National Renewable Energy Laboratory
Innovation for Our Energy Future

Advanced Thermal Interface Materials (TIMs) for Power Electronics

U.S. Department of Energy
Annual Merit Review

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NREL/PR-540-45793 **APE_10**

Overview

Timeline

- Start - FY06
- Finish - FY09
- 85% Complete

Budget

- Total project funding
  - DOE - $1,375 K
- Funding received in FY08
  - $375K
- Funding received in FY09
  - $450K

Barriers

- Barriers addressed
  - Improved TIM enables use of high temperature coolant and/or air cooling
  - Availability of accurate and consistent TIM performance data
  - Enables reduction in cost, weight and volume of power electronics
- Target
  - Identify TIM with thermal resistance of 5 mm^2K/W for 100 microns bondline thickness

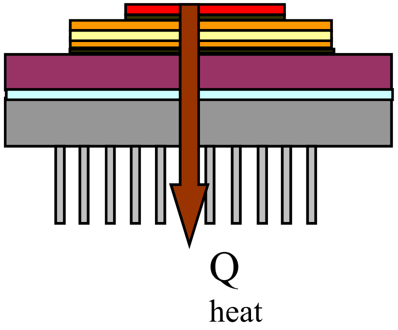
Partners

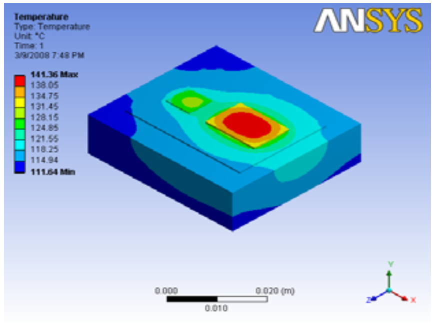
- Delphi
- Btech
- Virginia Tech
- GM

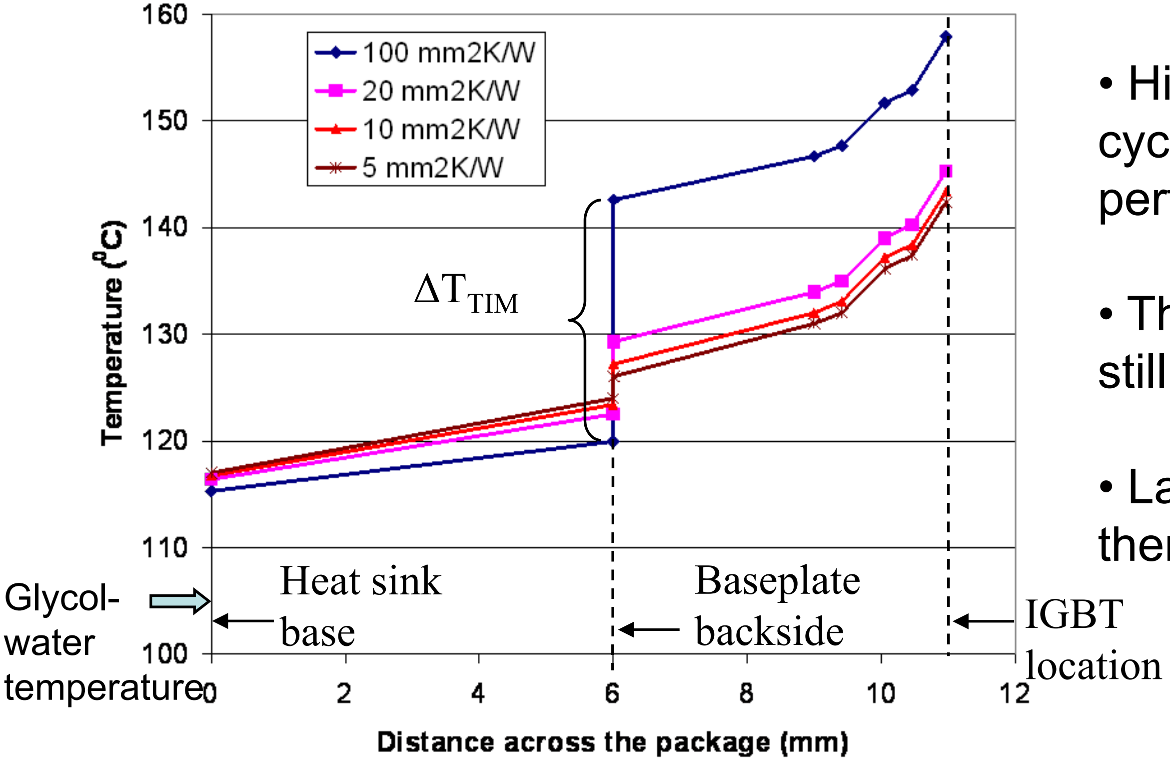
Project Relevance

- Excessive heat can degrade the performance, life, and reliability of power electronic components
- Advanced thermal control technologies are critical to enabling higher power densities and lower system cost
- Thermal interface materials pose a major bottleneck to heat removal

The Problem







- Thermal grease is the primary bottleneck to heat removal
- In-situ performance of greases may be substantially worse than material specifications
- High temperatures and thermal cycling can degrade TIM performance
- Thermal transport at interfaces is still poorly understood
- Lack of consistent and objective thermal performance data

Objectives

- To establish high-accuracy, objective and consistent database on the performance of an array of thermal interface materials
  - Assist DOE and industry partners in making technology development decisions

- Identify/develop TIM which meets the target thermal performance of 5 mm^2K/W for 100 microns bondline thickness, as well as meets the reliability and cost constraints for power electronics applications

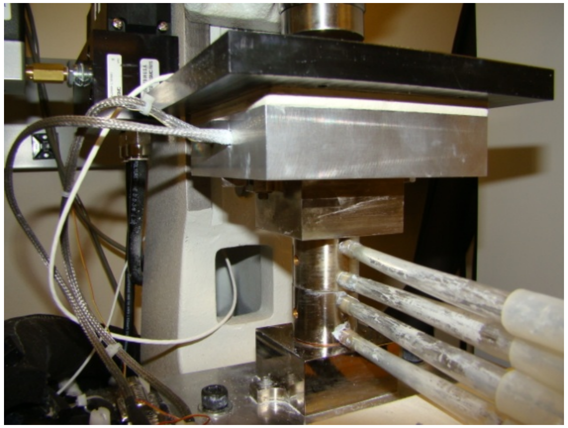
- High thermal performance, reliable and cost-effective TIM helps enable the use of high-temperature coolant and/or air cooling

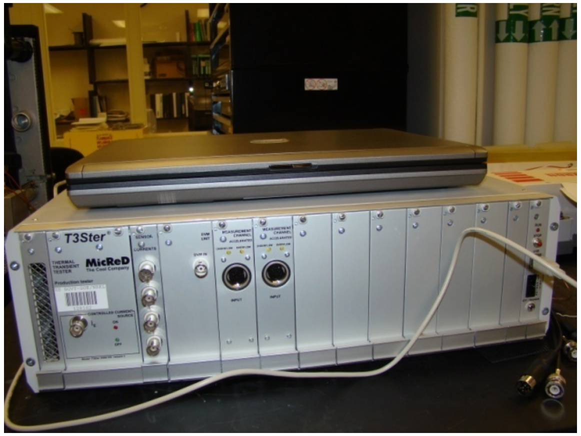
Milestones

Month/Year	Milestone or Go/No-Go Decision
November- 2008	Completed thermal resistance measurements on greases, gels and phase change materials (PCMs) via the steady-state ASTM test approach. Created an objective, consistent, high-accuracy database on the performance of these materials, and compared to target thermal performance of 5 mm^2K/W for 100 microns bondline thickness.
September 2009	Characterize thermal performance of sintered interfaces via the steady-state ASTM approach. These sintered interfaces will be based on silver nanoparticles. Characterize thermal performance of novel thermoplastics with embedded carbon fibers via the steady-state ASTM approach. All thermal results will be compared to target performance of 5 mm^2K/W for 100 microns bondline thickness.
September 2009	Establish the transient thermal resistance measurement technique, based on the structure function approach, for measuring resistance of materials mentioned above.

Approach

- Establish baseline thermal performance of commercially available materials used by the Power Electronics industry
- Work with partners to identify and develop high thermal performance, reliable TIM
- Evaluate performance using NREL's TIM apparatus for thermal resistance measurement
  - Based on the ASTM D5470 steady state method
  - Capable of thermal resistance measurements from 0°C to 130°C and over a load of up to 500 lbf (2220 N)
- Establish transient technique for in-situ characterization and reliability (thermal cycling, aging effects) study
- Modeling to understand interfacial thermal transport
- Transfer information to industry

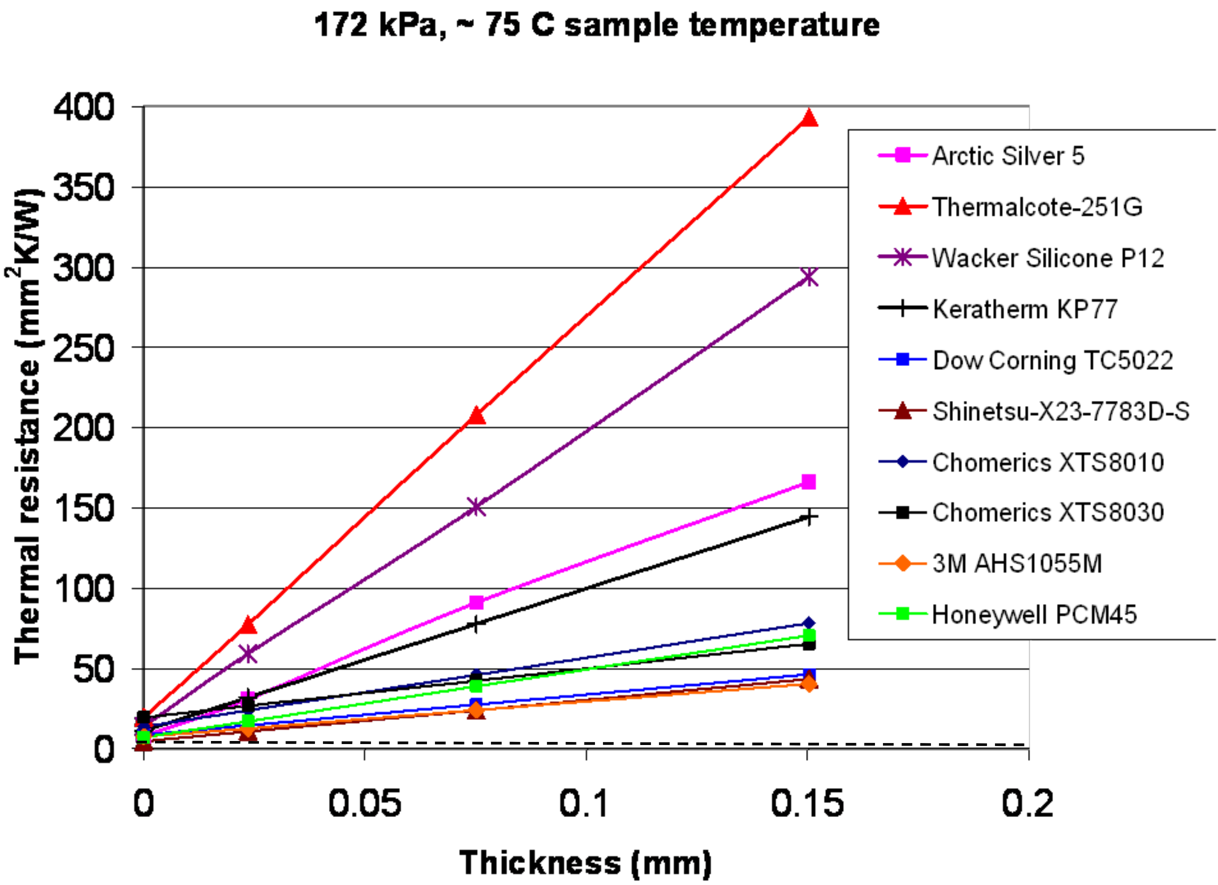




Technical Accomplishments

- Over 40 materials have been tested (steady-state ASTM method):
    - greases
    - gels
    - PCMs
    - filler pads
    - graphite
    - indium
    - thermoplastics
    - carbon nanotubes

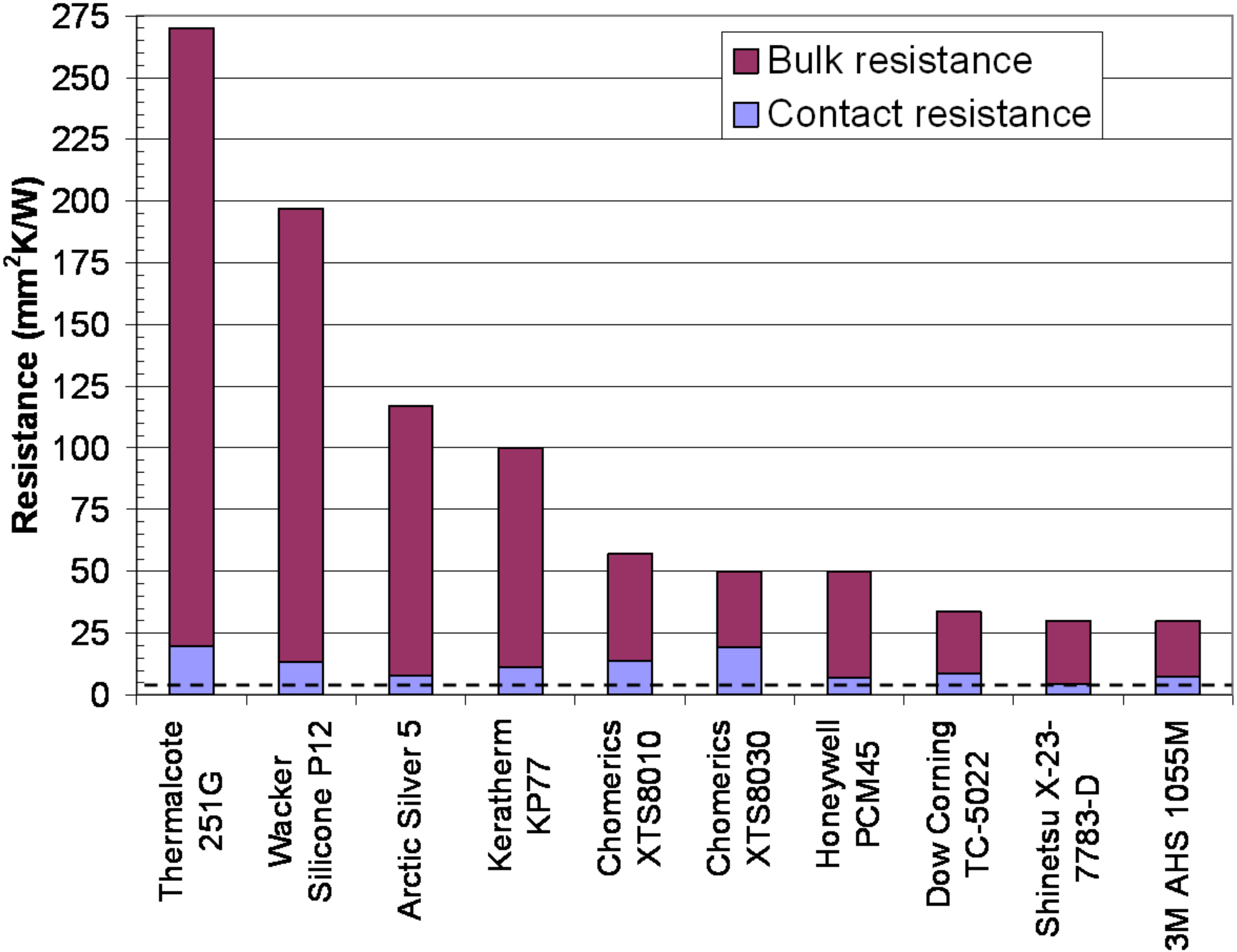
- Collaborations and information exchange:
    - Delphi
    - Ford
    - Semikron
    - UQM
    - Parker Chomerics
    - Shinetsu
    - Btech
    - NIST



- Identified materials which have potential of meeting target thermal performance

Technical Accomplishments

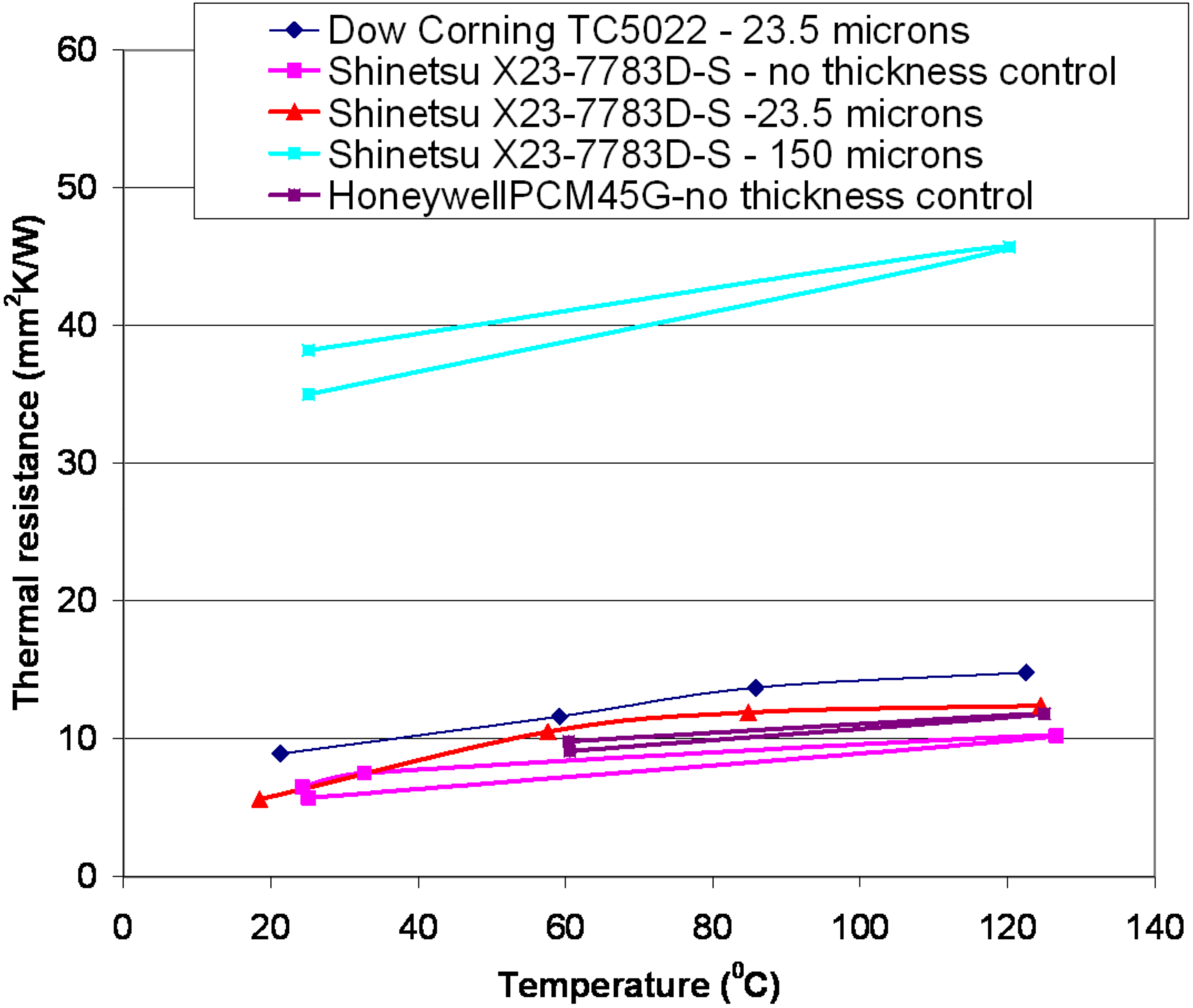
Contact and bulk resistance of various polymeric TIMs



- TIM thickness in all cases is 100 microns
- Pressure is 172 kPa (25 psi)
- Average sample temperature ~ 75 ^{0}C

Technical Accomplishments

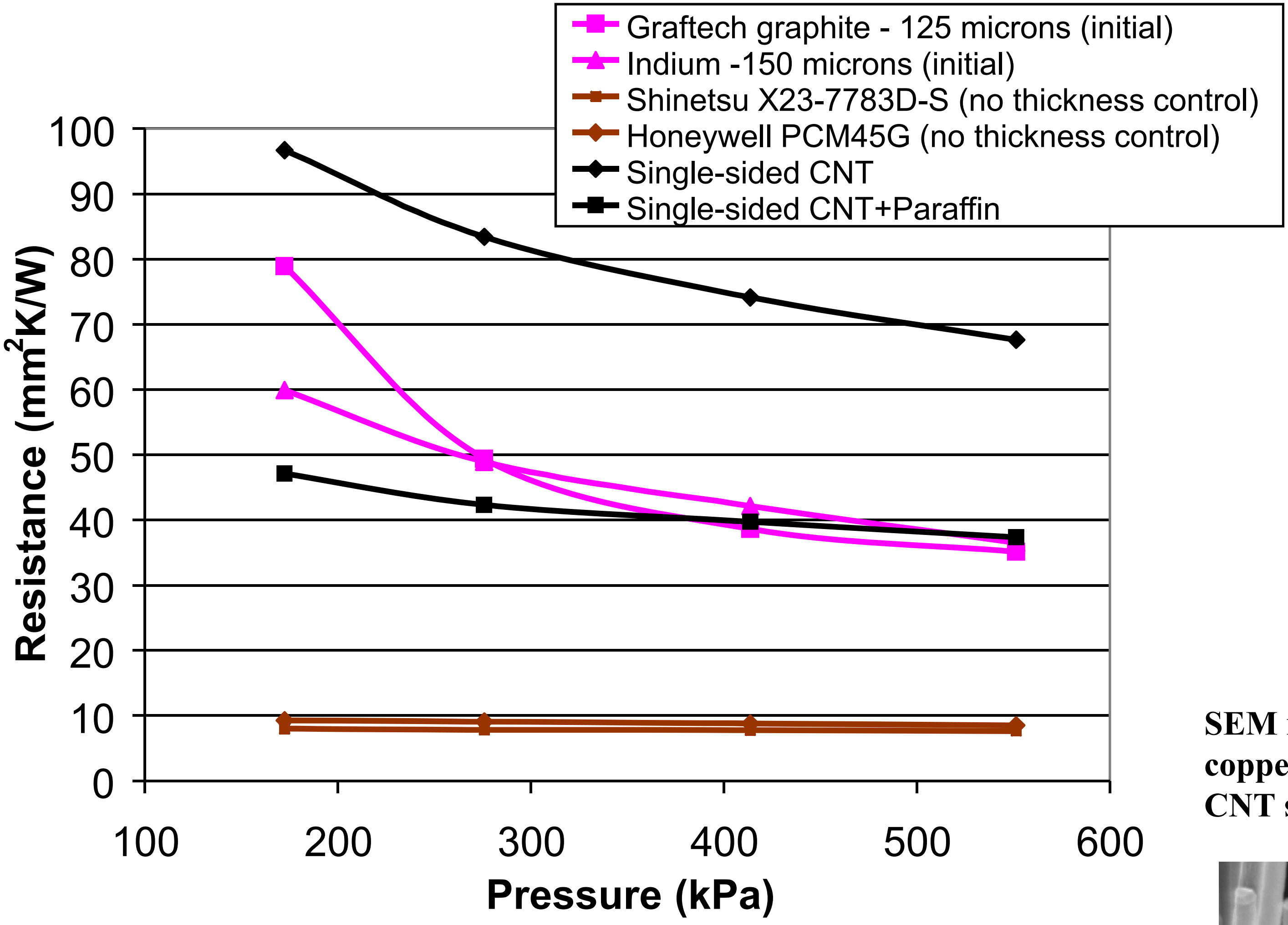
Temperature-dependence of thermal resistance of polymeric TIMs



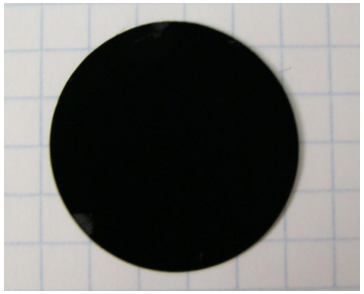
Resistance of TIM increases with increase in temperature

Technical Accomplishments

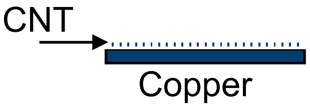
Resistance versus pressure for different TIMs

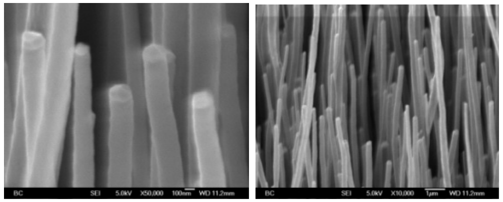


10^9 CNTs/cm², 300 nm Cr coating, 150-200 nm multiwalled CNT diameter, 40 microns height – growth via PECVD;



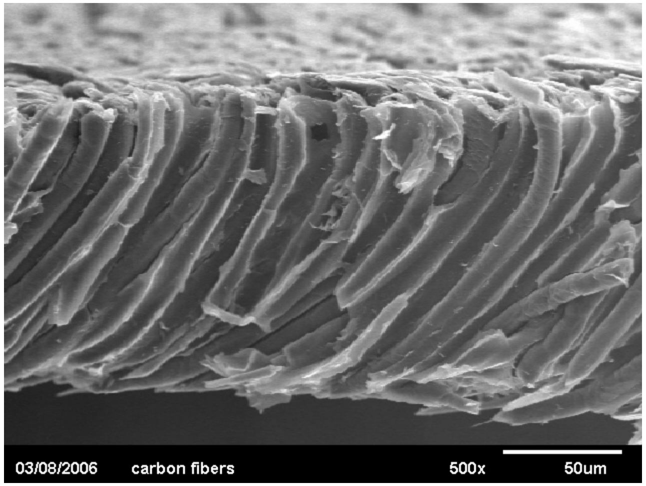
SEM images of CNT growth on a copper substrate (single-sided CNT sample)





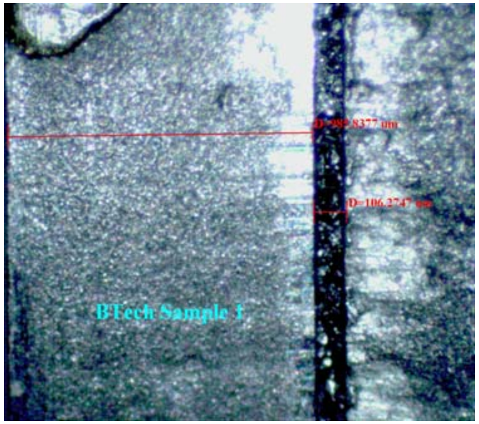
Technical Accomplishments

Thermoplastics as interface materials

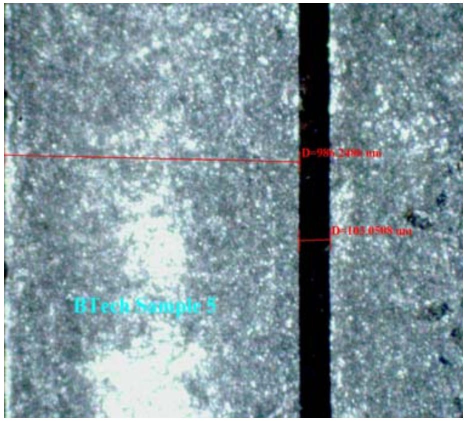


Courtesy:
Jay Browne, Btech
Carbon fibers in epoxy

Btech HM-2 Thermoplastic Thermally Conductive Adhesive, based on polyamide thermoplastic with vapor grown and pitch carbon fibers



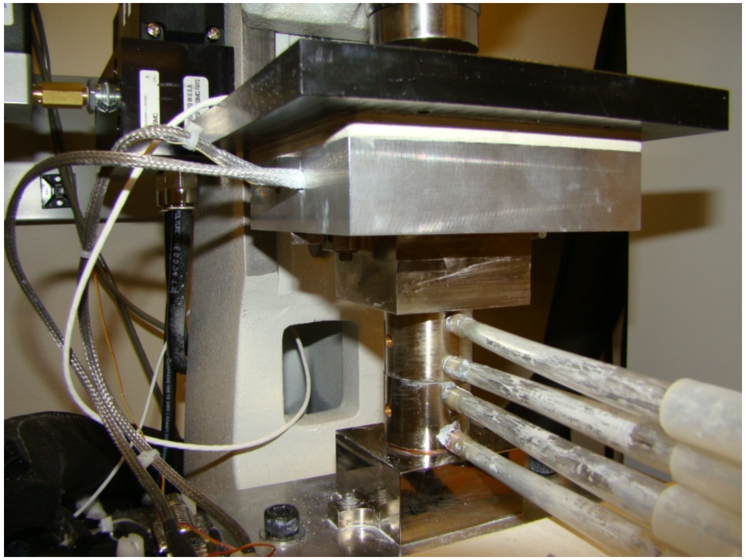
Vapor-grown carbon fibers

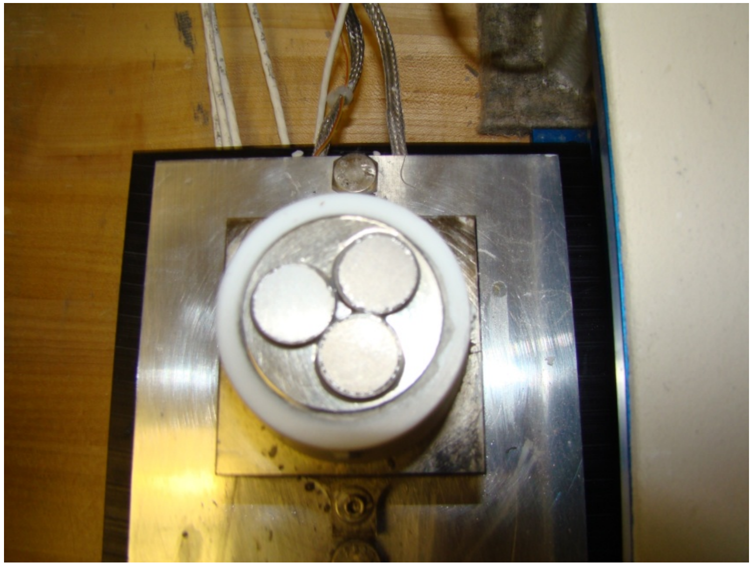


Pitch carbon fibers

Technical Accomplishments

Btech HM2 Thermoplastics approach target thermal performance

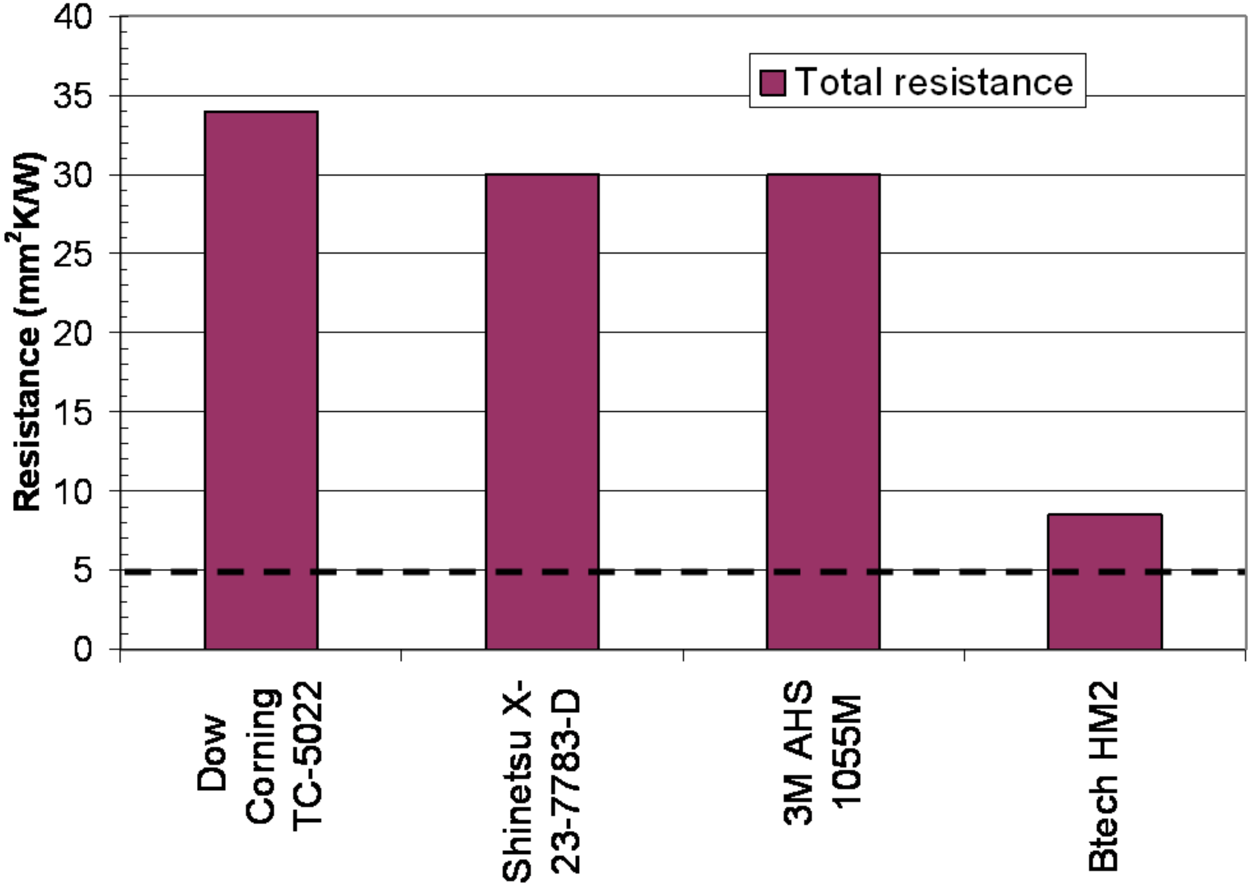




- Three samples measured together – total area of 381 mm^2 (ASTM-based steady-state approach)
- 25 micron grease layer used to interface between substrates and the metering block
- Average sample temperature ~ 64°C
- Thermoplastic resistance
  - Vapor-grown carbon fibers (70 microns thick) ~ 5 to 7 $\text{mm}^2\text{K/W}$
  - Pitch carbon fibers (70 microns thick) ~ 8 to 9 $\text{mm}^2\text{K/W}$
  - Pitch carbon fibers with metal-coating on fiber ends (100 microns thick) ~ 8 to 9 $\text{mm}^2\text{K/W}$

Technical Accomplishments

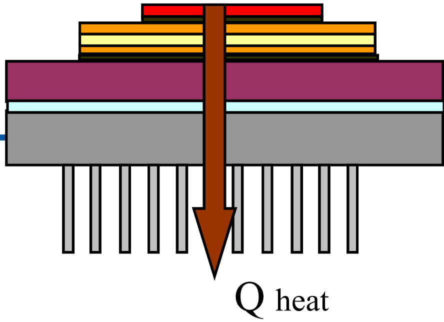
Btech HM2 Thermoplastics approach target thermal performance

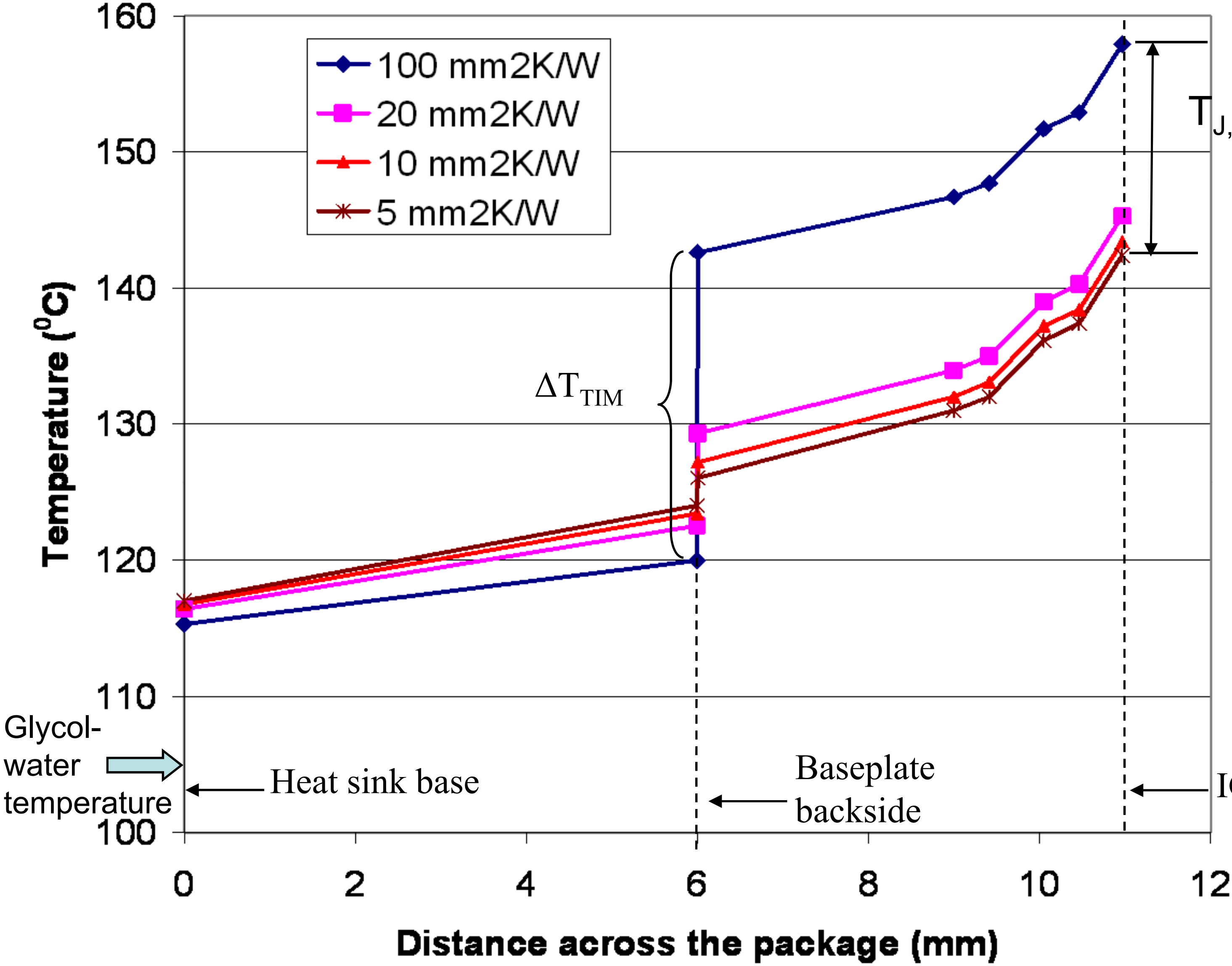


- At 100 microns thickness, Btech HM2 thermoplastic with embedded carbon fibers has a factor of 3 to 4 lower resistance than the best commercial greases

Temperature Across a Package

- *FEA analysis using Toyota package*



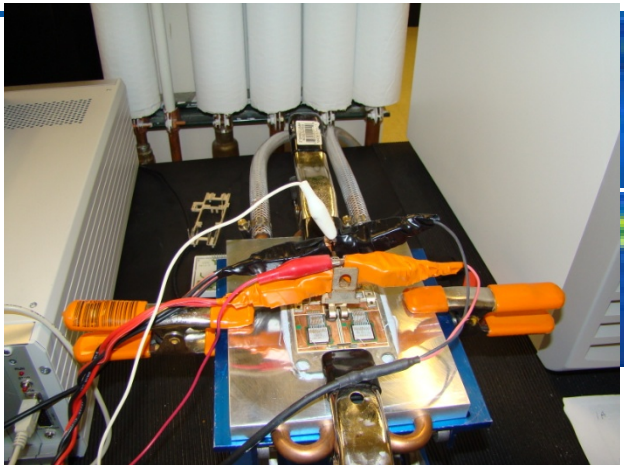


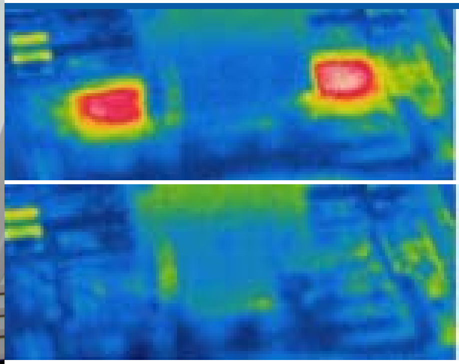
At 100 W/cm^2 heat dissipation in the die, the maximum junction temperature ($T_{J,max}$) decreases by 16°C when TIM resistance decreases from 100 to 8 mm^{2}K/W

Future Work

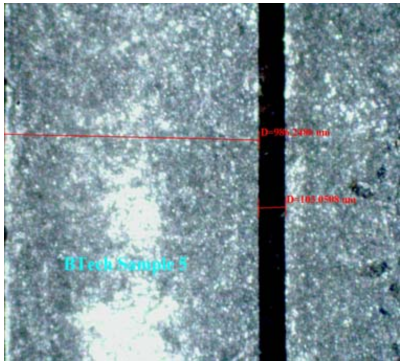
Remainder of FY09

- In-situ characterization
  - Critical to establish material performance in a more “real-world” application environment
  - Establish transient thermal technique to measure in-situ package thermal resistance





- Industry trend is towards bonded interfaces
  - Work with Btech to develop and test (via ASTM steady-state approach) improved thermoplastics meeting target thermal performance
  - In collaboration with Virginia Tech, initiate thermal resistance (ASTM steady-state) measurement of sintered interfaces (based on silver nanoparticles)



Future Work

FY10

- Transition to detailed investigation of bonded interfaces (both sintered interfaces and thermoplastics)
  - Close interaction with industry and research partners
  - Impact of substrate metallization on thermal resistance
  - In-situ characterization of bonded interfaces via the transient technique
  - Impact of thermal cycling on thermal resistance of the interfaces

- Leverage NREL internal R&D project on atomistic computations
  - Impact of interface conditions on thermal transport
  - Phonon (energy) transmission at interfaces will be computed
  - Define conditions under which thermal resistance can be minimized

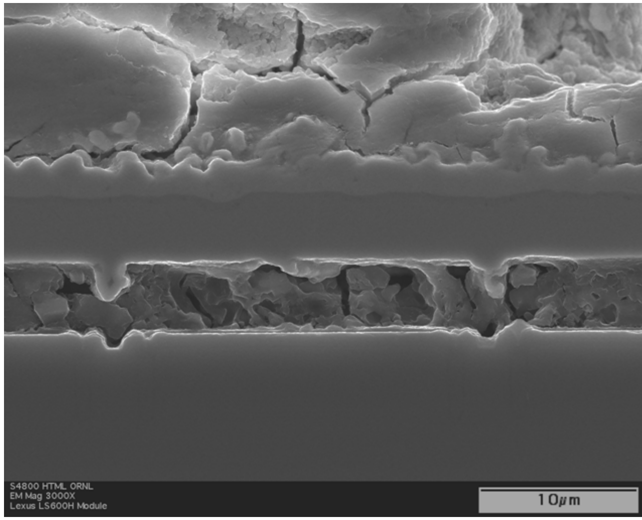


Photo Courtesy: ORNL, Tim Burress

Summary

DOE Mission Support

- TIMs are a key enabling technology for high temperature coolant and air cooling technical pathways

Approach Accomplishments Collaborations

- An extensive consistent, objective, and high-accuracy database (via the steady-state approach) on thermal performance of a number of materials has been established
  - Results transferred to industry partners (Delphi, GM, Ford, Semikron, UQM)
  - None of the measured greases, gels and PCMs yield the target performance of 5 mm^2K/W at 100 microns bondline thickness
  - Certain classes of Btech thermoplastics with embedded carbon fibers yield results approaching target thermal performance

Summary

Future work
Collaborations

- From viewpoint of both performance and reliability, there is an industry trend towards bonded interfaces
  - Very limited information on thermal resistance and reliability of these interfaces – especially in an in-situ framework
  - In conjunction with partners, we will work towards optimized bonded interfaces from the viewpoint of performance, reliability and cost

Publications and Presentations

Publications

Narumanchi, S., 2008, “Thermal interface materials for power electronics applications”, NREL technical report, MP-540-43970, September 2008.

Narumanchi, S.V.J., Mihalic, M., Kelly, K., Eesley, G., 2008, “Thermal interface materials for power electronics applications”, Proceedings of the 2008 ITherm conference, May 2008, Orlando, FL.

Narumanchi, S. V. J., 2007, “Advanced thermal interface materials for power electronics cooling applications”, NREL technical report, NREL/MR-540-36085, September 2007.

Narumanchi, S.V.J., et al., 2006, “Advanced Thermal Interface Materials to Reduce Thermal Resistance”, NREL Technical/Milestone Report, NREL Report No. TP-540-40617, September 2006.

Presentations

Narumanchi, S., 2009, “Advanced thermal interface materials for power electronics”, Presentation to the Electrical and Electronics Technical Team, Southfield, MI, January 2009.

Narumanchi, S., 2008, “Advanced thermal interface materials for power electronics”, DOE VTP APEEM Projects FY09 Kickoff Meeting, Knoxville, TN, November 2008.

Narumanchi, S., 2007, “Advanced thermal interface materials for power electronics”, DOE FreedomCAR APEEM FY08 Kickoff Meeting, Knoxville, TN, November 2007.

Narumanchi, S., 2006, “Advanced thermal interface materials to reduce thermal resistance”, 2006 DOE FreedomCAR APEEM Annual Review, Oak Ridge, TN, August 2006.

Narumanchi, S., 2006, “Advanced thermal interface materials for power electronics”, Presentation to the Electrical and Electronics Technical Team, Southfield, MI, November 2006.

Critical Assumptions and Issues

- The results presented to date have been obtained under controlled conditions (pressure, temperature) with the materials spread over a small area (7.9 cm^2). Larger area package in-situ performance can be different from material performance obtained under controlled conditions over smaller areas. Hence, we will characterize performance of promising materials such as thermoplastics and sintered materials in an in-situ framework in FY10.

- A number of materials have promising initial performance, but the biggest problem with TIMs is reliability. We will address the issue of reliability in FY10.

- Thermoplastics with embedded carbon fibers have the potential to meet the TIM targets. However, industry acceptance depends on the cost of the TIM and integration into power module processing steps. To address this, we plan to work closely with industry to understand process integration of the TIM in the remainder of FY09 and FY10.