Enabling Materials for High Temperature Electronics

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Overview

Timeline

- Started Q4-FY13
- Completion FY16
- 23% Complete

Budget

- Total project funding
  - 100% DOE
  - 50/50: DOE OVT Propulsion Materials Program + DOE OVT Advanced Power Electronics and Electric Motor Program
- FY13: $50k
- FY14: $170k

Barriers*

1. Enabling materials needed for wide bandgap (WBG) exploitation
2. Reliability and lifetime of power electronic modules (PEMs) degrade rapidly with increased temperature#
3. PEMs need improved thermal management# for higher temps
4. New cooling paradigms# would enable higher PEM power densities without compromise to reliability

Partners/Collaborations

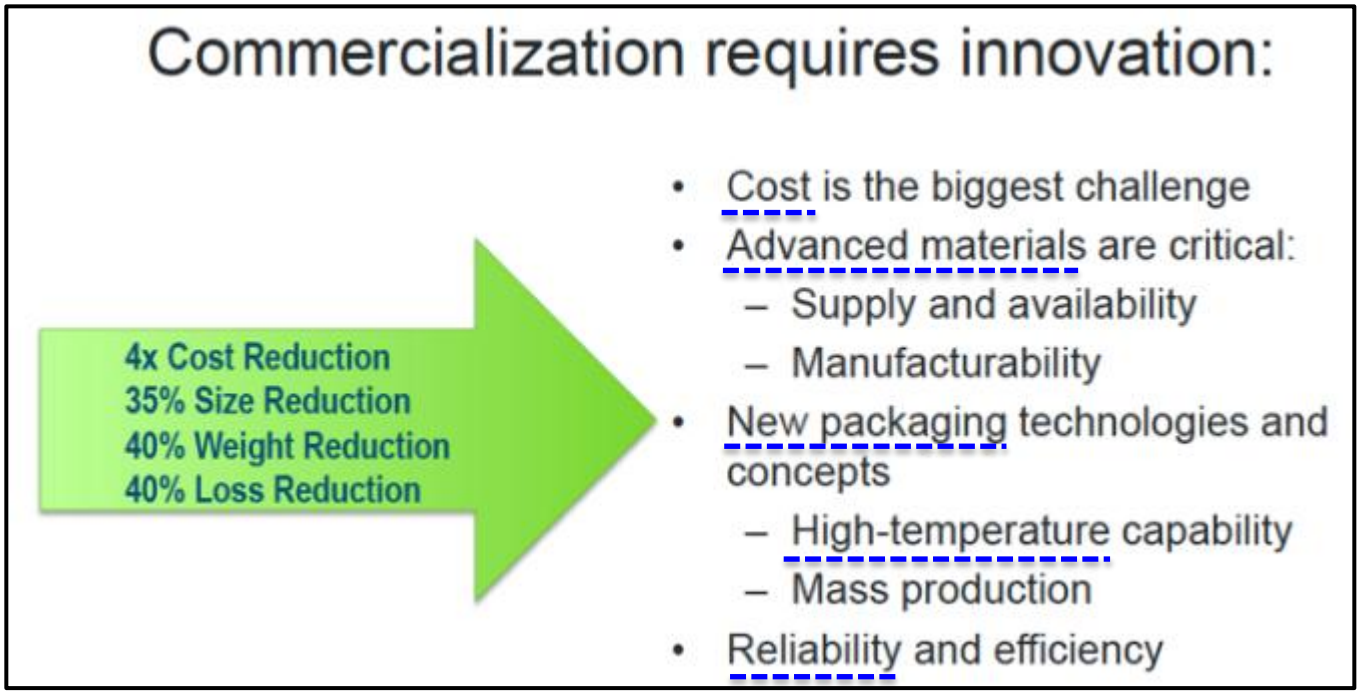
- Indium Corporation
- Heraeus and Henkel
- General Metal Finishing
- Interface Solutions, DuPont, and Martin Marietta
- NREL

* OVT Multi-Year Program Plan 2011-2015

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

Relevance/Objectives

President Obama announced EV Everywhere Challenge on 07 March 2012; produce affordable and convenient electric vehicles for the average family by 2022



This Project Directly or Indirectly Addresses All of These Barriers

Source: S. Rogers, "APEEM Overview and Meeting Expectations," APEEM FY14 Kickoff Meeting, Oak Ridge, TN, 05 Nov 2013.

Milestones

FY13-Q4. **New start. Defined FY14 test matrix for sintered-Ag interconnect and identified 200°C-capable polymer dielectric. [Achieved]**

FY14-Q1. **Demonstrate efficacy of bonding WBG die to copper-cladded substrate using silver sintering interconnection. *[Achieved]***

FY14-Q2. **Measure thermal properties of high-temperature-capable perfluoropolymers for PEM use. *[On track]***

FY14-Q3. **Compare shear strength of Ag- and Au-plating on DBC substrates. *[On track]***

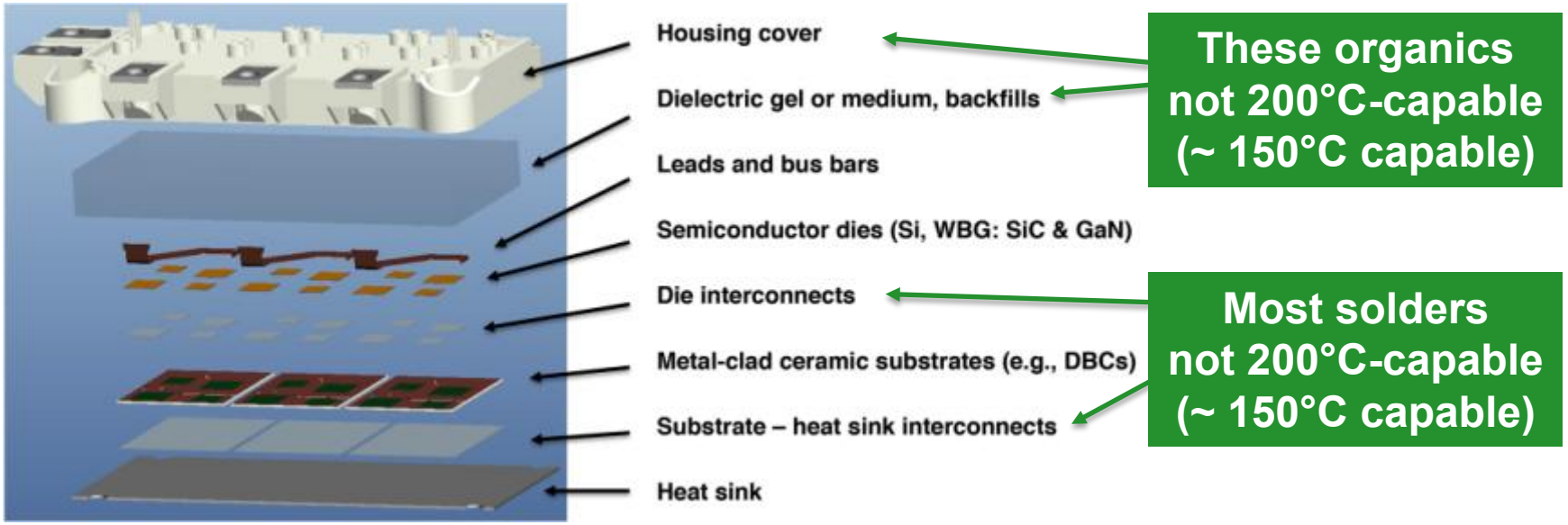
FY14-Q4. **Submit article to conference on silver sintering. *[Achieved – paper submitted to IMAPS HiTEC 2014]***

Technical Approach (1 of 2):
Address High-Temperature Incapability

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 at 200°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***
- ***Approach: use innovative materials science AND engineering***

Technical Approach (2 of 2):
Two Parallel Efforts

200°C-Capable Interconnects (Sintered-Ag)

- Plate Substrates With Ag or Au
- Bond with Sintered-Silver and Other High-Temp-Capable Interconnects
- Measure Shear Strengths
- Compare and Interpret Results
- Make Recommendations and Disseminate Them

200°C-Capable Organic Dielectrics

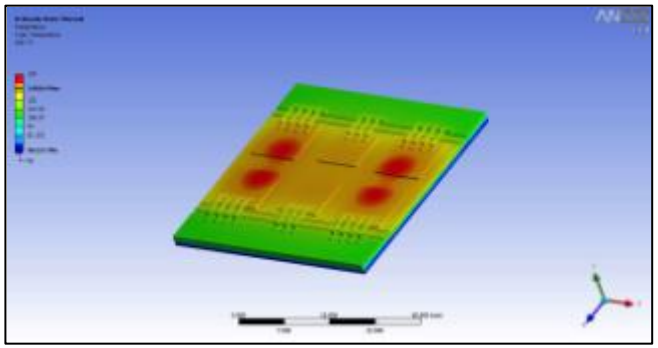
- Process MgO-Filled Perfluoropolymer with Different Vf%
- Harvest Test Coupons For Property Measurements
- Measure ρ, E, ν, CTE, Tg, λ, Cp, and κ
- Compare and Interpret Results
- Make Recommendations and Disseminate Them

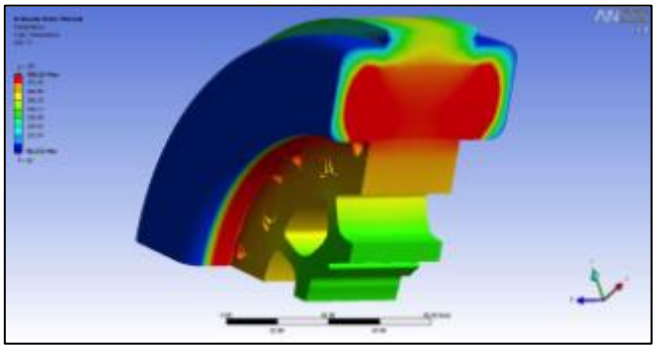
Technical Accomplishments (1 of 6)

Overview of FY14's Accomplishments So Far:

- **Successfully sintered-Ag-bonded SiC (WBG) die to substrates**
- **Determining the mechanical strength of sintered-Ag bonds as a function of several parameters**
- **Assessing the mechanical reliability of sintered-Ag bonds**
- **Establishing a method to process 200ÁC-capable thermally-conductive dielectric and characterized its properties and microstructure.**

High Temperatures Must Be Managed in Power Electronic (left) and Electric Motor (right) Components



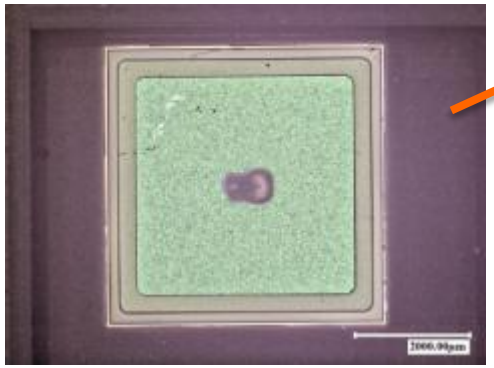


Technical Accomplishments (2 of 6)

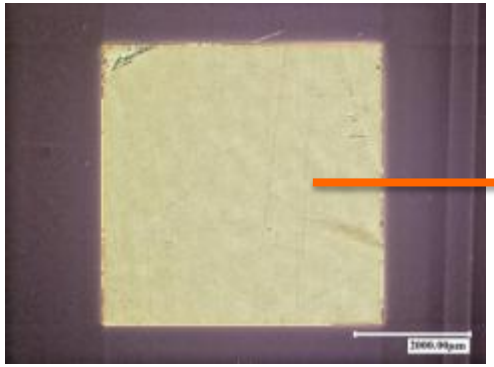
Demonstrated Efficacy of Sintered-Ag Bonding with SiC (WBG) Die

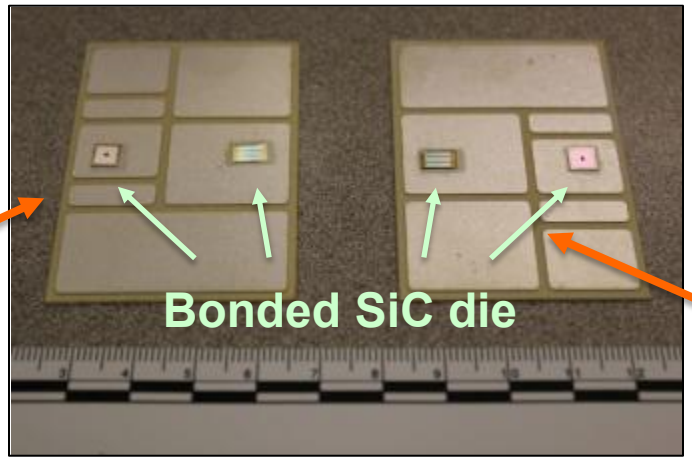
SiC Diode

Top Side

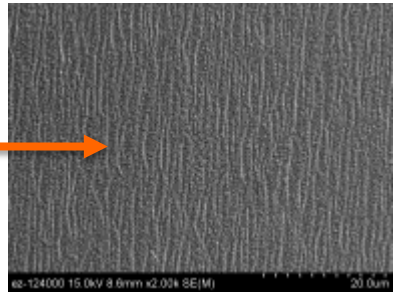


Bonding Side

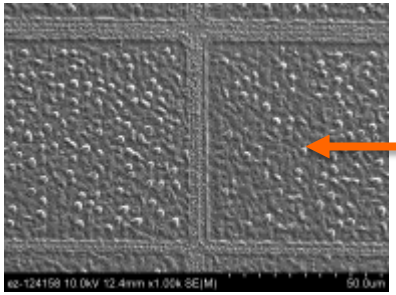




Bond-Side Microstructure

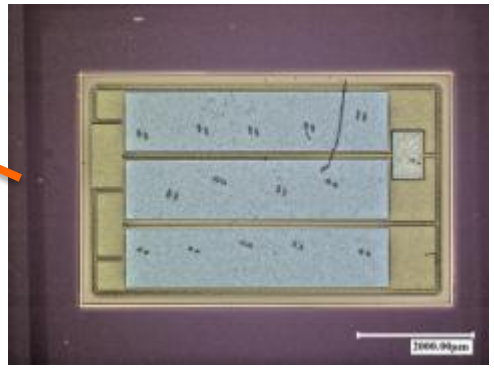


Bond-Side Microstructure

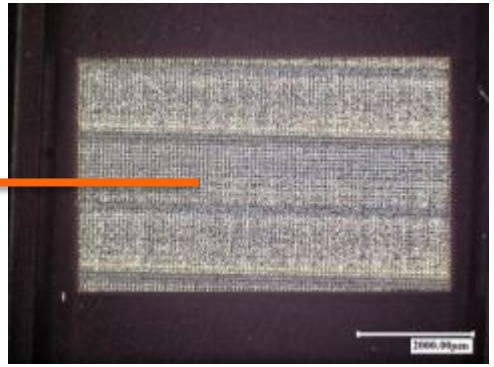


SiC MOSFET

Top Side



Bonding Side

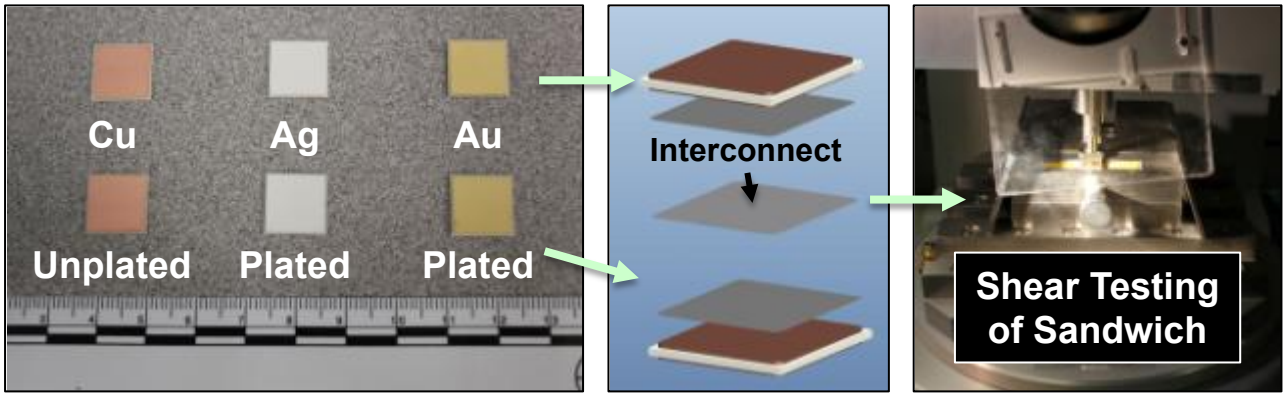


Topological Alteration on SiC Die Would Be Beneficial …

Technical Accomplishments (3 of 6)

Improved Understanding of Sintered-Ag Bonding Needed

"DBC Substrate Sandwich" Specimens for Plating and Interconnect Evaluations



- **Dependent parameter: shear strength**
- **Independent parameters:**
  - **Ag versus Au plating**
  - **Comparison of sinterable-Ag pastes**
  - **Sintering pressure**
  - **Sulfided/oxidized surfaces versus clean surfaces**

Technical Accomplishments (4 of 6)

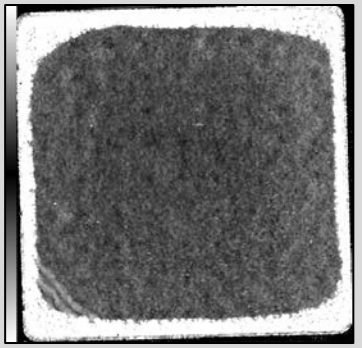
Collaboration with NREL Underway Involving Interconnect Reliability

- **D. J. DeVoto, P. P. Paret, and A. A. Wereszczak, "Stress Intensity of Delamination in a Sintered-Silver Interconnection," submitted to IMAPS HiTEC 2014.**

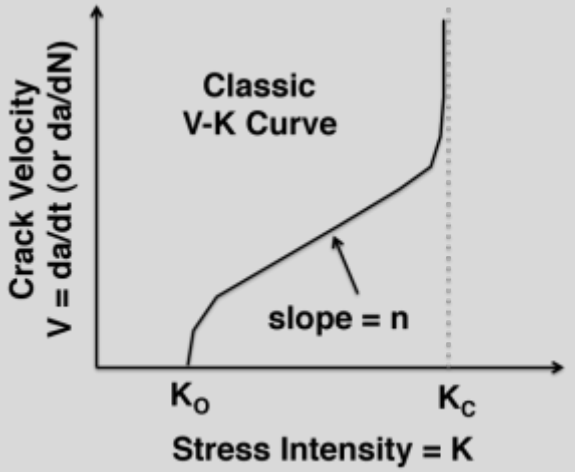
- **A. A. Wereszczak, D. J. DeVoto, and P. P. Paret, "Perimetric Structure for Improved Reliability in Electronic Device Interconnection," DOE S-Number S-124,788, Invention Disclosure Number 201303197, 13 October 2013.**

Influences this

Example of delamination ingress



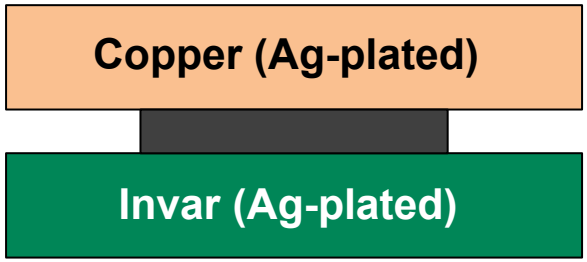
Source: DeVoto and Paret, NREL



Technical Accomplishments (5 of 6)

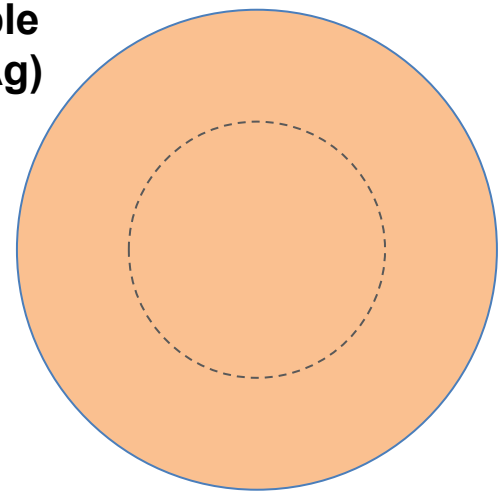
Thermal Cycling, Residual Stresses, Stress Intensities, and Delamination (NREL Collaboration)

Side View



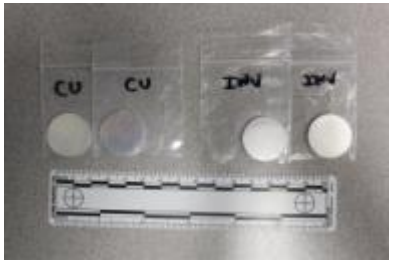
Sinterable Silver (Ag)

Top View



Pre-Plating

Post-Ag-Plating



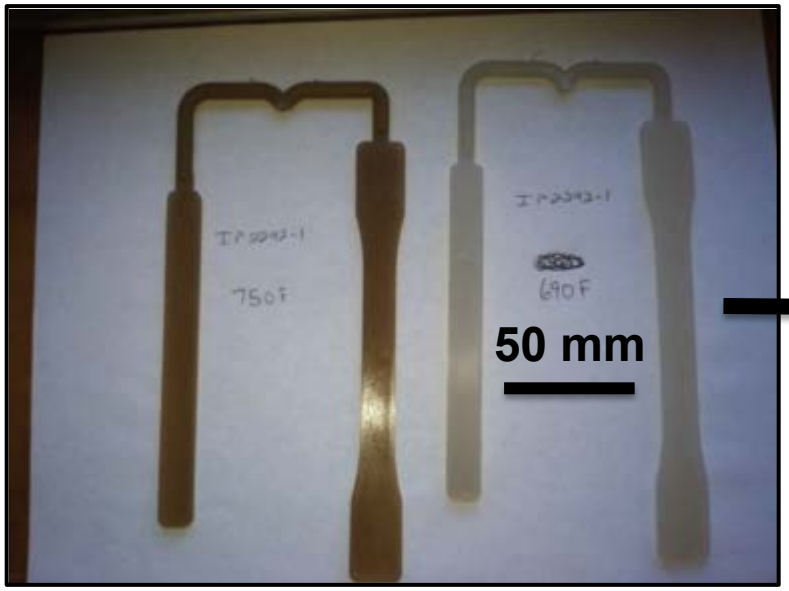
- Invar: model material used to simulate low CTE of silicon and substrates in electronic devices
- Vary diameter of bond layer
- Vary residual stress
  - Copper-copper disk pair
  - Invar-invar disk pair
  - Copper-invar disk pair
- Neutron diffraction to quantify residual stress in sintered-Ag bond layer (?)
- Thermal cycling & track delamination response

Nominal Properties:

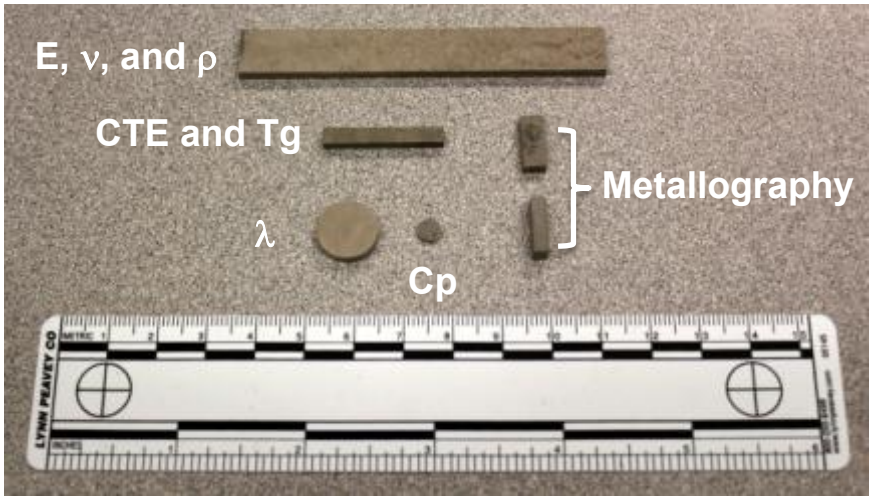
Material	CTE (ppm/°C)	E (GPa)
Copper	17	115
Sintered Ag	20	15-60
Invar	1.3 - 2.7	145

Technical Accomplishments (6 of 6)

MgO-Filled (High-Temperature) Perfluoropolymer



Harvested Test Coupons



IP2292		% by weight in formulation		
Sample #	Description	RS1174-OR1 Dupont ECA 3000	CH1302-OR1 MgO	CH972 vinyltrimethoxy silane
IP2292-1	Control	100	0	
IP2292-2	60% MgO by weight	40	60	
IP2292-3	90% of 60% MgO by weight	46	54	
IP2292-4	80% of 60% MgO by weight	52	48	
IP2292-5	60% MgO by weight plus silane	39.5	60	0.5
IP2292-6	90% of 60% MgO by weight plus silane	45.5	54	0.5
IP2292-7	80% of 60% MgO by weight plus silane	51.5	48	0.5

Responses to Previous Year Reviewer Comments

Project not reviewed last year

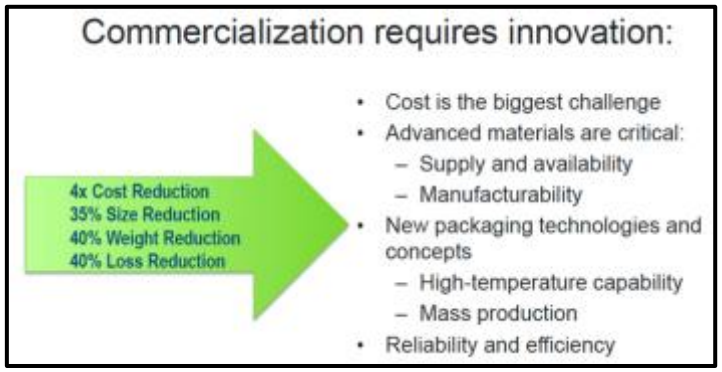
(Because it started in FY13 – Q4)

Collaborations / Interactions

- **Indium Corporation: Established manufacturer of electronic interconnect materials**
- **Interface Solutions: Composite fabricator**
- **DuPont and Martin Marietta: Manufacturers of high-temp-capable polymers and MgO, respectively**
- **National Renewable Energy Laboratory: Collaboration involving reliability testing and analysis of interconnects**
- **Heraeus and Henkel: Manufacturers of sinterable-silvers**
- **General Metal Finishing: Plater**

Proposed Future Work

- **Complete characterization of 200°C-capable dielectric**
- **Complete evaluation of effects of plating material on strength of 200°C-capable sintered-Ag interconnect**
- **For FY15**
  - **Thermal cycling of high-temp bonded interfaces (with NREL)**
  - **Develop performance predictive model (with NREL)**
- **Future concepts beyond FY15**
  - **200°C-capable thermal interface materials**
  - **Improved ferrite ceramics (for inductors); improve power density and loss characteristics through improved or refined microstructural ceramic engineering**



Source: S. Rogers, "APEEM Overview and Meeting Expectations," APEEM FY14 Kickoff Meeting, Oak Ridge, TN, 05 Nov 2013.

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., so K < Ko)?**
- **In future years:**
  - **Can 200°C-capable, thermally-conductive dielectric materials be transitioned into thermal interface materials?**
  - **Can improved and refined ceramic microstructural engineering be inexpensively employed with ferrite ceramics so to improve their loss and power density characteristics?**

Summary

- **Relevance:**
  - Addresses cost, need for higher-temperature-capable materials, new packaging technologies, and reliability and efficiency
  - Addresses major materials needs for the EV/HV sectors
- **Approach/Strategy**: 200°C-capable interconnects and dielectrics for power electronics
- **Accomplishments:** New materials, patent applications and invention disclosures, and published articles
- **Collaborations:** Industry - suppliers and end-users
- **Proposed Future Work:**
  - Develop model for interconnect design and reliability
  - Develop new thermal interface materials and improve ferrite ceramics for inductors (if new resources permit)