National Renewable Energy Laboratory
Innovation for Our Energy Future

Thermal Performance and Reliability of Bonded Interfaces

U.S. Department of Energy
Annual Merit Review

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APE028

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Overview

Timeline

- Start – FY10
- Finish – FY12
- 10% Complete

Budget

- Total project funding to date
  - DOE - $400K.
- Funding received in FY10
  - $400K.

Barriers

- Barriers addressed
  - Interfaces with improved thermal performance and reliability enables use of high temperature coolant and/or air cooling,
  - Enables reduction in cost, weight and volume of power electronics.
- Target
  - Bonded interface materials that meet thermal performance (< 5 mm^2K/W) and reliability targets (15 year life).

Partners

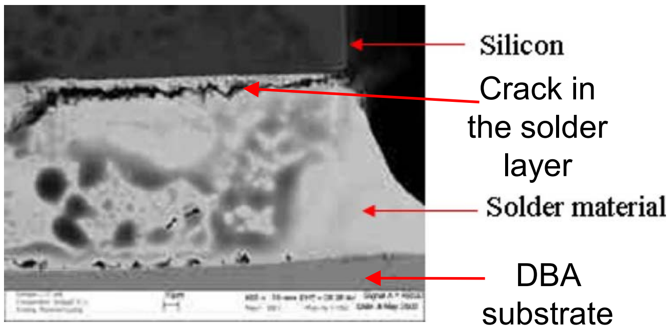
- Electrical and Electronics Technical Team.
- Delphi.
- Btech.
- Virginia Tech.
- GM.

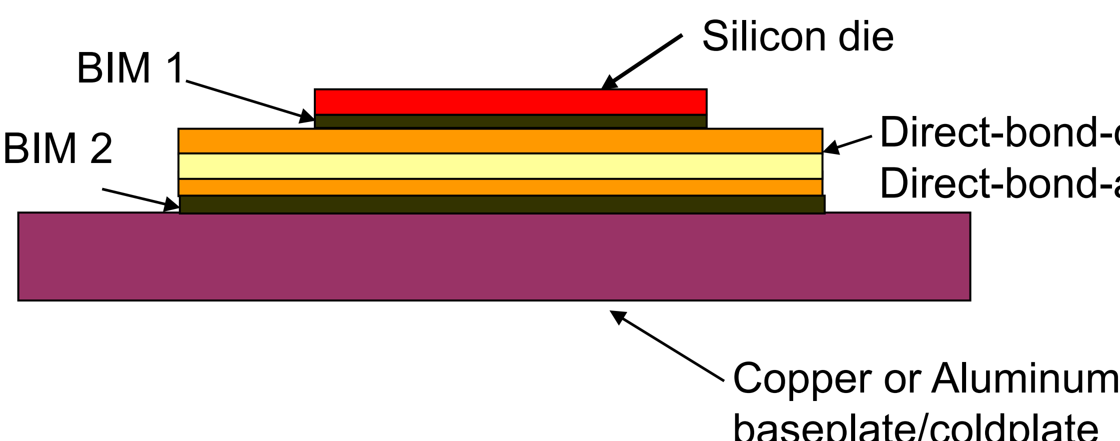
Project Relevance

- Excessive temperature 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.
- Interfaces pose a major bottleneck to heat removal.
- Bonded interface materials (BIMs) based on solder are associated with thermomechanical reliability concerns under temperature cycling, as well as degradation at higher temperatures (>120°C).

The Problem

K. Stinson-Bagby, M.S. Thesis, Virginia Tech, 2002.





- Conventional TIMs do not meet thermal performance and reliability targets.
- Due to advantages from a packaging viewpoint, industry is trending toward bonded interfaces.
- Bonded interfaces such as solder degrade at higher temperatures, and are prone to thermomechanical failure under large temperature cycling.

Objectives

- Develop/identify bonded interface material which meets the target thermal performance (< 5 mm^2K/W thermal resistance) and the reliability and cost constraints for power electronics applications.

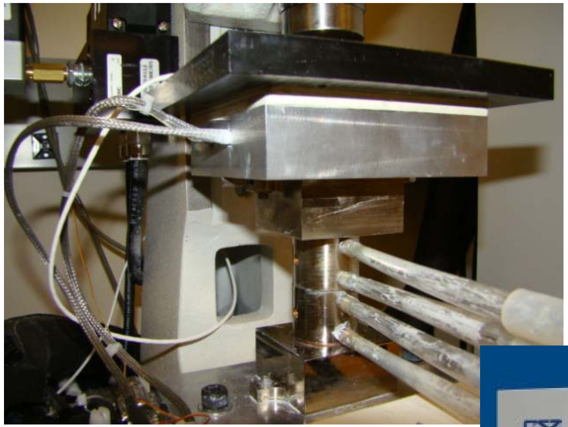
- High thermal performance, reliable and cost-effective BIM helps enable the use of high-temperature coolant and/or air cooling.

Milestones

Month/Year	Milestone or Go/No-Go Decision
December 2009	In conjunction with industry partners, established workplan for characterizing thermal performance and reliability of bonded interfaces. Plan includes investigation of thermal performance and reliability of different bonding technologies – lead-based and lead-free solder, sintering based on silver micro/nano particles, brazing, and thermoplastics with embedded carbon fibers.
April 2010	Results for thermal resistance of sintered and thermoplastic materials from the ASTM test method based on bond between 31.8 mm diameter copper coupons. Ion-implantation and metal-sputtering/evaporation techniques applied on thermoplastics with embedded carbon fibers (to improve/lower contact resistance).
September 2010	Synthesize (in collaboration with Virginia Tech, Btech) large-area bonded interface between DBA/DBC and aluminum/copper baseplate. Bonding based on lead-free and lead-based solder, sintered silver, brazed material, and thermoplastic with embedded carbon fibers. Acquire furnace and thermal shock chamber in-house at NREL. Initiate thermal shock experiments on the samples.

Approach

- Work with partners to identify and develop high thermal performance, reliable BIM
  - Collaborate with partners on synthesis (soldered, brazed, sintered joint, thermoplastic adhesive joint),
  - Initiate synthesis at NREL.
- Evaluate initial thermal performance using NREL's steady-state ASTM apparatus and transient technique for thermal resistance measurement.
- Subject bonded samples to thermal shock
  - Characterize thermal resistance after select cycles,
  - Subject samples to high-potential test,
  - Inspect quality of the joint under CSAM.
- Degradation data feed into a reliability/end-of-life model for the joint.
- Modeling to understand thermomechanical phenomena.
- Transfer information to industry.



Accomplishments

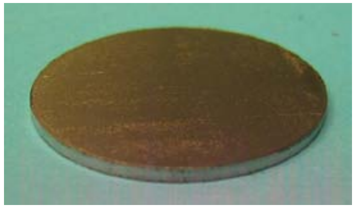
- In close collaboration with industry partners (GM, Delphi), developed plan for bonded interface synthesis, and characterization of thermal performance and reliability.

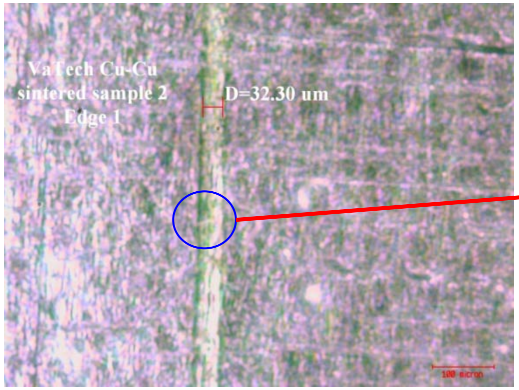
- Preliminary results on thermal resistance of sintered joint based on silver nanoparticles (in collaboration with Virginia Tech).

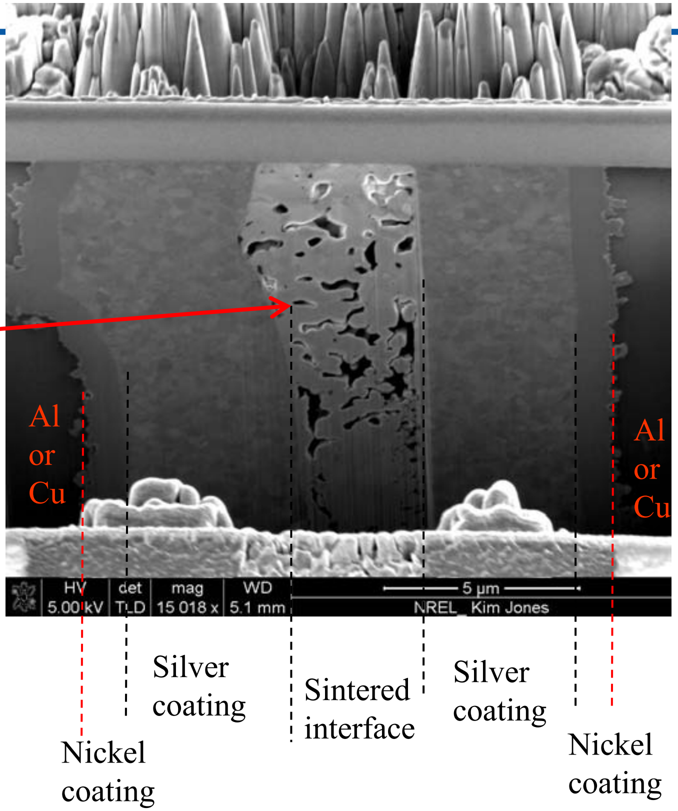
- Promising thermal resistance results for thermoplastics (collaboration with Btech and NREL materials scientists) with embedded carbon fibers
  - Thermal resistance of 8 mm^2K/W at 100 microns bondline thickness,
  - Metal-sputtering and ion-implantation techniques at NREL to reduce contact resistance further.

Accomplishments

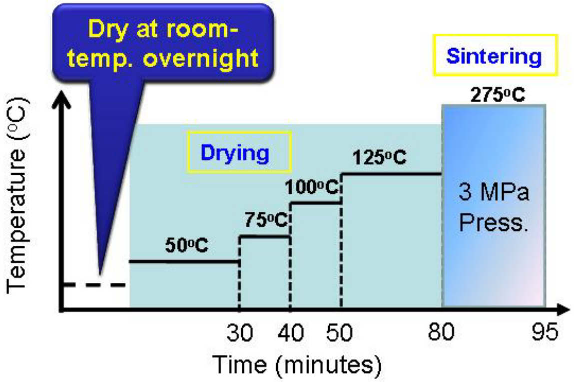
Sintered interfaces – based on silver nanoparticles







Fixture



Sintering cycle

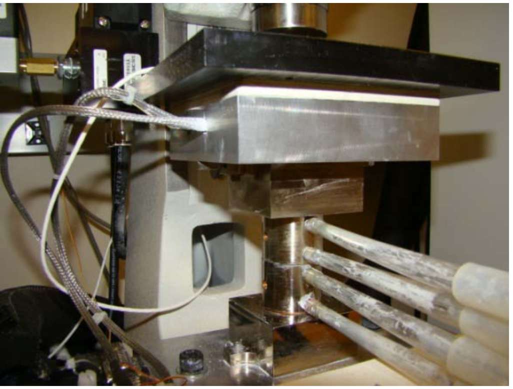
- Sintered interfaces synthesized between silvered Cu-Cu and Al-Al disks (31.8 mm diameter) at Virginia Tech.
- A nickel coating (~2 μm) followed by silver coating (~ 2 μm) is applied on the copper and aluminum disks.
- For comparison, lead-free solder (SN100C) interface synthesized between Cu-Cu disks (31.8 mm diameter).
- Different thicknesses fabricated (20 ~ 200 microns).

G.-Q. Lu, Virginia Tech

Synthesis of sintered interface

Accomplishments

Sintered interfaces – preliminary experimental results



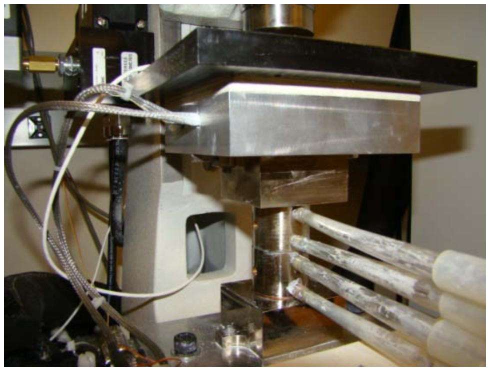
ASTM test fixture

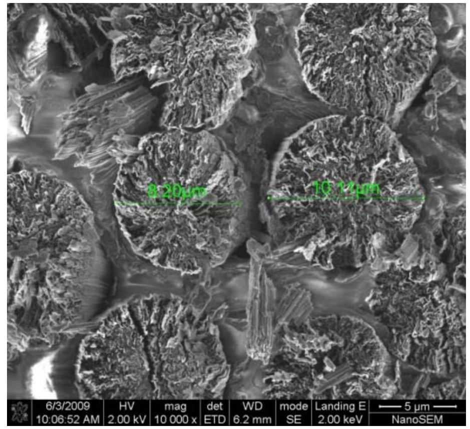
Samples	Thickness (µm)	Resistance (mm^2K/W)
Silvered Cu-Cu sintered interface	**20**	**5.8**
	27	**8.0**
	64	**5.4**
Silvered Al-Al sintered interface	**28**	**14.9**
	103	**25.2**
	144	**5.0**
Cu-Cu soldered interface (SN100C)	**80**	**1.0**
	150	**4.8**
	200	**3.7**

- The thermal resistance tests were performed using the NREL ASTM TIM apparatus
  - Average sample temperature ~ 65°C, pressure is 276 kPa (40 psi).
- The silvered Cu-Cu sintered interface shows promising thermal performance.
- Results hint at some problems with the bonding of the silvered Al-Al interface.
- The lead-free solder (SN100C) interface initial thermal results are very promising.

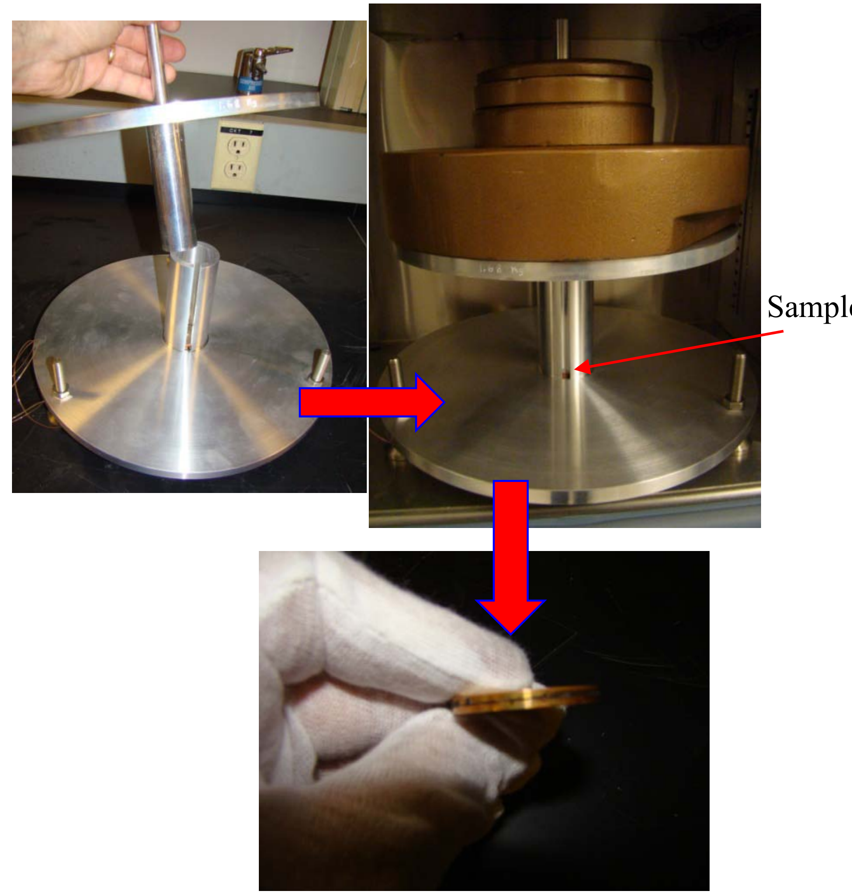
Accomplishments

Thermoplastics with embedded carbon fibers



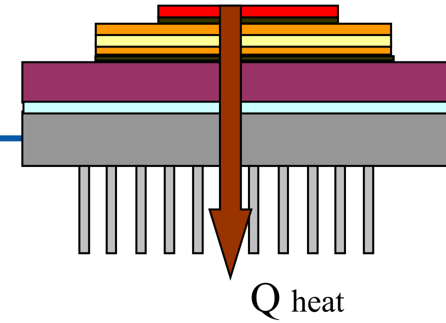


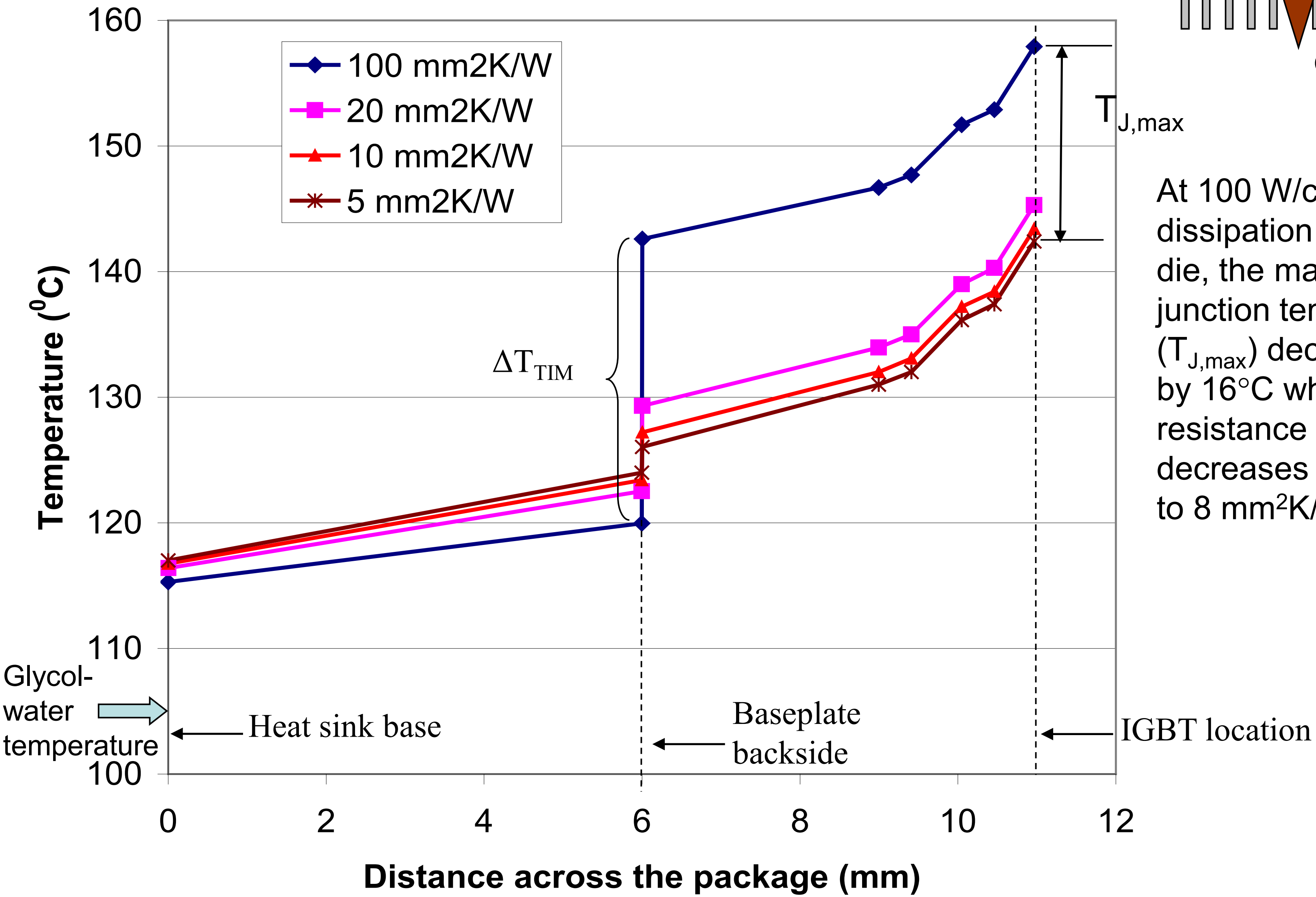
Sequence of bonding steps



- Thermoplastic films (provided by Btech) bonded between 31.8 mm diameter copper disks.
- Promising thermal results (8 mm^2K/W for 100 microns bondline thickness).
- Continuing work at NREL to further decrease contact resistance to approach target thermal performance, as well as characterize reliability.

Temperature Across a Package
- FEA analysis using Toyota package





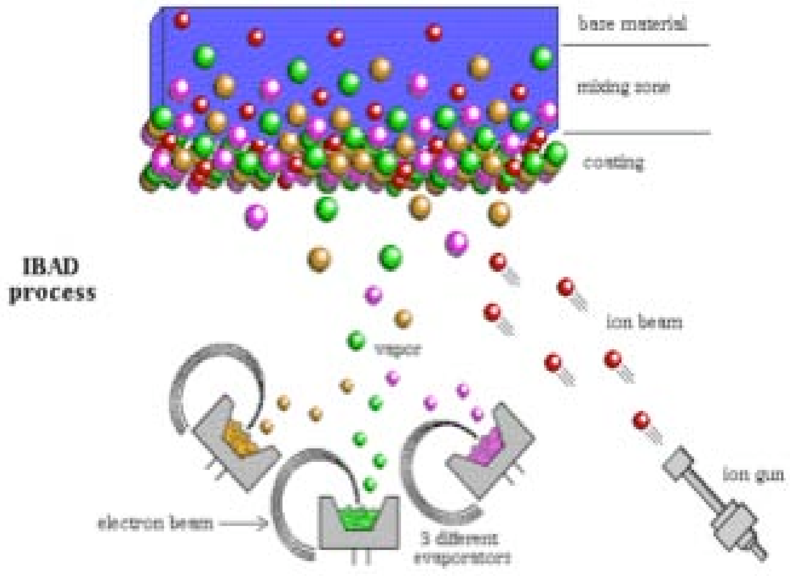
At 100 W/cm² heat dissipation in the die, the maximum junction temperature ($T_{J,max}$) decreases by 16°C when TIM resistance decreases from 100 to 8 mm²K/W.

Future Work

Remainder of FY10

- Work with Btech to develop and test (via ASTM steady-state approach) improved and reliable thermoplastics with embedded carbon fibers meeting target thermal performance
  - Reduce contact resistance via ion-implantation and metal evaporation/sputtering techniques.

- In collaboration with Virginia Tech and Btech, synthesize and characterize various joints between DBA/DBC and aluminum/copper baseplate
  - Synthesis of soldered, sintered, brazed and thermoplastic joints,
  - Subject joints to thermal shock,
  - Thermal resistance measurement after select cycles,
  - CSAM after select cycles,
  - High-potential test after select cycles,
  - Modeling of the joint thermomechanical behavior (physics-of-failure) – end-of-life predictive model.



Tom Gennett, NREL

Future Work

FY11, FY12

- Detailed synthesis and characterization of thermal performance and reliability of joints based on the matrix given below
  - Synthesis of bond/joint,
  - Subject joint/bond to thermal shock,
  - Thermal resistance measurements after select cycles,
  - Joint quality characterization (CSAM) after select cycles,
  - High-potential test after select cycles,
  - Modeling of thermo-mechanical behavior of the joints,
  - Degradation/end-of-life model of the joints and the package.

Joint Material	Substrate	Metallization	Coating	Baseplate
Solder Joints (Pb free & Pb)	AlN	Al	Ag	Al
Brazed Joints	Al_2O_3	Cu	Au	Cu
Sintered Joints	Si_3N_4			AlSiC
Thermoplastics				

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PROCESS
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REPETITIONS

Summary

DOE Mission Support

- BIMs are a key enabling technology for compact, light-weight, reliable packaging, and for high temperature coolant and air cooling technical pathways.

Approach

- Approach includes – synthesis of various joints between DBA/DBC and baseplate (Cu/Al/AlSiC), thermal shock cycles, thermal resistance measurements, hi-potential test and joint inspection (CSAM), and physics-of-failure models.

Accomplishments

- In close collaboration with industry partners (GM, Delphi), established a workplan to characterize thermal performance and reliability of a number of bonded interfaces (soldered, sintered, brazed, thermoplastic with embedded carbon fibers).
- Promising initial results for sintered interfaces (silver nanoparticles – Virginia Tech) and promising performance of thermoplastic adhesives with embedded carbon fibers (Btech).

Summary

Future work

- Thermoplastics with embedded carbon fibers
  - Ion-implantation and metal-sputtering to reduce contact resistance further.
- Thermoplastics, sintered, soldered and brazed joints
  - Various substrates/baseplates combination,
  - Synthesis (recipe),
  - Thermal shock cycles,
  - Thermal resistance measurements,
  - Hi-potential test and CSAM,
  - Physics-of-failure models.

Collaborations

- GM and Delphi (all bonded interfaces).
- Virginia Tech (synthesis of sintered and soldered joints).
- Btech (thermoplastics with embedded carbon fibers).
- NREL materials group (ion-implantation and metal-sputtering – thermoplastics).
- ORNL (sintered and soldered joints).