Enabling Materials for High Temperature Power Electronics

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Overview

Timeline

- Started Q4-FY13
- Completion FY16
- 54% Complete

Budget

- Total project funding
  - 100% DOE
  - DOE VTO's Propulsion Materials (PM) & Electric Drive Technologies (EDT) Programs - 57% and 43%, respectively
- FY14: $175k (combined)
- FY15: $175k (combined)

Barriers*

1. Reduce cost of Electric Drive System from $30/kW in 2012 to $8/kW by 2020 (1.4 kW/kg, 4 kW/l, and 94% efficiency)
2. Enabling materials needed for wide bandgap (WBG) devices
3. Reliability and lifetime of power electronic (PE) modules and electric motors (EM) degrade rapidly with increased temperature#
4. PEs and EMs need improved thermal management# for higher temps
5. New cooling paradigms# would enable higher PE and EM power densities without compromise to reliability

Partners/Collaborations

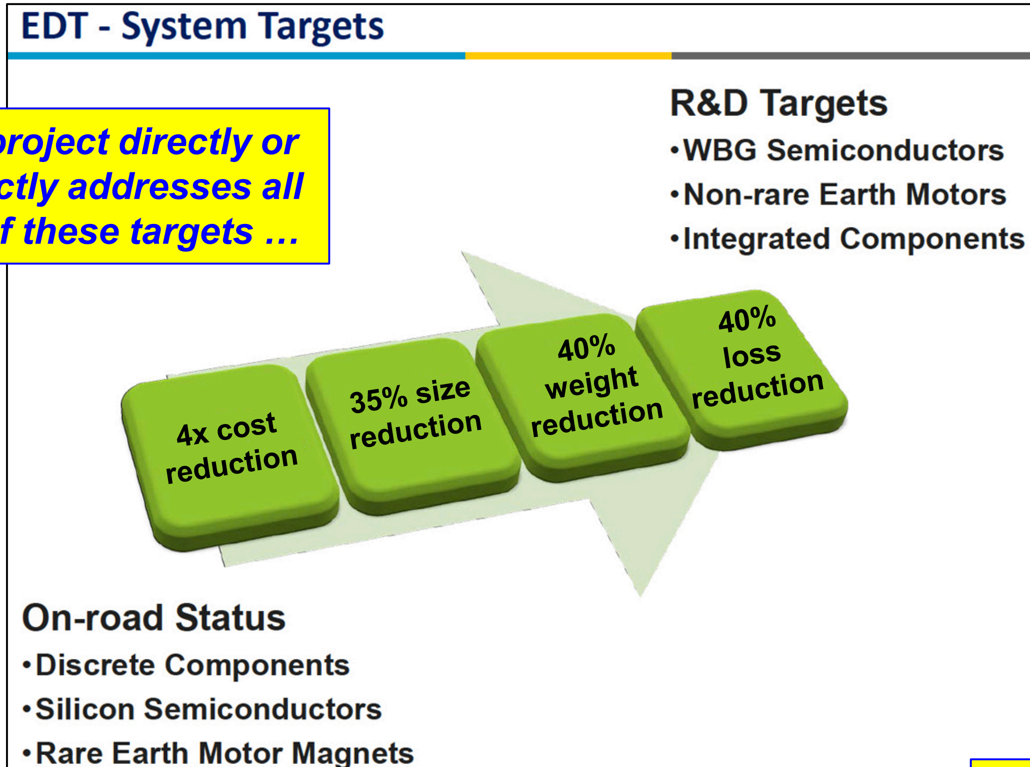
- Indium Corporation, Heraeus, and Henkel
- General Metal Finishing
- Interface Solutions, DuPont, and Martin Marietta
- SolEpoxy and Lord Corporation
- NREL

* S. Rogers, "Meeting Expectations and Program Review," EDT FY15 Kickoff Meeting, Oak Ridge, TN, 18 Nov 2014.

\# Enabled by using materials having 200° C-capability or increased thermal conductivity or both

Relevance/Objectives

This project directly or indirectly addresses all four of these targets …



ORNL Expertise and Unique Capabilities

- Power electronics
- Packaging
- WBG devices
- Electric motors

… by using ORNL's materials science and engineering expertise to advance PEs, PE packaging, WBG devices, and EM technologies

Source of above graphics:
S. Rogers, "Meeting Expectations and Program Review," EDT FY15 Kickoff Meeting, Oak Ridge, TN, 18 Nov 2014.

Milestones

FY14-Q4. Submit article to conference on silver sintering. [Surpassed; published in *Journal of Microelectronics and Electronic Packaging*]

FY15-Q1. Go/No-Go. DuPont's perflouropolymer candidate matrix for high-temperature-capable, thermally conductive dielectric composites? [No-Go; needs substantially more R&D to work for that particular material system]

FY15-Q2. Complete processing of direct bonded copper (DBC) substrate sandwiches and coefficient of thermal expansion (CTE) - mismatched disk specimens. [Achieved]

FY15-Q3. Complete mechanical testing of DBC sandwiches and thermal cycling of CTE-mismatched disk specimens. [On track]

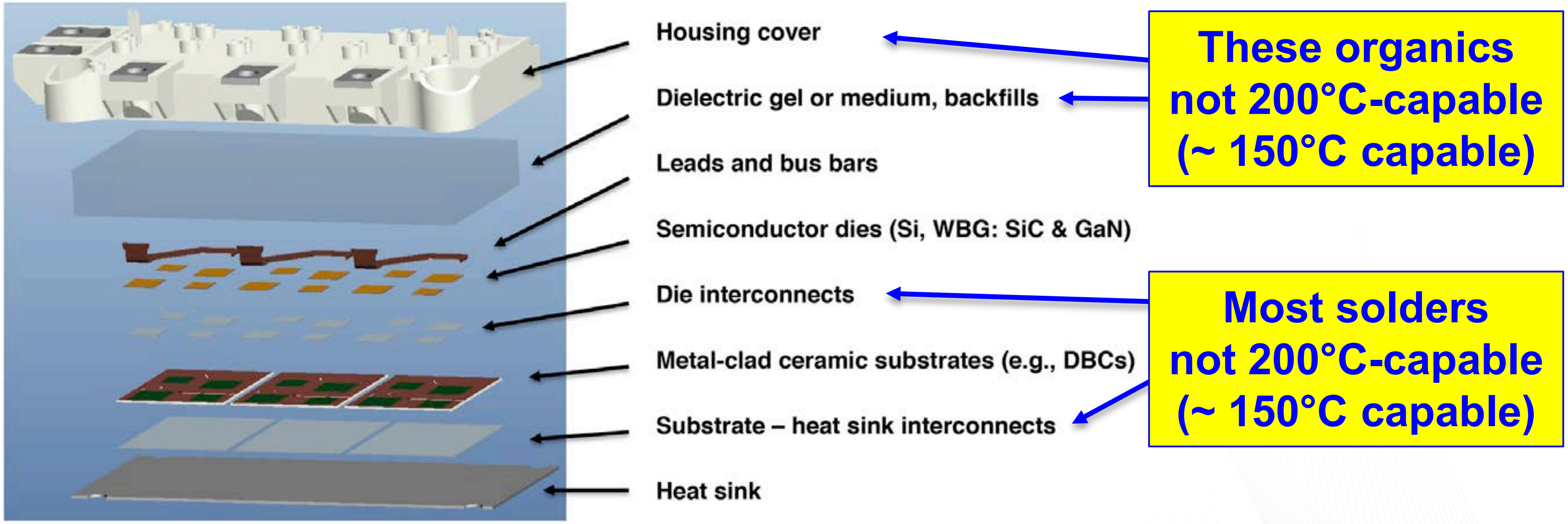
FY15-Q4. Correlate delamination response of interconnects in CTE-mismatched specimens with crack velocity – stress intensity (V-K) analysis. [On track]

Technical Approach (1 of 3): Address High-Temperature Incapability in PEs

Contemporary PE devices cannot operate at 200°C because:

- **Conventional interconnect materials (solder) in non-equilibrium at 200°C**
- **Most organics/polymers not stable for long times above ~ 175°C**

Example of a single-sided PE device



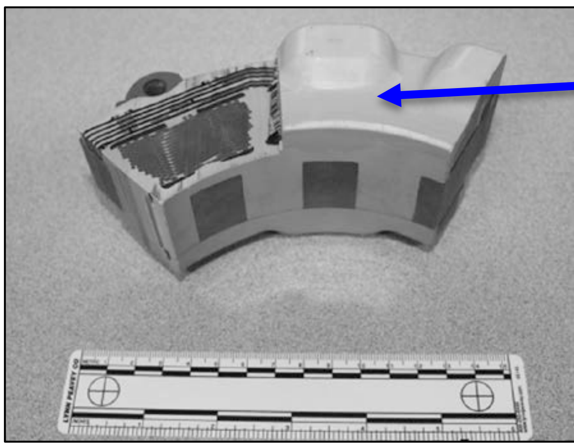
Goal: develop material technologies that enable a 200°C-capable, low-cost, and reliable electronic package with at least 15-year-life

Technical Approach (2 of 3): Address Low Heat Transfer Performance in EMs

Contemporary EMs have marginal heat transfer because:

- **Encapsulants and potting compounds have low thermal conductivity (TC)**
- **Thermal transfer between constituents is poor**

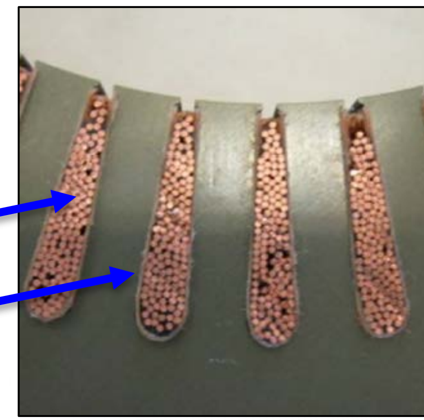
Sectioned Electric Generator



Encapsulant has low TC

Poor heat transfer within windings and at slot-liner laminate-winding interfaces

Sectioned Windings in Slot Liners



Sato, *et al.*, SAE International, 2011-01-0350

Goal: develop material technologies that enable more rapid overall thermal transfer <u>out</u> of the EM windings

Technical Approach (3 of 3): Summarizing This Project's Two Parallel Efforts

Power Electronics (PEs)

- ✓ 200°C – capable materials
- ✓ Materials and engineering:
  - Sintered-Ag interconnects
    - Process improvement
    - Geometrical limitations
    - Aid maturation
  - Higher TC encapsulants
- ✓ NREL collaboration
- ✓ About 80% of project's effort (or ~ 0.3 FTE)

Leveraged

Electric Motors (EMs)

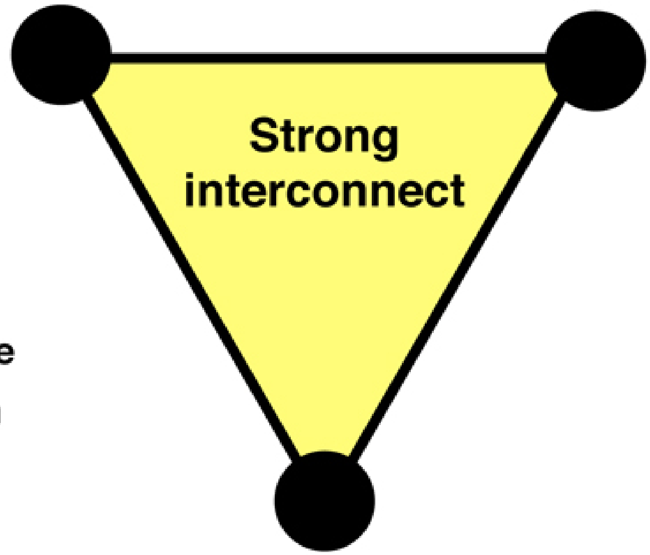
- ✓ Improve thermal transfer
- ✓ Materials and engineering:
  - Higher TC dielectrics
    - Encapsulants
    - Potting compounds
  - Phase-change materials
- ✓ Improve intra-winding TC and interfacial heat transfer
- ✓ NREL collaboration
- ✓ About 20% of project's effor (or ~ 0.08 FTE)

Technical Accomplishments (1 of 8)

Ultimate Bonding Strength is a Function of Many Parameters

Sintered Silver

- Pressure
- Temperature
- Time
- Processing cadence
- Strain or expansion joint relief
- *Cohesive strength contribution*



Plating

- Thickness
- Cleanliness
- O, C, and S contamination
- Promote metallurgical bond
- *Chemical component of adhesive strength*

Die, Substrate, or Baseplate

- Surface finish & topography
- CTE (mismatch)
- Size/area
- *Mechanical component of adhesive strength*

... but is only as strong as the strength of the weakest link

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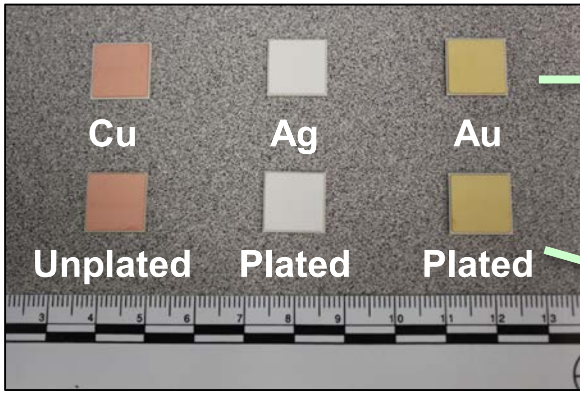
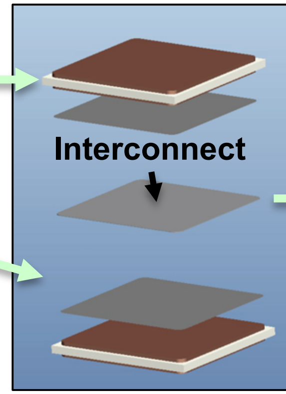
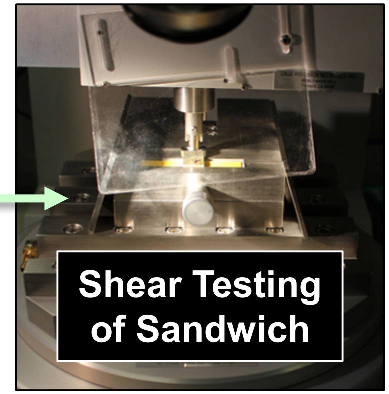
Technical Accomplishments (2 of 8)

Improved Understanding of Sintered-Ag Bonding Needed

"DBC Substrate Sandwich" Specimens for Plating and Interconnect Evaluations



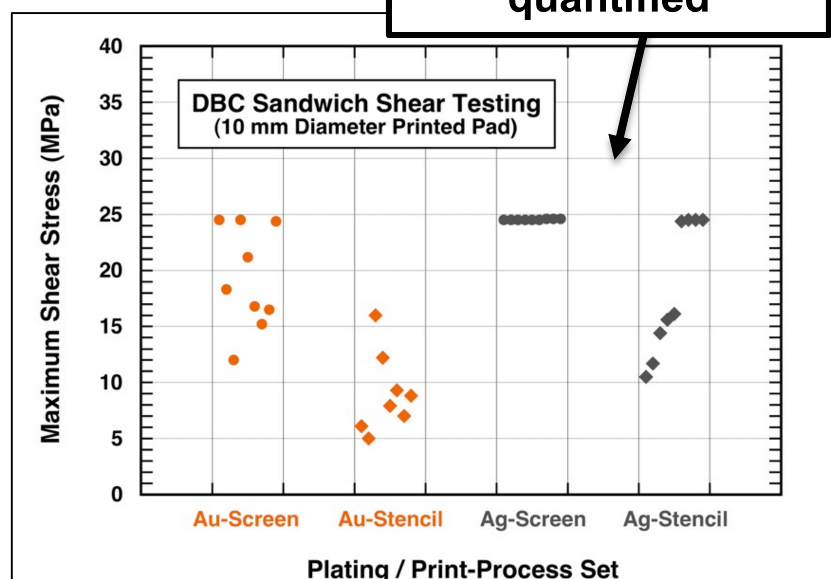




Being redone with smaller bonding area (20 mm^2) so failure is alway produced & failure shear stress can be quantified

- **Dependent parameter: shear strength**
- **Pad size: 10 mm diameter (or bonding area = 79 mm^2) interconnect bonding the two square DBCs**
- **Shear tester load capability = 1960 N**

Independent Parameters:
Ag vs. Au plating
Screen vs. stencil printing



Technical Accomplishments (3 of 8)

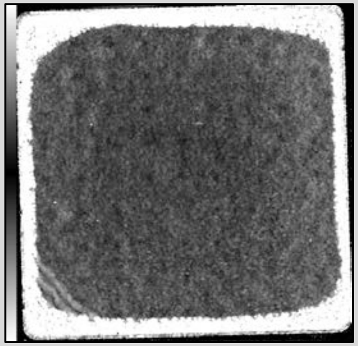
Collaboration with NREL Underway Involving Interconnect Reliability

- **D. Devoto, P. Paret, and A. A. Wereszczak, "Stress Intensity of Delamination in a Sintered-Silver Interconnection, Paper WA26, pp. 190-197 in Proceedings of the IMAPS HiTEC 2014, Albuquerque, NM, 2014.**

- **A. A. Wereszczak, D. J. DeVoto, and P. P. Paret, "Perimetric Structure for Improved Reliability in Electronic Device Interconnection," DOE S-Number S-124,788, Invention Disclosure Number 201303197, 13 October 2013.**

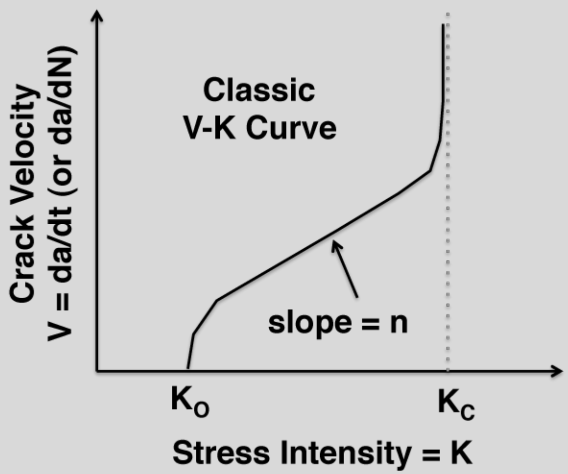
FY14 analysis influenced the following disk-bonding study in FY15

Example of delamination ingress



Source: DeVoto and Paret, NREL

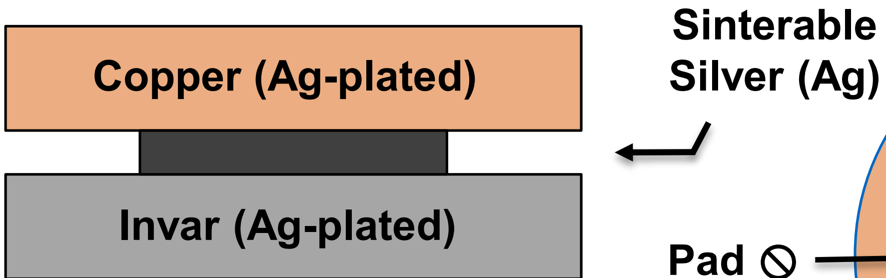
But corners complicate delamination interpretation; a circle is a better shape for fundamental analysis



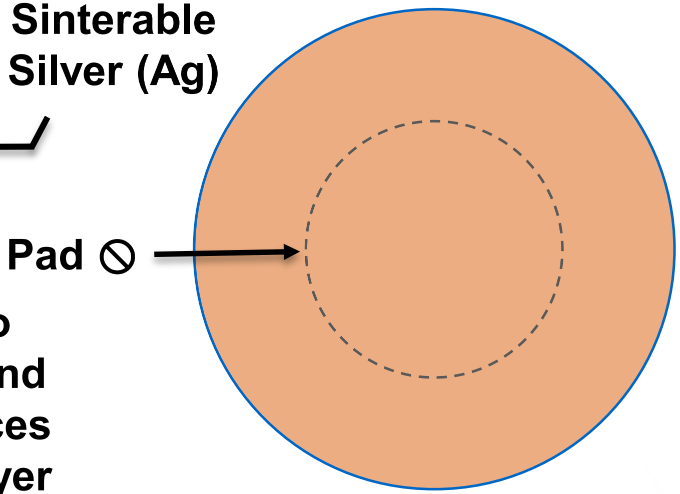
Technical Accomplishments (4 of 8)

Thermal Cycling, Residual Stresses, Stress Intensities, and Delamination (NREL Collaboration)

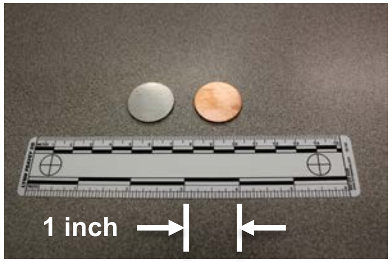
Side View



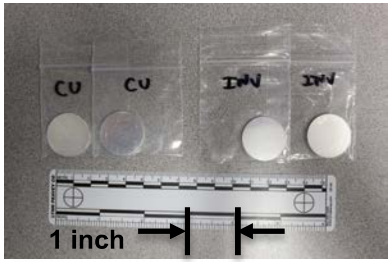
Top View



Pre-Plating



Post-Ag-Plating



- **Invar: model material used to simulate low CTE of silicon and substrates in electronic devices**
- **Vary pad diameter of bond layer**
- **Vary residual stress**
  - **Copper-copper disk pair**
  - **Invar-invar disk pair**
  - **Copper-invar disk pair**
- **Thermal cycling (-40°C to 140°C) & track delamination response**

Independent Parameters:
Magnitude of residual stress
Orientation of residual stress

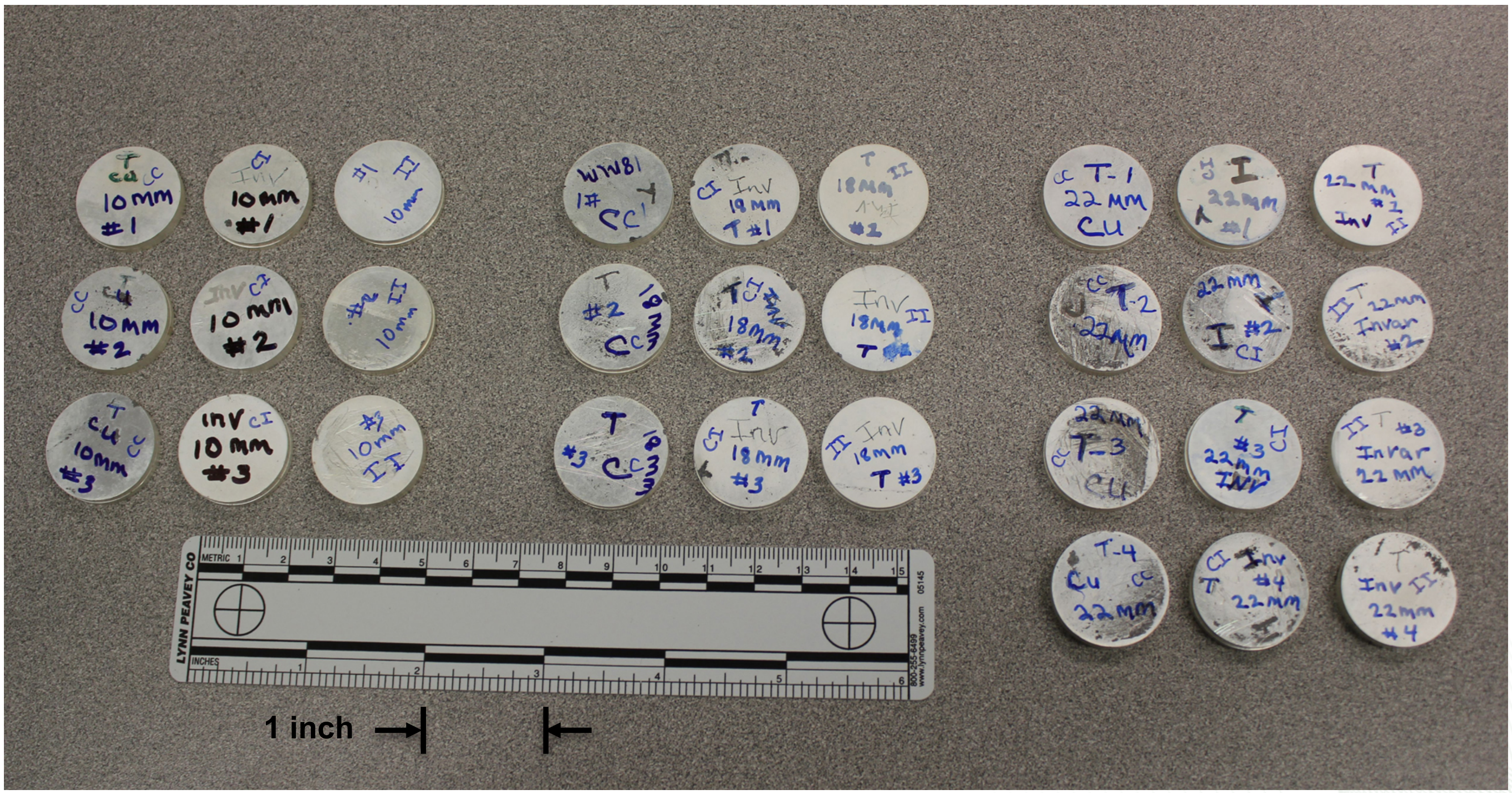
Nominal Properties:

Material	CTE (ppm/°C)	E (GPa)
Copper	17	115
Sintered Ag	20	15-60
Invar	1.3 - 2.7	145

Technical Accomplishments (5 of 8)

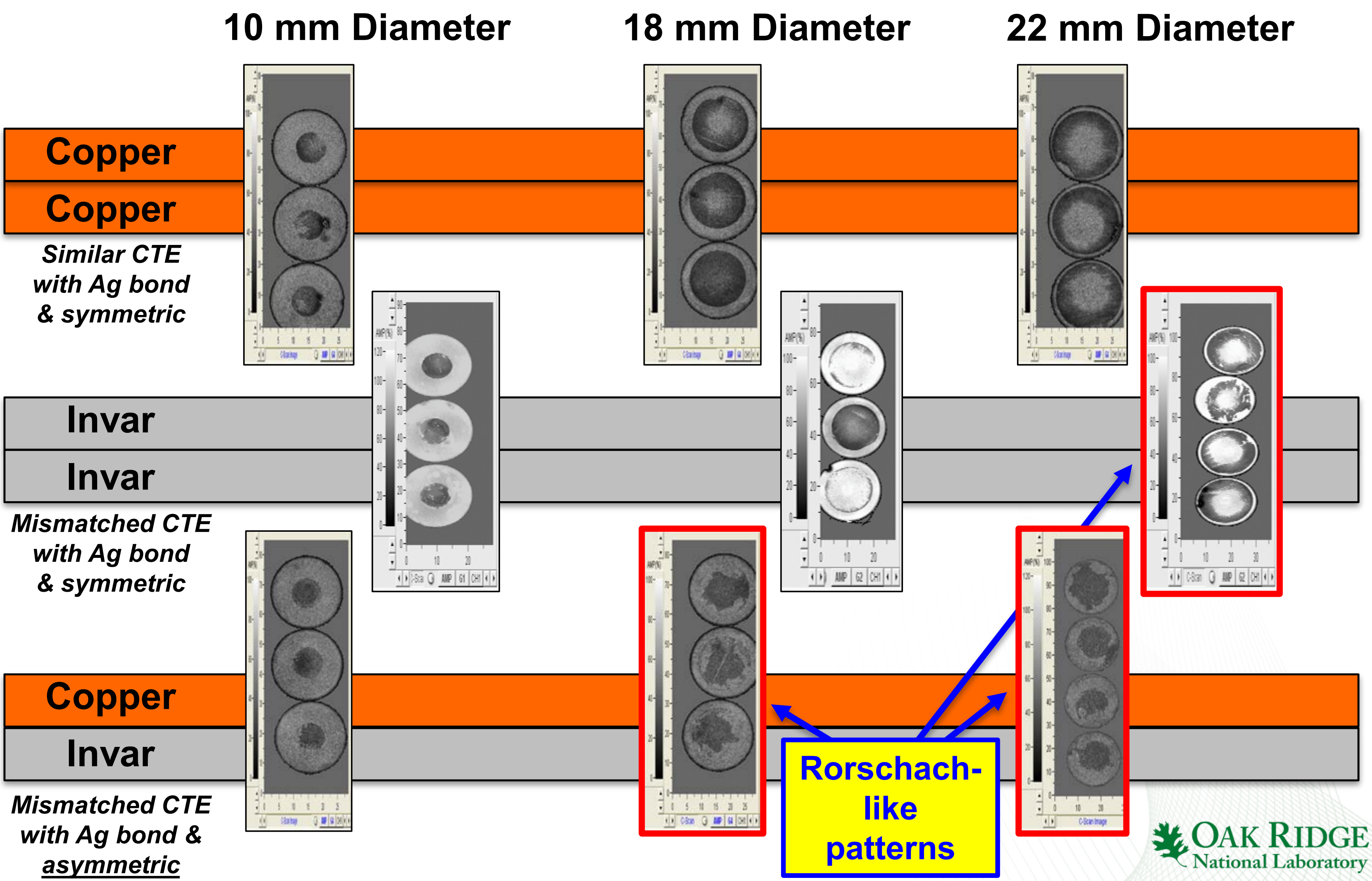
Matrix of ORNL-Fabricated Sintered Disks ("Oreo-Like Cookies")

10 mm Diameter Pad			18 mm Diameter Pad			22 mm Diameter Pad		
Cu-Cu	Cu-Inv	Inv-Inv	Cu-Cu	Cu-Inv	Inv-Inv	Cu-Cu	Cu-Inv	Inv-Inv



Technical Accomplishments (6 of 8)

Scanning Acoustic Microscopy Images Showed Delamination Onset



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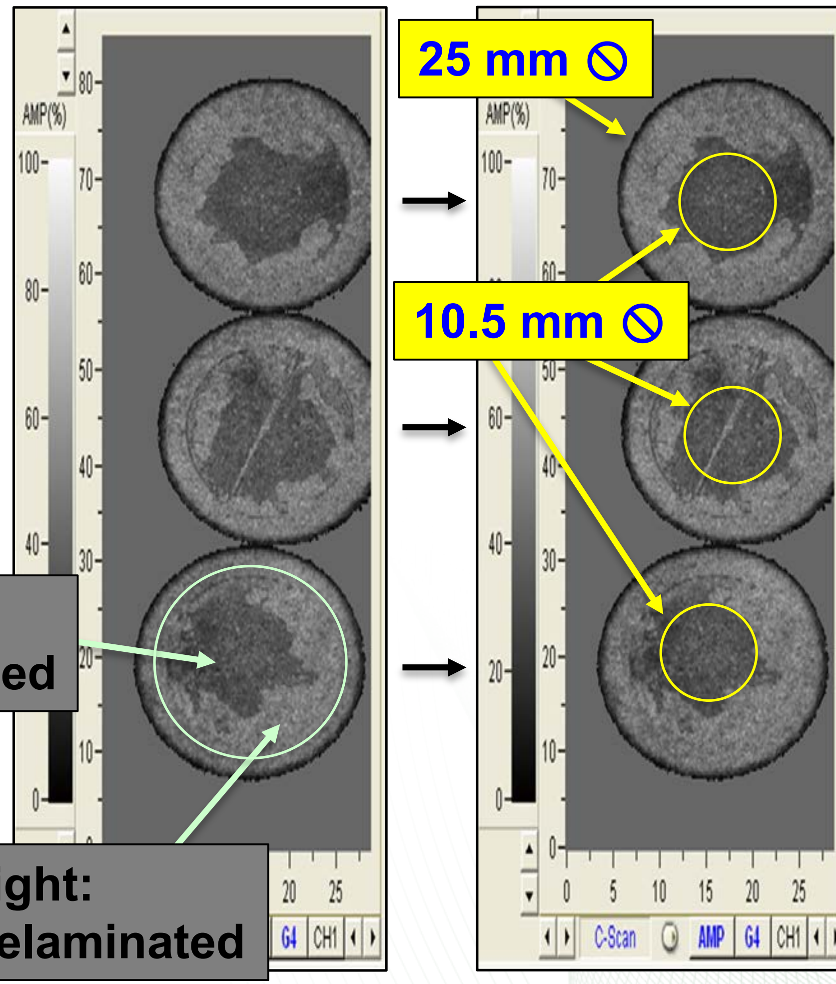
Technical Accomplishments (7 of 8)

Important: Maximum Allowable Bonding Size Is Estimatable

- **The "Rorschach-like" bond size is illustrative of the net achievable bond strength of the "system"**
- **This bond size is a convoluted function of many parameters:**
  - **Dominated by esidual stress (CTE-induced); both magnitude and orientation**
  - **Plating materials and processing**
  - **Sintered-Ag processing conditions**
  - **Ag paste cohesive strength**
  - **Adhesive strengths of all the various interlayers**
  - **Cleanliness of all the surfaces**
  - **Etc., etc., etc.**
- **Useful for small- and large-area bonding strategies for PEs**

Example: Copper-Invar 22-mm Print Diameter



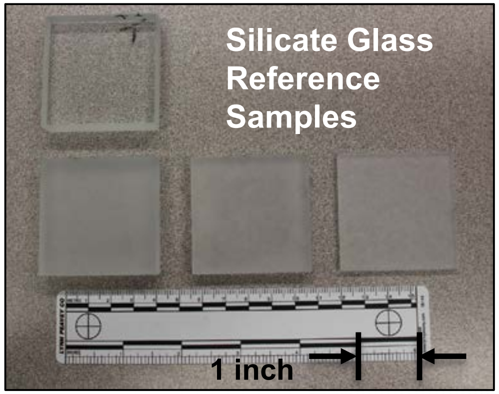
A. A. Wereszczak, S. B. Waters, D. J. DeVoto, and P. P. Paret, "Method to Determine Maximum Allowable Sinterable Silver Interconnect Size," in preparation, *Journal of Electronic Materials*, (2015).

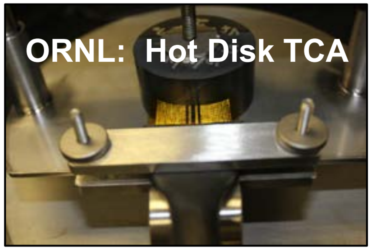
Technical Accomplishments (8 of 8)

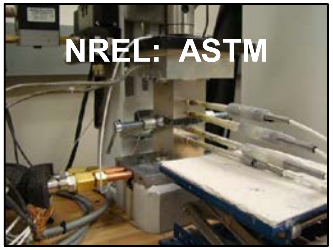
Thermal Conductivity of Electric Motor (EM) Copper Windings

- **Motivation: Improve understanding of thermal transfer in EM copper windings to ultimately improve thermal modeling and thermal performance**
- **Partner: NREL (Bennion)**
- **Approach:**
  - **Use different TC tests to capture transient and steady-state**
  - **Measure TC of reference materials: high TC (SiC) & low TC (silica glass)**
  - **Fabricate copper wound coupons for transversely isotropic TC measurement**
  - **Develop model to account for variability, # of wires per volume, wire- packing and -geometry and varnish characteristics**

Sato, *et al.*, SAE International, 2011-01-0350







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Responses to Previous Year Reviewer Comments

Reviewer 3:

The reviewer stated that cost was the first barrier identified
but it was never addressed in the presentation, which seemed like the approach was hitting all other metrics. Cost may have been competitive in a life-cycle approach or performance benefit, but it was never addressed in the presentation.

Question 2: Technical accomplishments and progress toward overall project and DOE goals – the degree to which progress has been made, measured against performance indicators and demonstrated progress toward DOE goals.

Reviewer 1:

The reviewer indicated that the project team had made impressive accomplishments to date with limited funding. Other, lower-cost sintering options were not considered but the reviewer understood that this was because of the limited funding received.

Comments about "cost" the only issue:

PI response: Cost minimization is inherently sought by working with established manufacturers who are already suppliers to the automotive industry and already employ mass production with cost minimization in mind; the PI (who is from a DOE laboratory and not from industry) believes it best to entrust those manufacturers with cost minimization as they are experienced with seeking that and know what is legitimately possible to achieve it.

Collaborations / Interactions

- **Indium Corporation, Heraeus, and Henkel: Established manufacturers of electronic interconnect materials including sinterable silvers**
- **General Metal Finishing: Plater**
- **Interface Solutions/Stratasys: Composite fabricator and additive manufacturer**
- **DuPont and Martin Marietta: Manufacturers of high-temperature-capable polymers and MgO**
- **SolEpoxy and Lord Corporation: Established manufacturers of encapsulant materials**
- **National Renewable Energy Laboratory (NREL): Reliability testing and analysis of interconnects (Devoto and Paret) and materials for electric motors (Bennion)**

Proposed Future Work

- Submit journal article on simple method to determine allowable size of a sintered-Ag interconnect "system"
- Process reduced-sized sintered-Ag pad and quantify shear strengths for Au- and Ag-plated test coupons; submit article
- For FY16
  - Complete sintered silver process evaluations; submit results and interpretations to the open literature
  - Complete supportive thermal measurements and modeling of thermal transfer in electric motor constituents; submit results and interpretation to the open literature
- Overall sought outcome by project's end
  - Industry utilizing our developed/refined materials, methods, results, and interpretations
    - Manufacturers and end-users of sinterable paste and encapsulants
    - Manufacturers and end-users of copper winding
  - Disseminate our cross-cutting work to the open literature

Remaining Challenges and Barriers

- Will good shear strength manifest itself into good thermal cycling reliability too?
- Can a classical fatigue criterion enable designs of sintered-Ag bond shapes and sizes so delamination does not occur (i.e., is the applied stress intensity, K, always less than some critical threshold stress intensity, Ko)?
- Can the thermal interfacial losses be overcome in electric motors to improve the overall thermal transfer characteristics?

Summary

- Relevance:
  - Addresses need for higher-temperature-capable materials, new packaging technologies, improved thermal transfer in electric motors, and reliability and efficiency
  - Addresses major materials needs for the EV/HEV sectors
- Approach/Strategy: 200° C-capable interconnects and dielectrics for power electronics and strategies to improve thermal management of electric motors
- Accomplishments: New materials, patent applications and invention disclosures, and published articles
- Collaborations: Industry - suppliers and end-users
- Proposed Future Work:
  - Complete sintered silver process evaluations
  - Complete supportive thermal measurements and modeling of thermal transfer in electric motor constituents