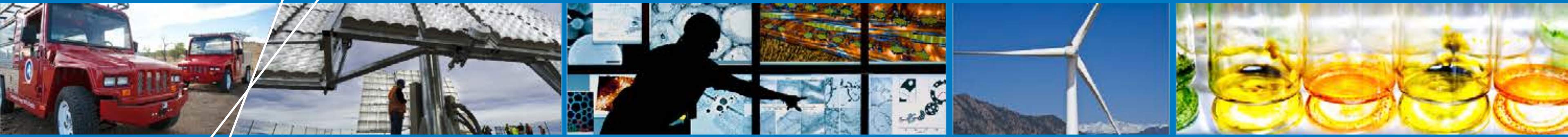
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Performance and Reliability of Bonded Interfaces for High-Temperature Packaging



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DOE Vehicle Technologies Office
Advanced Power Electronics and Electric Motors R&D
FY15 Kickoff Meeting

Oak Ridge National Laboratory
Oak Ridge, Tennessee
November 19, 2014

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

USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

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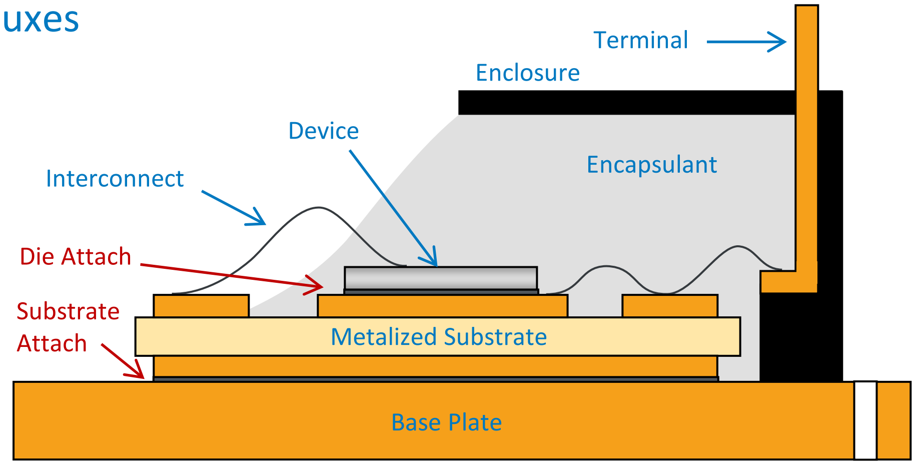
State of the Art

- 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

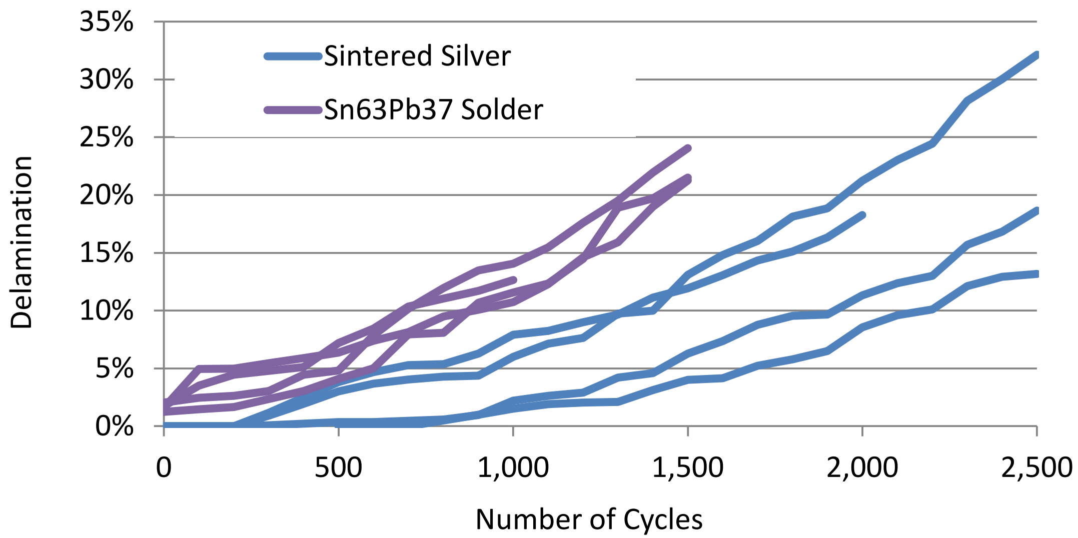


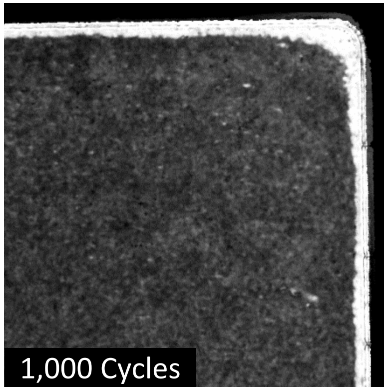
Traditional Power Electronics Package

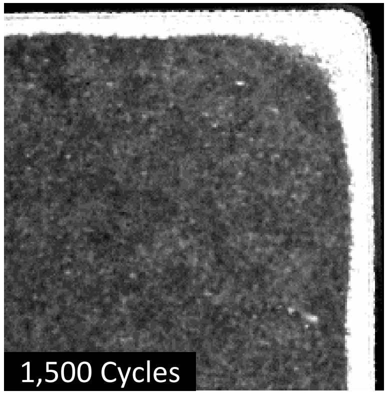
- Current solder alloys do not meet packaging requirements

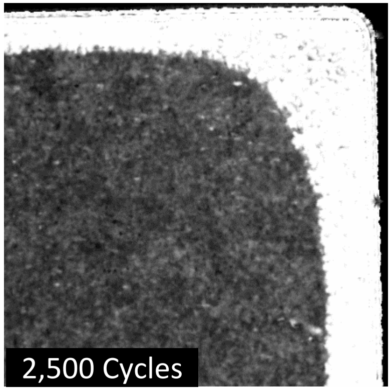
Proposed Technology

- Prior temperature cycling has shown sintered-silver to be more reliable than $Sn_{63}Pb_{37}$ solder as a substrate attach material
- Sintered-silver's thermal performance makes it an attractive bonded interface material (BIM) solution:
  - High re-melt temperature (962°C)
  - High thermal conductivity



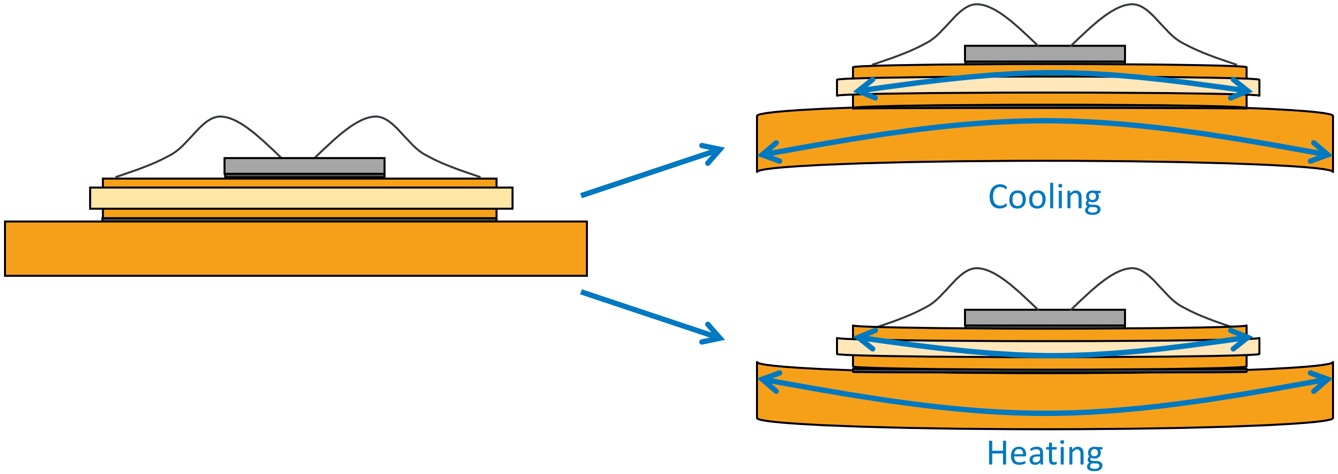






Challenges/Barriers to Meet Project Goals

- As operating temperatures increase, the coefficient of thermal expansion (CTE) mismatch between the substrate and the base plate causes defect initiation and propagation in the joining layer

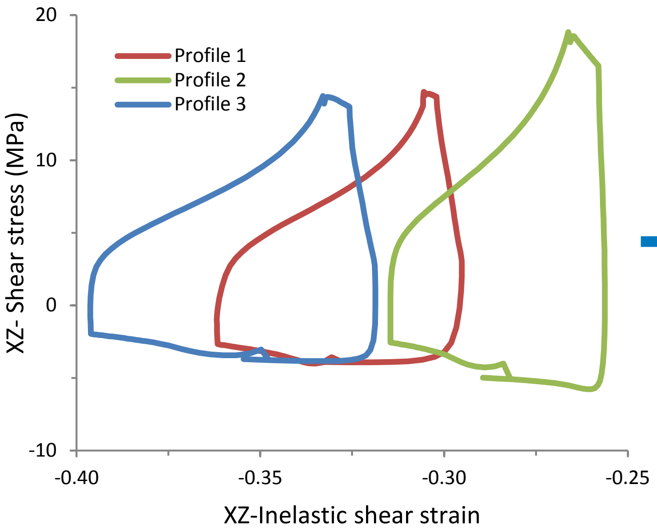


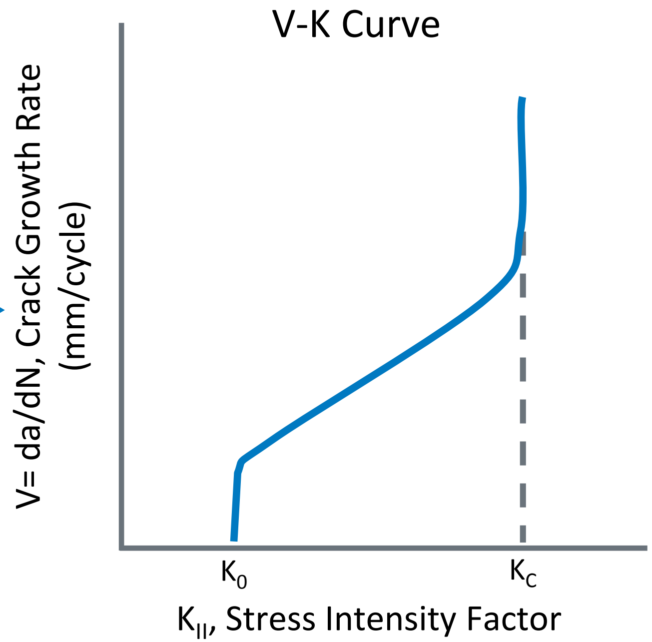
CTE (ppm/°C)
Silicon: 2.6
AlN: 4.5
Si_3N_4: 3.2
Copper: 16.5
Aluminum: 22.7
$Sn_{63}Pb_{37}$ Solder: 24.7
Silver: 19.5

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

FY14 Accomplishments

- Identified threshold at which stress intensity factor is sufficient to cause delamination initiation
  - The stress intensity factor 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}

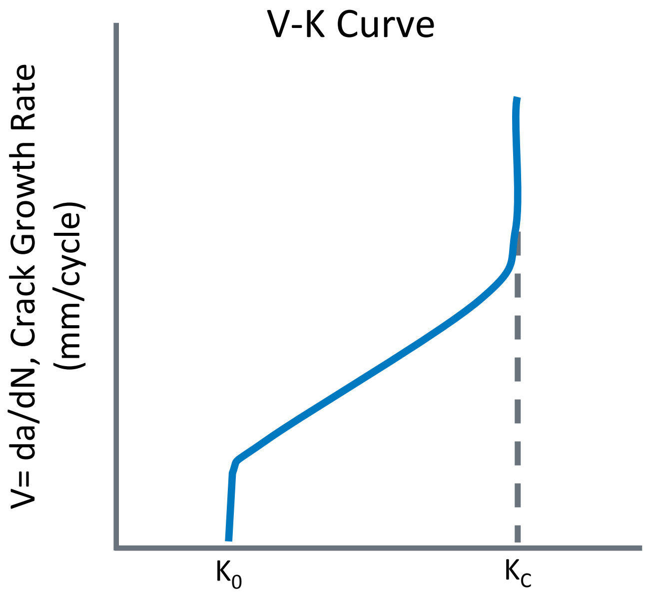




V= da/dN, crack growth rate (mm/cycle)
K = stress intensity factor

FY14 Accomplishments

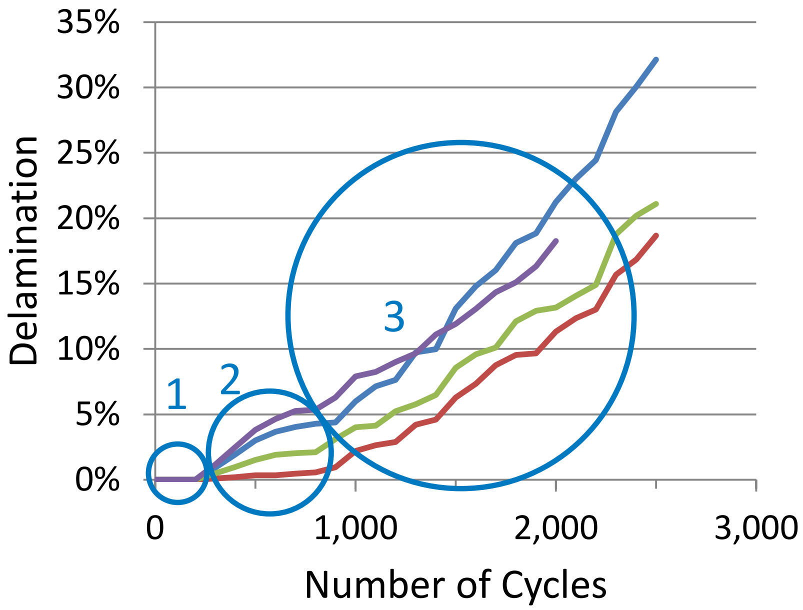
- Identified threshold at which stress intensity factor is sufficient to cause delamination initiation
  - Measured delamination rate of FY13 sintered-silver samples
  - Modeled stress intensity factor with finite element analysis (FEA)

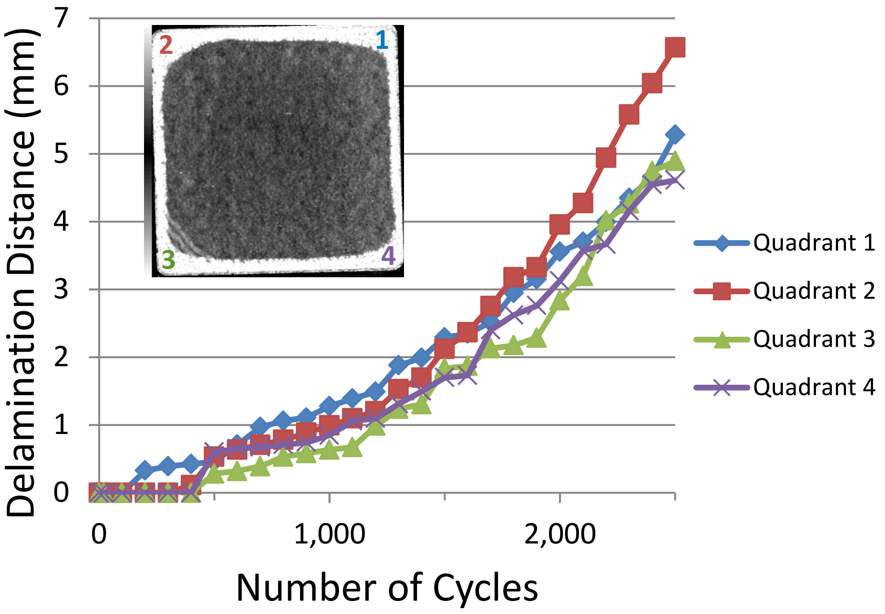


V= da/dN, crack growth rate (mm/cycle)
K = stress intensity factor

FY14 Accomplishments

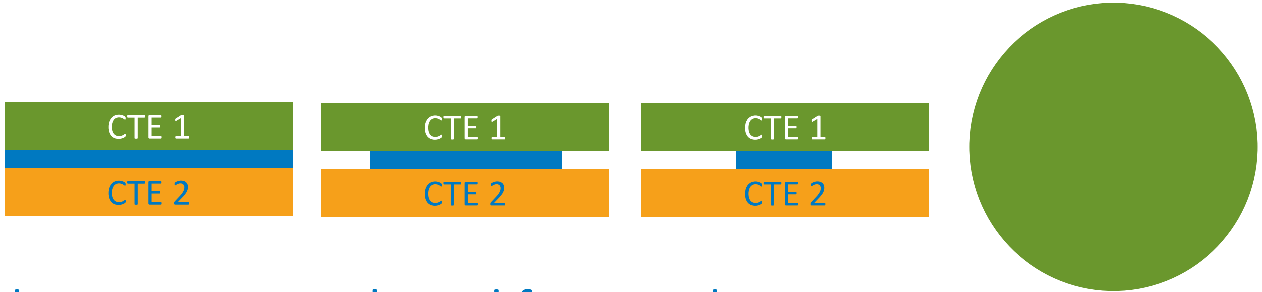
- Focused on optimizing and understanding key synthesis parameters for sintered-silver:
    1. Identified threshold at which stress intensities are sufficient to cause defect initiation
    2. Evaluated the defect region where a transient delamination rate occurs
    3. Evaluated the defect region where a constant slope delamination rate occurs



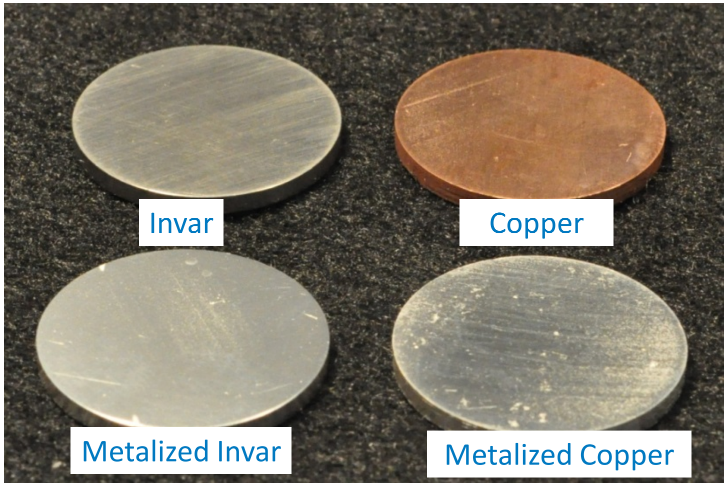


FY14 Accomplishments

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

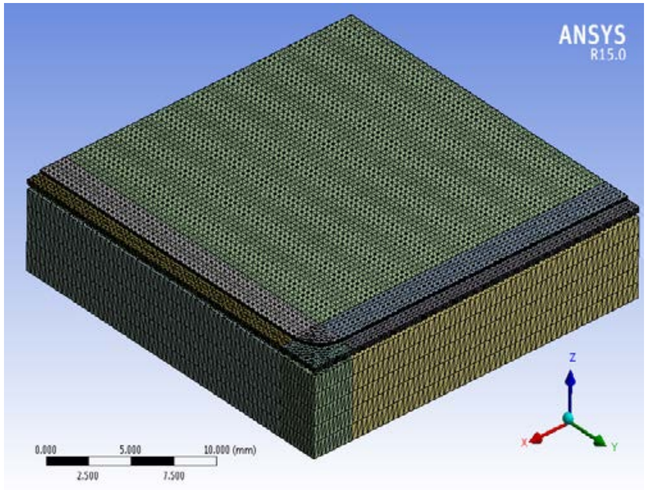


- Invar and copper were selected for round test coupons
  - Coupon dimensions are 25.4 mm in diameter, 2 mm in thickness
  - Materials were chosen for CTE mismatch
  - Surfaces were blanchard ground and metalized with silver

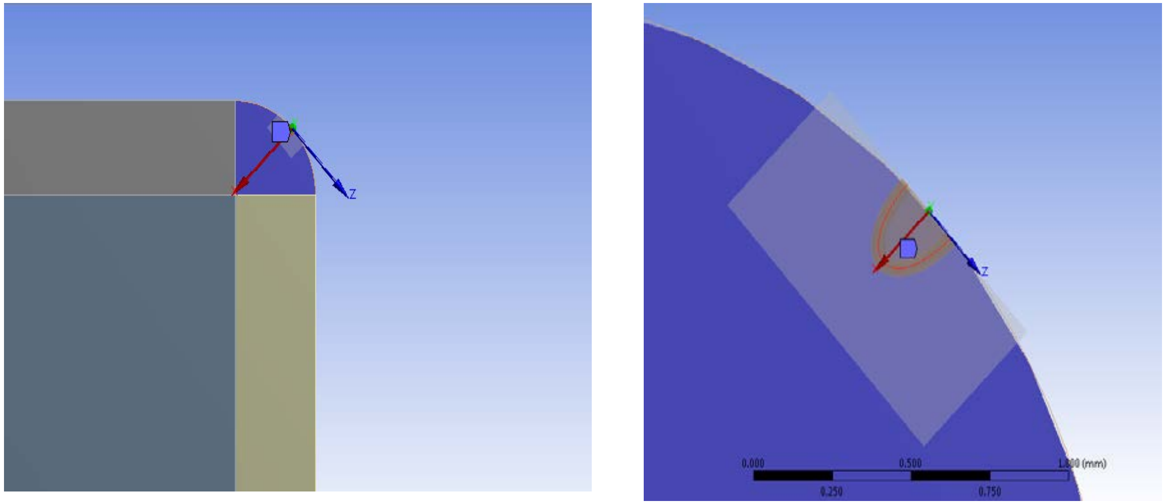


Invar and Copper Test Coupons

FY14 Accomplishments



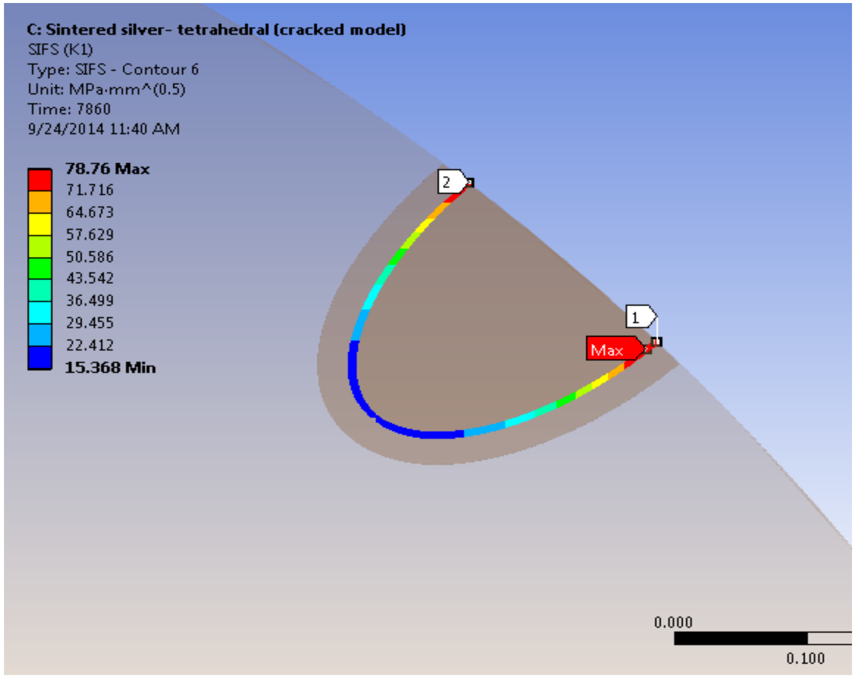
Quarter symmetry model



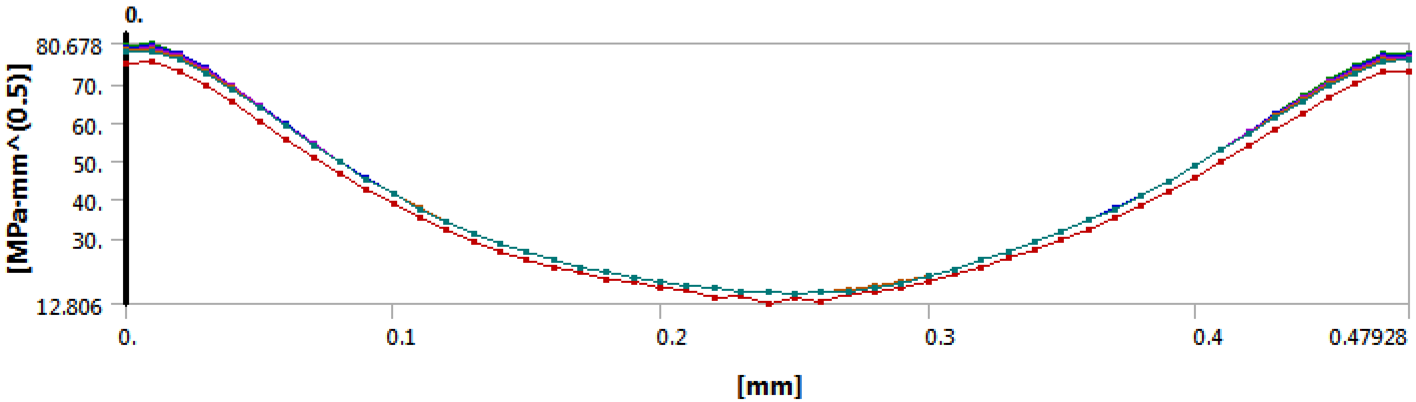
Crack modeled in interface layer

- Fracture-mechanics-based crack modeling adopted for sintered-silver
- Crack size and location needs to be known in advance
- An elliptical crack is built in the area of interest before solving
- Mesh re-adjusts to a denser grid around the crack accordingly

FY14 Accomplishments

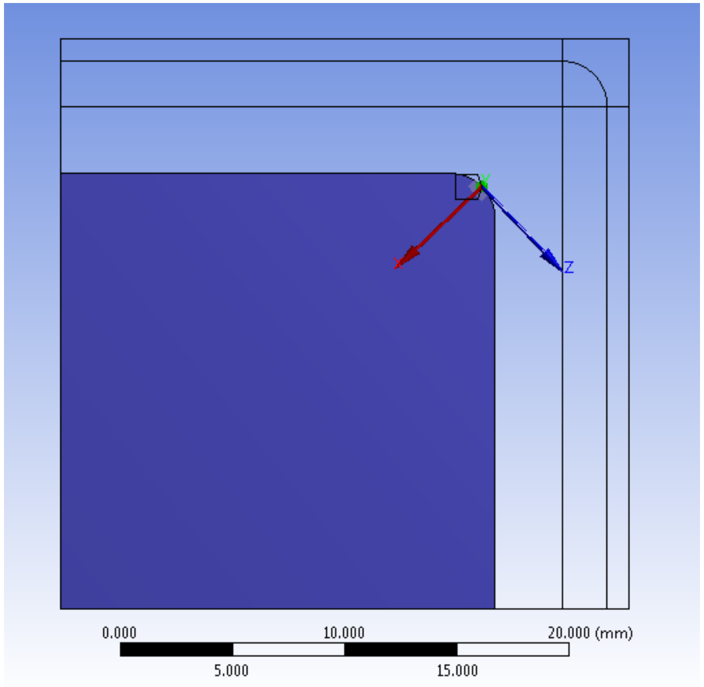


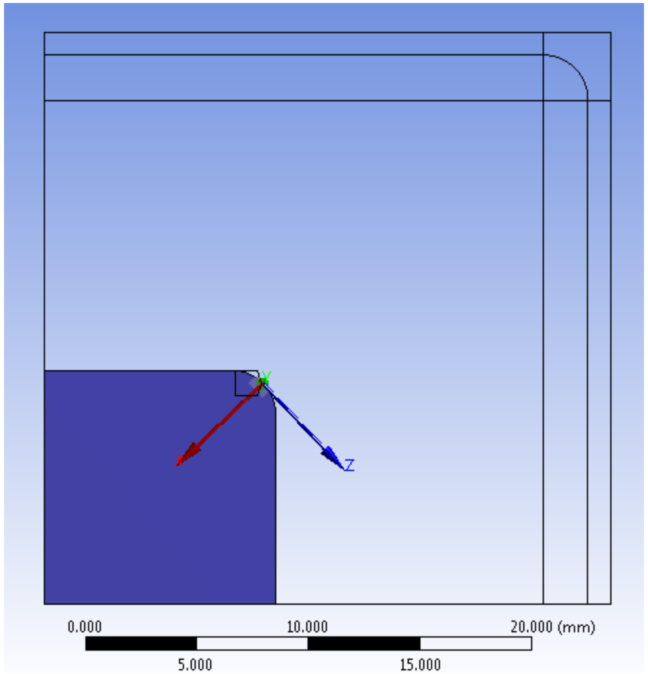
- K values for each crack mode at a given location are obtained
  - Stress intensity factor (K) is a parameter that describes the stress field near a crack tip
- Stress is infinite at the crack tip
- K values at different locations along the crack propagation path can be obtained



K versus distance along crack contour

FY14 Accomplishments

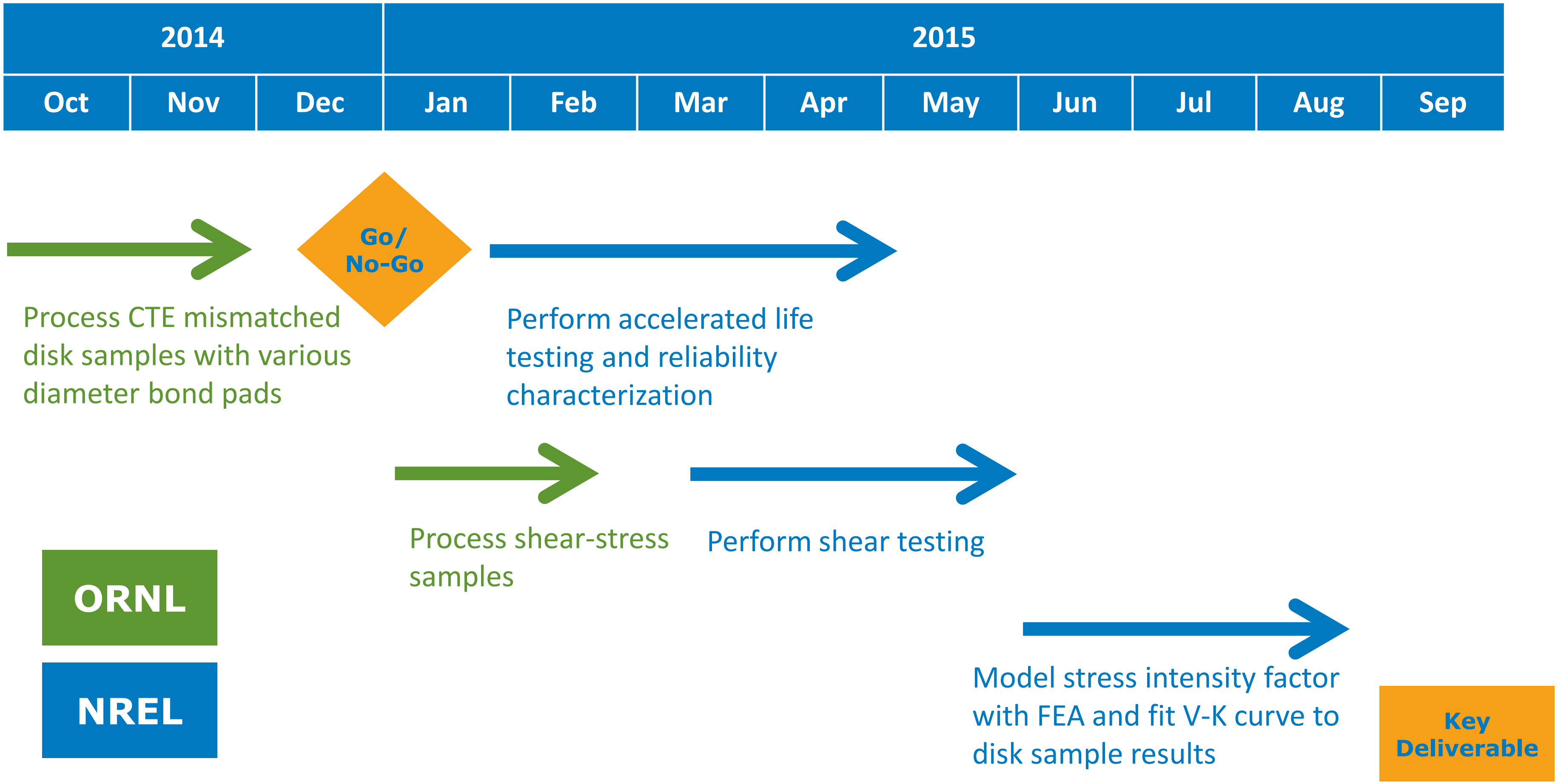




Quarter symmetry models to replicate crack propagation

- Crack is modeled at greater incremental distances from the far corner
- Crack propagates when $K > K_{critical}$
- Geometry is manually changed as propagation cannot be modeled

FY15 Tasks to Achieve Key Deliverable

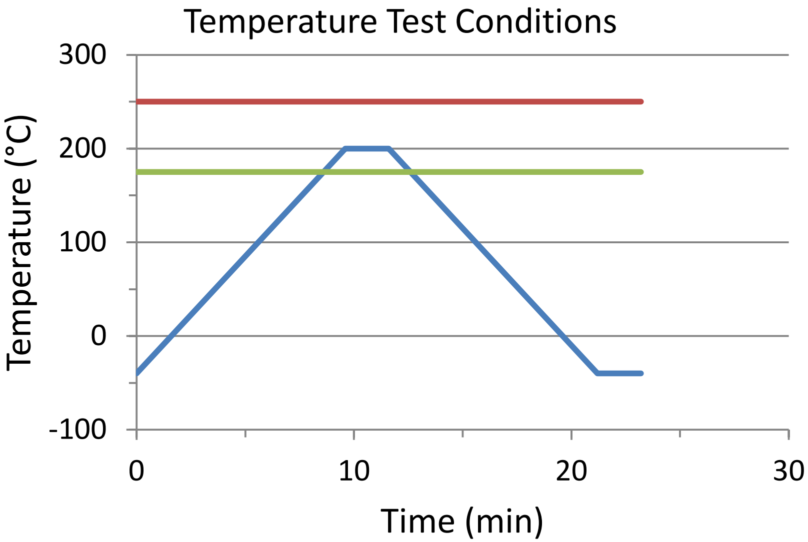


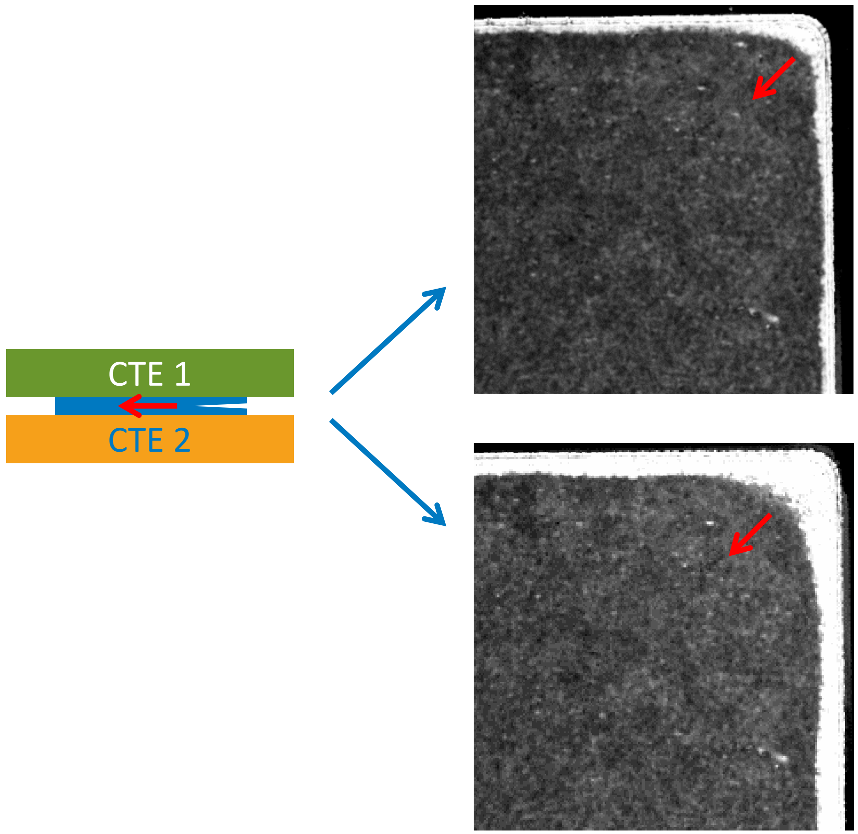
Go/No-Go: Do bonds meet minimum strength requirements?

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

FY15 Tasks

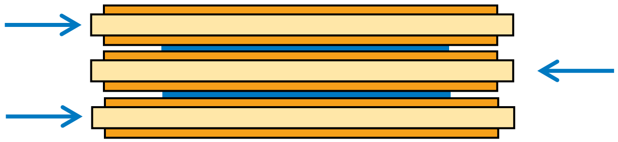
- Subject round samples to accelerated temperature testing:
  - –40°C to 200°C thermal shock
  - 175°C and 250°C temperature elevation
- Monitor delamination rates through acoustic microscopy





FY15 Tasks

- 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
- Sintered-silver interfaces are bonded between direct bond copper substrates



Proposed Sample

Shear Test Fixture and Sample

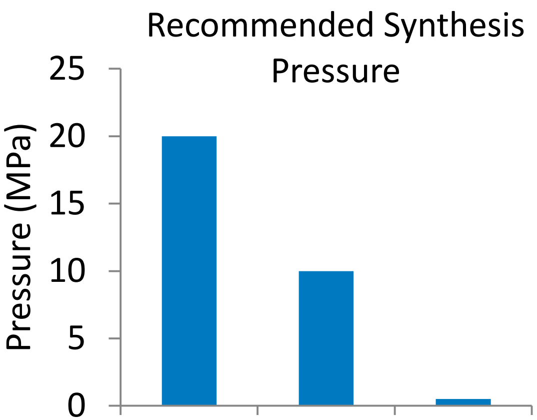
FY15 Tasks

- Evaluate material properties
  - Stress-strain curves obtained from shear testing
  - Compare temperature-dependent material properties of bulk versus sintered-silver
- Establish confidence in stress intensity factor results
  - How does ANSYS compute K?
  - Onset of plasticity – elastic plastic fracture mechanics
  - Develop crack propagation modeling
- Establish V-K curve for sintered-silver

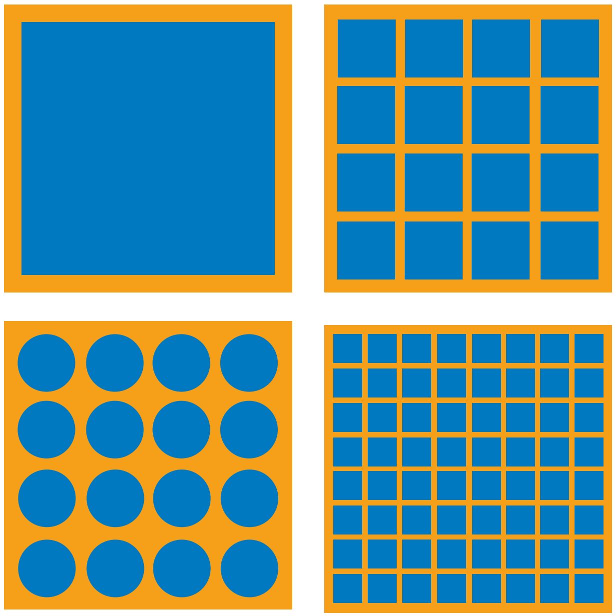
FY16 Tasks

- 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

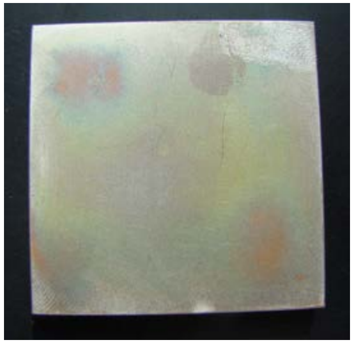


Optimize pad geometries for a large-area bond pad



Recommend industry standard practices for plating

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



Poor Ag Plating

Project Summary

Project Duration: FY14 – FY16
Overall Objective: Provide data to support broad industry demand for improving sintered-silver reliability.

FY14 Focus: Identify threshold at which stress intensities are sufficient to cause defect initiation.

Deliverable: Publish defect initiation findings for sintered-silver.

Go/No-Go: Can threshold stress before delamination initiation be defined?

FY15 Focus: Evaluate the delamination rate of sintered-silver round test coupons, update sintered-silver material properties from shear testing, and develop V-K curves through modeling.

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

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

FY16 Focus: Evaluate the delamination rate of sintered-silver test coupons under various parameters and develop correlation between interface patterning/degradation and junction temperature rise.

Deliverable: Defect initiation and progression as a function of sintered-silver material and bonding parameters.

Go/No-Go: Adjust bonding parameters to meet minimum shear strength.

Technology-to-Market Plan

- This research is on the path to commercialization of high-temperature bonded interface materials
  - Coordinates with industry suppliers of sintered-silver-based interface material
  - Addresses key barrier to improve thermal performance of power electronics package under high-temperature operation
  - Will impact manufacturing parameters of sintered-silver material for large-area substrate attachment
- Research directly impacts industry needs for high-temperature attach solutions
- Research focuses on achieving targets of a low-cost, high temperature (200°C) power electronics package with 15-year rated lifetime

Partners/Collaborators

- **ORNL:** technical partner on sintered-silver samples

- **Fraunhofer:** modeling collaboration
- **Henkel:** sintered-silver material guidance
- **Heraeus:** sintered-silver material guidance
- **General Motors:** technical guidance

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