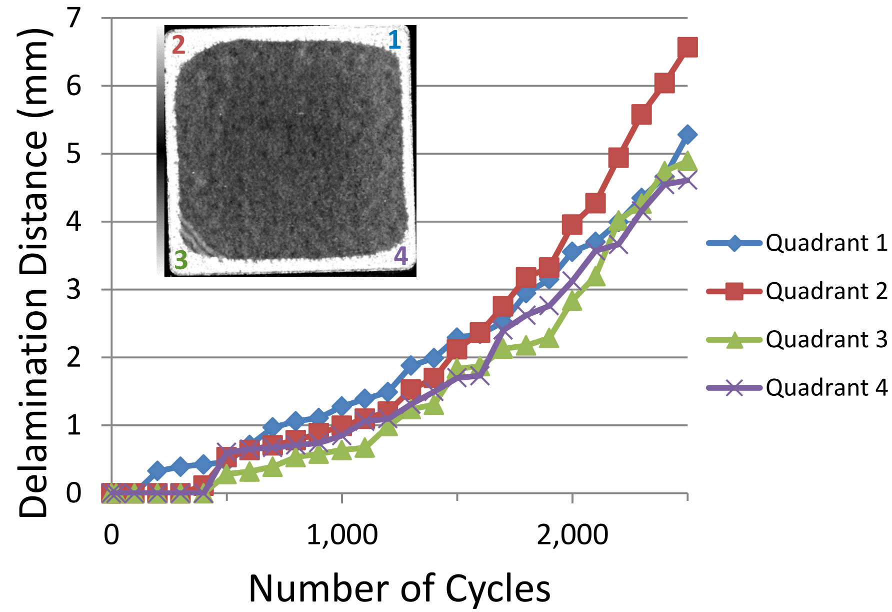


- Synthesize initial samples for mechanical characterization of sintered-silver
  - Attempt to measure residual stress at room temperature
  - Estimate stress-strain curves
  - Use information to model plastic deformation
- Subject samples to shear tests for development of stress-strain curves and replace bulk silver material properties

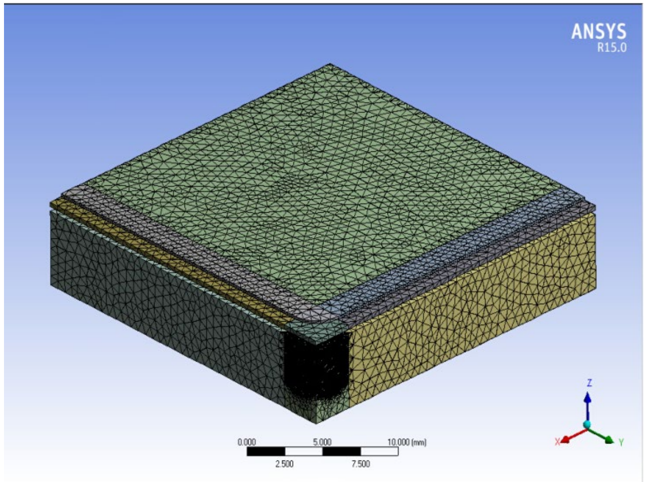
Crack Evaluation

- Identified threshold at which stress field is sufficient to cause delamination initiation
  - Measured delamination rate of 50-mm-x-50-mm sintered-silver samples
    1. Identified threshold at which stress intensities are sufficient to cause defect initiation
    2. Evaluated the defect region where a transient delamination rate occurs
    3. Evaluated the defect region where a constant slope delamination rate occurs
  - Modeled stress field with FEA

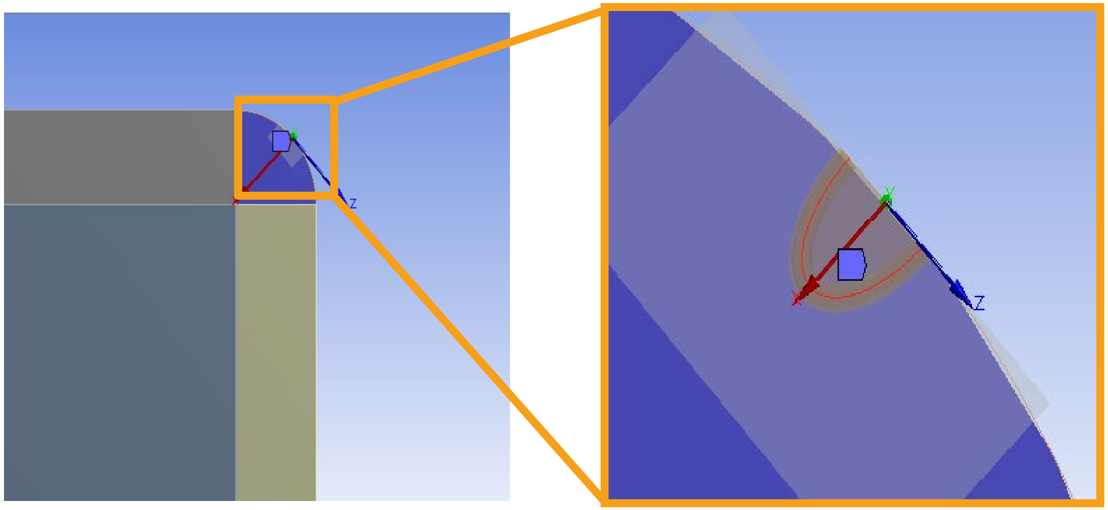




Interface Modeling – Crack Modeling



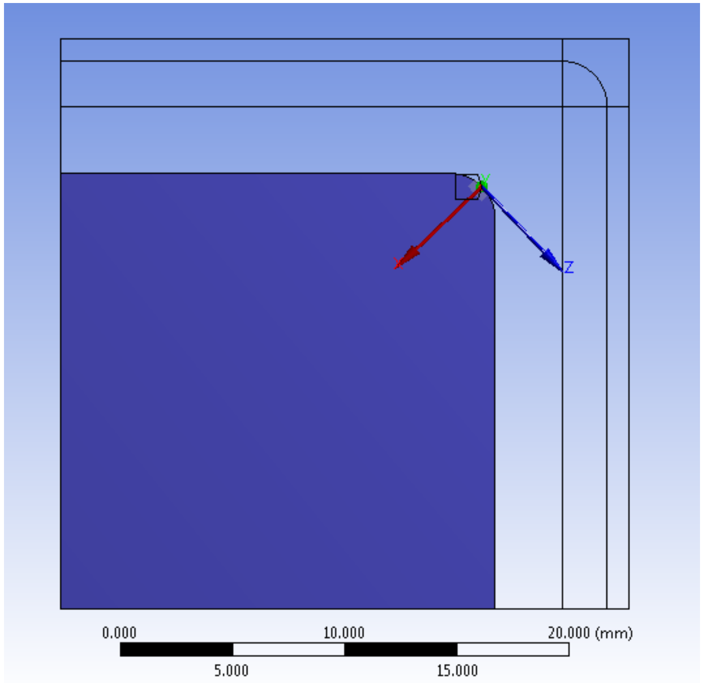
Viscoplastic Analysis

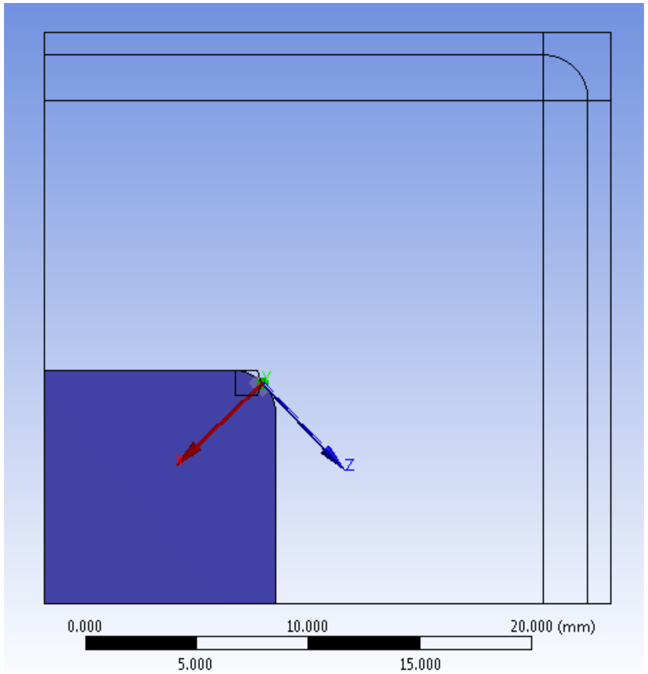


Elliptical Crack Modeled in Interface Layer

- Fracture-mechanics–based crack modeling adopted for sintered-silver
  1. A non-linear viscoplastic analysis (without an embedded crack) is first completed to determine the maximum stress location
  2. An elliptical crack is created around this location
  3. A subsequent analysis determines the stress field around the crack

Interface Modeling – Crack Growth



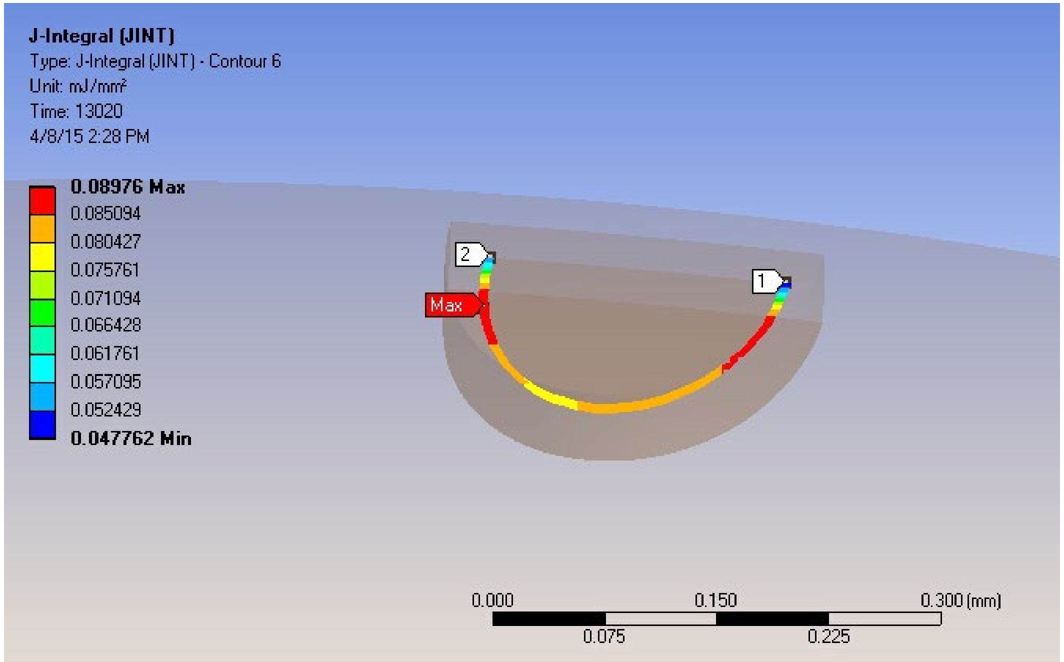


Elliptical Crack Models Replicating Crack Propagation

- The elliptical cracks are modeled at increasing distances from the far corner to replicate crack propagation
- The geometry is manually changed as propagation cannot be modeled
  - A crack growth law would need to be considered for directly modeling crack growth

Interface Modeling – J-Integral

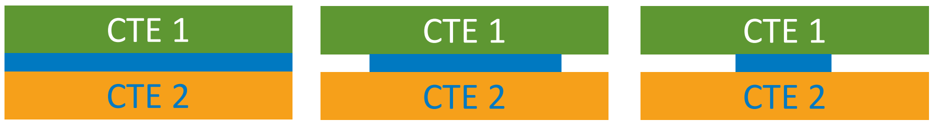
- J-integral (mJ/mm^2) is a path independent fracture mechanics parameter which describes the stress field near a crack tip for inelastic deformation
    - J-integral values along the crack propagation path can be obtained
- As the bonded interface region decreases, J-integral value increases

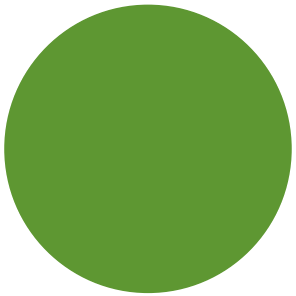


J-Integral Plot along a Crack Contour

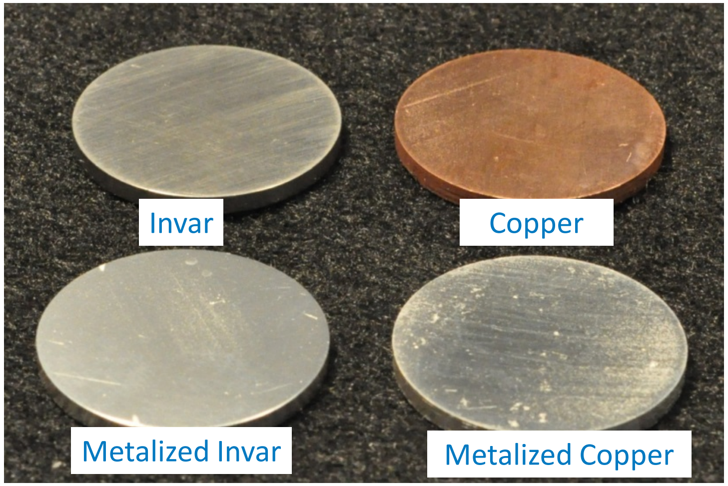
CTE-Mismatched Disk Samples

- Processed CTE-mismatched disk samples with various diameter bond pads to validate stress field relationship with delamination initiation

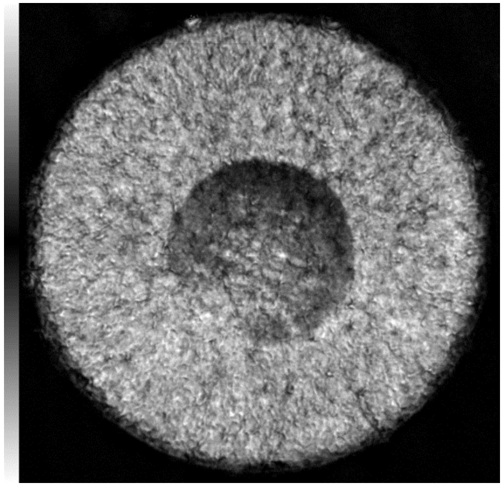




- Invar and copper were selected for round test coupons
  - Coupon dimensions are 25.4 mm in diameter, 2 mm in thickness
  - Materials were chosen for CTE mismatch
  - Surfaces were blanchard ground and metalized with silver



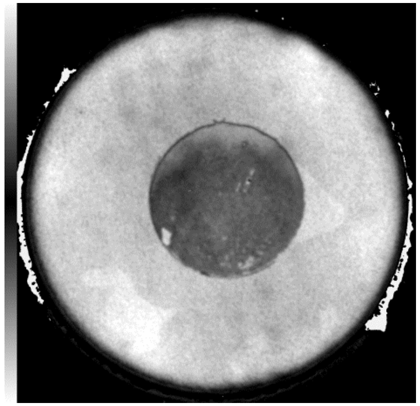
Invar and Copper Test Coupons



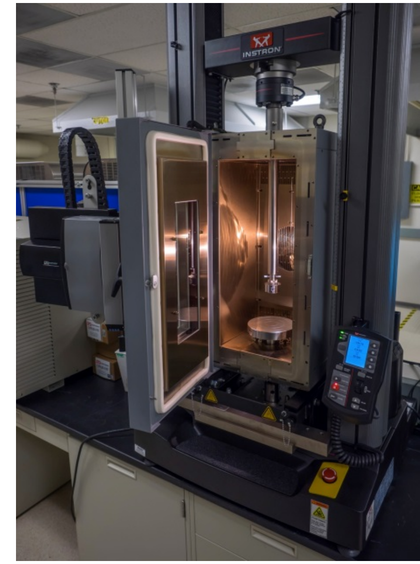
Initial 10 mm Bond Scan

Mechanical Characterization

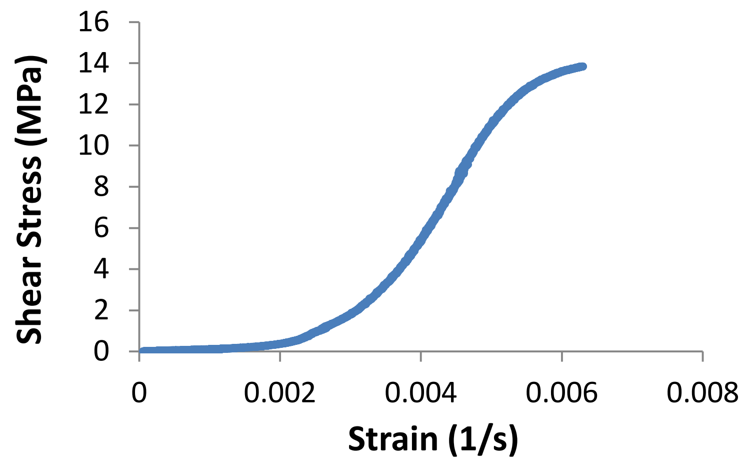
Sample Synthesis



Shear Testing

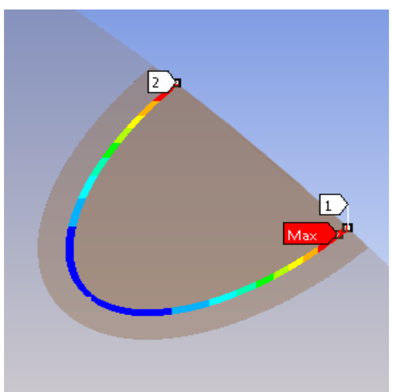


Shear Stress Measurement



Literature Comparison

Interface Modeling



Responses to Previous Year Reviewers' Comments

The reviewer questioned why it was desired to start module packaging work by selecting materials with different coefficients of thermal expansion.

It was desired to create a test sample package that imparted the greatest CTE mismatch possible to accelerate degradation.

The reviewer suggested that the effort would benefit from collaboration with power module manufacturers.

Synthesis and reliability findings are being openly shared with power module manufacturers. It is a future goal to see the integration of sintered-silver bonding in a production module.

Collaboration and Coordination

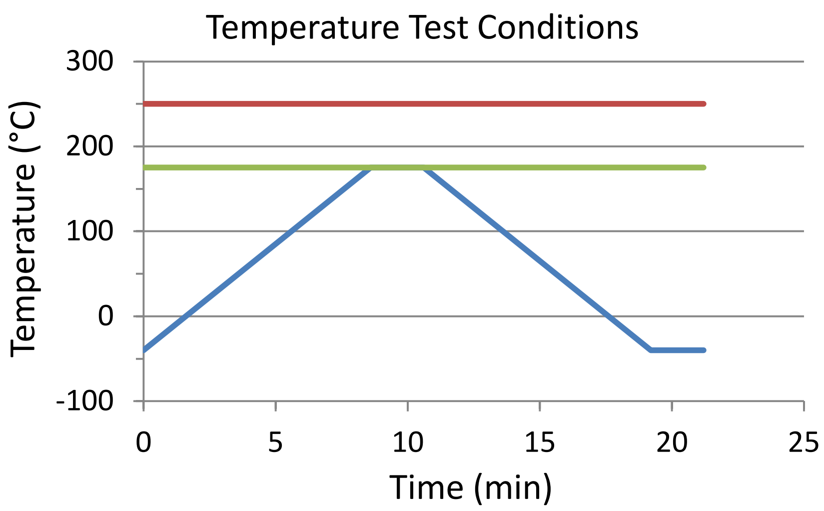
- **ORNL:** technical partner on sintered-silver samples
- **Fraunhofer:** modeling collaboration
- **Henkel:** sintered-silver material guidance
- **Heraeus:** sintered-silver material guidance
- **General Motors:** technical guidance
- **APEI:** technical guidance

Remaining Challenges and Barriers

- Quality of sintered-silver joints is dependent on many parameters (temperature, pressure, and time of synthesis, plating quality)
- Obtaining accurate material properties for sintered-silver is critical for crack analysis modeling
- Fracture-mechanics–based crack modeling must replicate sintered-silver failure mechanism

Proposed Future Work (FY15)

- Subject round samples to accelerated temperature testing:
  - –40°C to 175°C thermal cycle
  - 175°C and 250°C temperature elevation
- Monitor delamination rates through acoustic microscopy

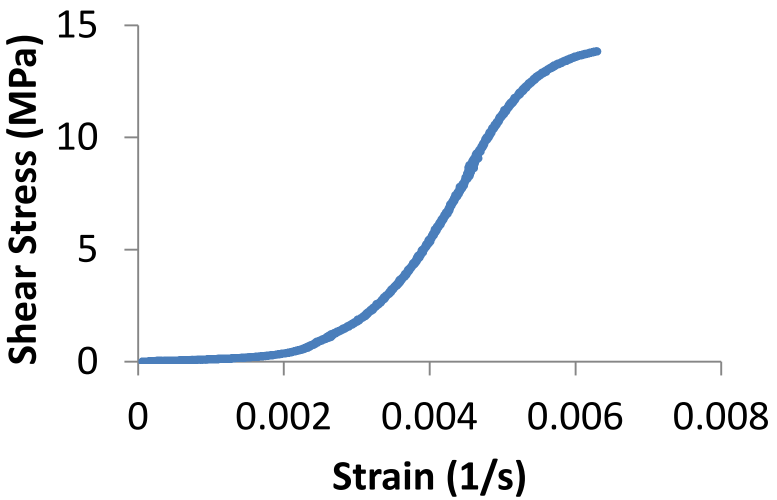


- Synthesize and shear test initial samples for mechanical characterization of sintered-silver
  - Attempt to measure residual stress at room temperature
  - Estimate stress-strain curves
  - Use information to model plastic deformation

Shear Test Fixture and Sample

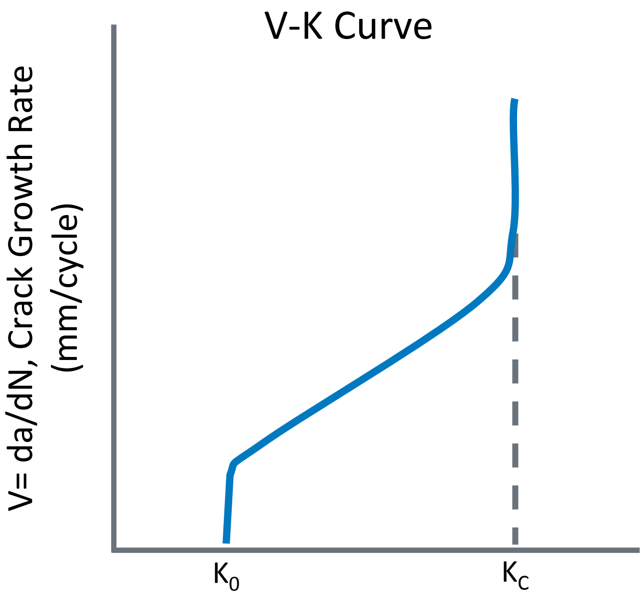
Proposed Future Work (FY15)

- Evaluate material properties
  - Stress-strain curves obtained from shear testing
  - Compare temperature-dependent material properties of bulk versus sintered-silver



- Model additional simulations with incrementally lower bond pad regions
- Perform sensitivity analysis of elliptical crack contour
- Initiate crack propagation modeling

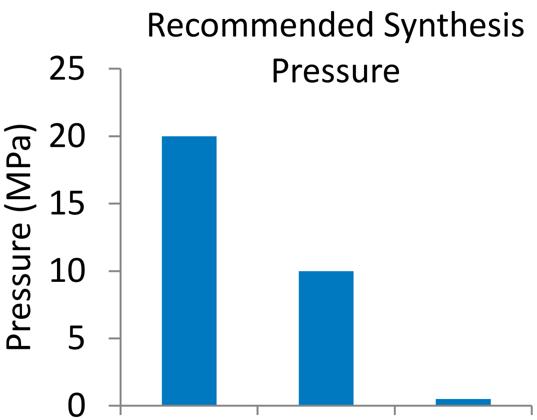
- Establish V-K curve for sintered-silver



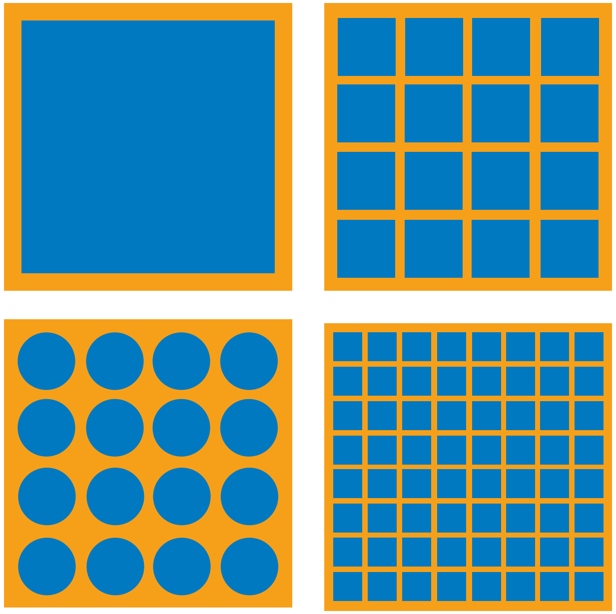
Proposed Future Work (FY16/17)

- Evaluate the delamination rate of sintered-silver test coupons under various pressure requirements, bond pad geometries, and surface plating materials

Evaluate low- and no-pressure sintered-silver materials

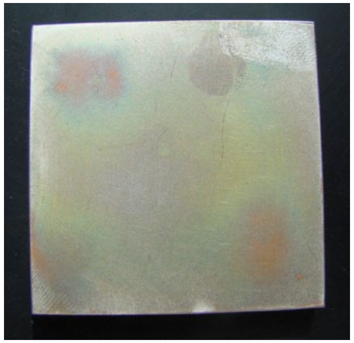


Optimize pad geometries for a large-area bond pad



Recommend industry standard practices for plating

Plating Material	Ag, Au
Cleaning	None, substrate cleaning, pre-oxidation



Poor Ag Plating

Summary

- **DOE Mission Support:**
  - Bonded interface materials are a key enabling technology for compact, lightweight, low-cost, reliable packaging and for high-temperature coolant and air-cooling technical pathways
- **Approach:**
  - Synthesis of sintered-silver bonds, thermal temperature cycling, bond inspection (acoustic microscope), and stress field versus cycles-to-failure models
- **Accomplishments:**
  - Established a procedure for the material and degradation characterization of sintered-silver
- **Collaborations**
  - ORNL, Fraunhofer, Heraeus, Henkel, GM, APEI

NREL
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Reviewer-Only Slides

Publications and Presentations

- **Publications**
  - D. J. DeVoto, A. A. Wereszczak, and P. P. Paret, 2014, “Stress Intensity of Delamination in a Sintered-Silver Interconnection,” IMAPS High Temperature Electronics (HiTEC), Albuquerque, NM.
  - A. A. Wereszczak, S. B. Waters, D. J. DeVoto, and P. P. Paret, 2015, “Method to Determine Maximum Allowable Sinterable Silver Interconnect Size,” in preparation, Journal of Electronic Materials.
- **Presentations**
  - D. J. DeVoto, 2013, “Performance and Reliability of Bonded Interfaces for High-Temperature Packaging,” Advanced Power Electronics and Electric Motors FY14 Kickoff Meeting, DOE Vehicle Technologies Program, Oak Ridge, TN, November 2014.
  - D. J. DeVoto, A. A. Wereszczak, and P. P. Paret, 2015, “Thermomechanical Reliability of Sintered-Silver Interface Materials,” International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (InterPACK), San Francisco, CA.

Critical Assumptions and Issues

- Large-area bonded interfaces can lead to thermomechanical stresses in the package and consequently cracks, voids, and delaminations. For any proposed solution, it is important to address issues related to thermomechanical reliability.
    - The issue of reliability is specifically being addressed in this project.
- Degradation mechanisms for sintered-silver are not well known and need to be addressed.
    - We are addressing these aspects to some extent in this project. The hypothesis is that we are developing generalized (i.e., independent of geometry) stress field versus cycles-to-failure relations for sintered-silver.
- The bonded-interface solution will have to be low cost and be easily integrated into the manufacturing process.
    - Arguably, sintered-silver is not particularly high cost, but pressure requirements during the manufacturing process will need to be addressed.