Low-Cost Direct Bonded Aluminum (DBA) Substrates

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Project ID #: PM036

Overview

Timeline

- Project start: October 2010
  (actual funding starts: Jan 2011)
- Project end: September 2013
- Percent complete: 40%

Budget

- Total project funding
  - DOE 100%
- FY11: $200k
- FY12: $200k
- FY13: $200k

Barriers*

- Barriers Addressed
  - High cost per kW
  - Low energy per kg
  - Low energy density
  - Insufficient performance and lifetime
- Targets:
  - DOE VTP* 2020 target: $3.3/kW
  - DOE VTP* 2020 target: 14.1 kW/kg
  - DOE VTP* 2020 target: 13.4 kW/l
  - 15 year life

Partners

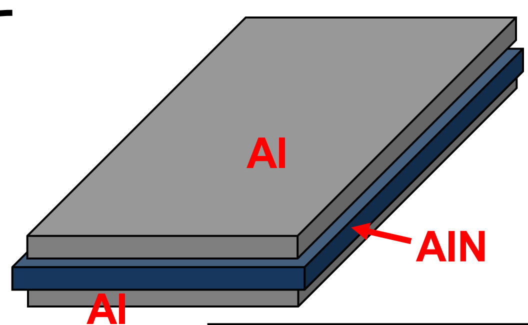
- NTRC – ORNL
- Marlow
- Materion (metal cladding supplier)

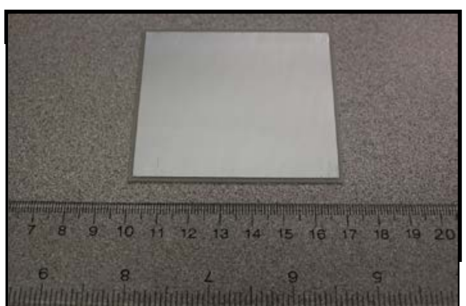
* VTP Multi-Year Program Plan 2011-2015

Objectives

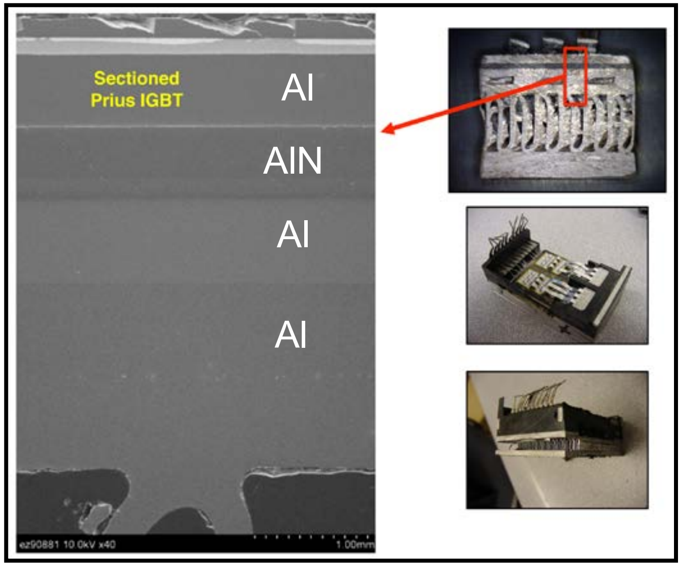
- Develop low-cost, high quality, and thermomechanically robust direct-bonded aluminum (DBA) substrates.
- Use ORNL’ s in-house unique processing capabilities to fabricate innovative DBA substrates using a process that is amenable for mass production and that produces high adhesive strength of the ceramic-metal interfaces.
- Consider the fabrication and use of low-cost AlN as a potential (and alternative) contributor to the low-cost.

DBA substrate





Example of a commercial DBA (with AlN) substrate



Example of Al to AlN bonding in 2010 Prius IGBT

Photo used with permission of Z. Liang (NTRC/ORNL)

Milestones

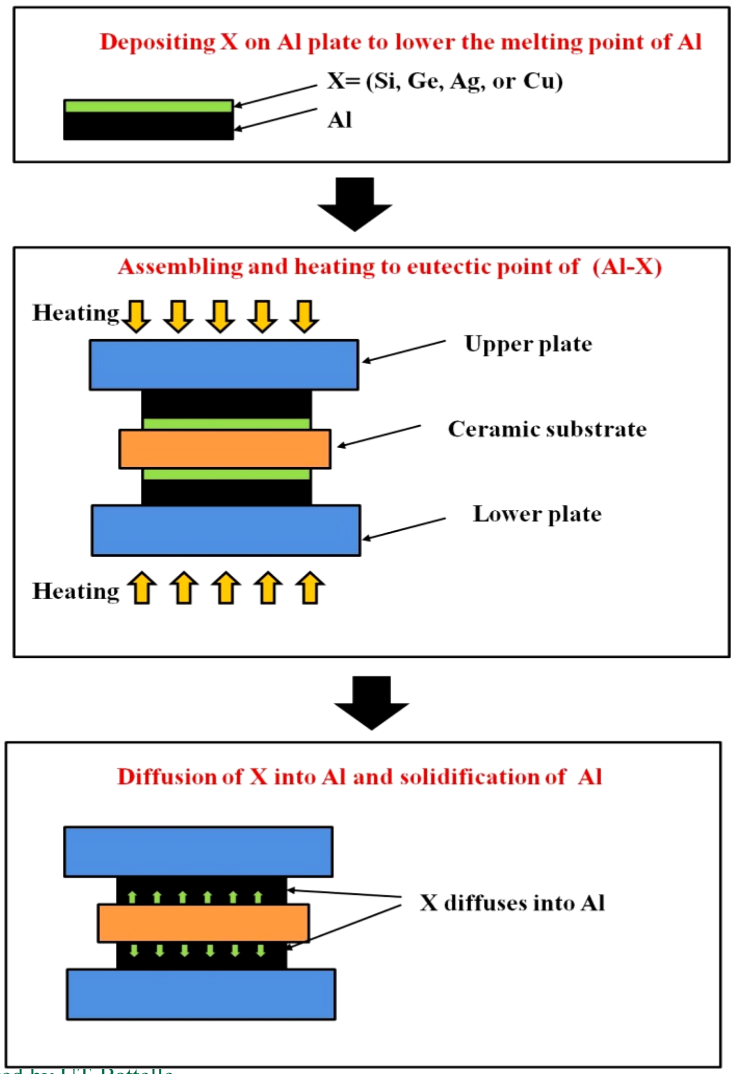
- **FY12 - 1: Complete characterization of microstructure, and physical (coefficient of thermal expansion and thermal conductivity) of commercially available DBA substrates up to 200° C.**
- **FY12 - 2: Complete fabrication of DBA substrates manufactured via new ORNL processing method and compare thermal cycling response between – 40° C and +150° C in air against that of commercial DBA substrates.**

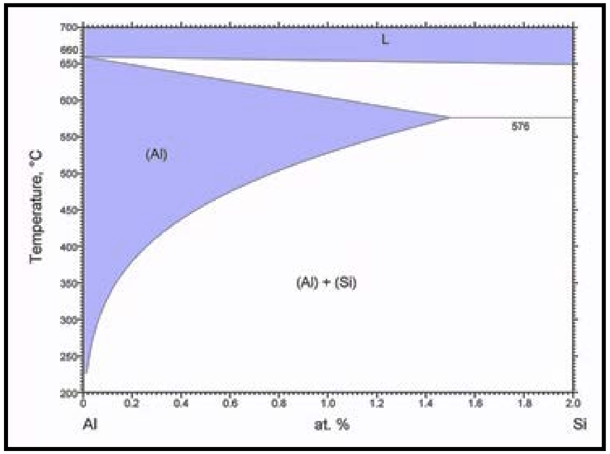
Technical Approach

- Study patent and open literature for DBA fabrication.
- Identify alternative processing method to fabricate large-sized DBA substrates that has potential for low-cost manufacture. This is the first primary step in creating availability of low-cost DBA substrates.
- Alternatively develop cost effective method to fabricate AIN substrates. The use of a low-cost AIN could be a potential contributor for in lower-cost DBA substrates.
- Benchmark existing commercial DBA substrates for eventual comparison against DBA substrates fabricated in this project. Also, benchmark select commercially available direct bonded copper (DBC) substrates.
- Develop test method to measure interfacial shear strengths of Al-ceramic interface.

Accomplishments

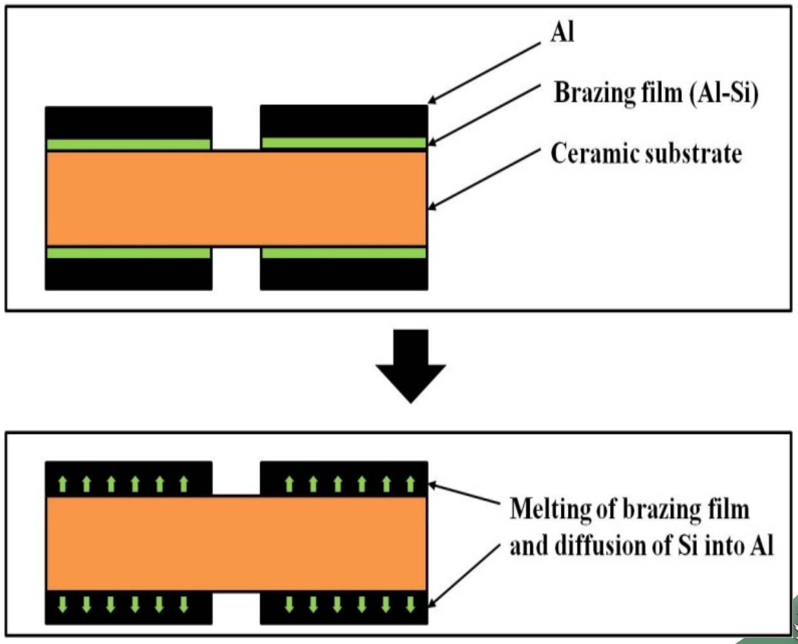
Transient Liquid Phase (TLP) Process





Al-Si phase diagram

Brazing Process



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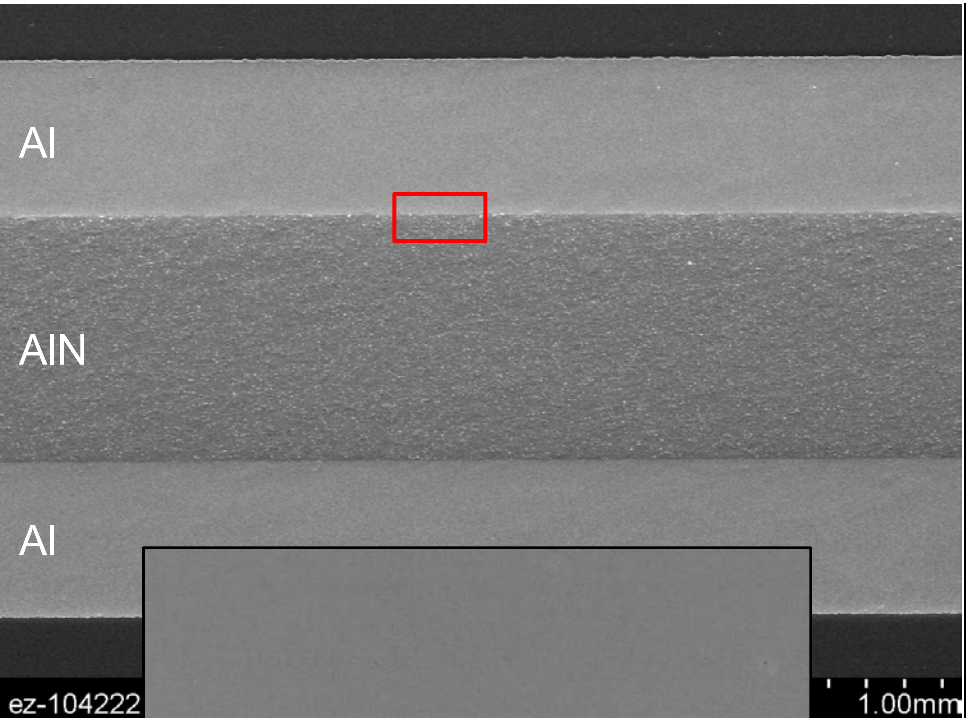
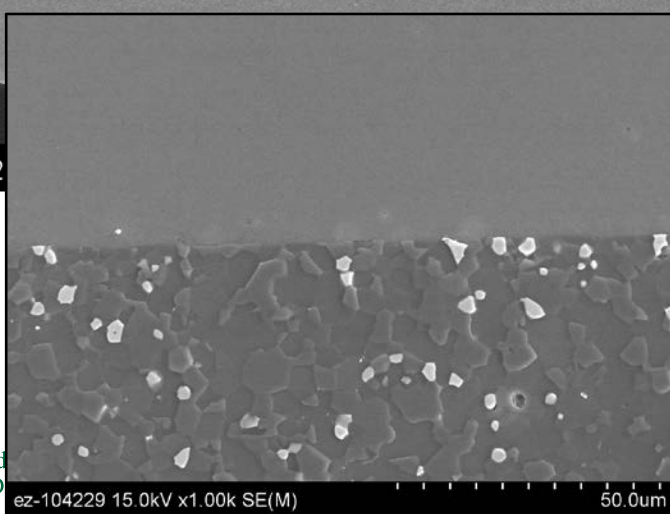
Accomplishments (continued)

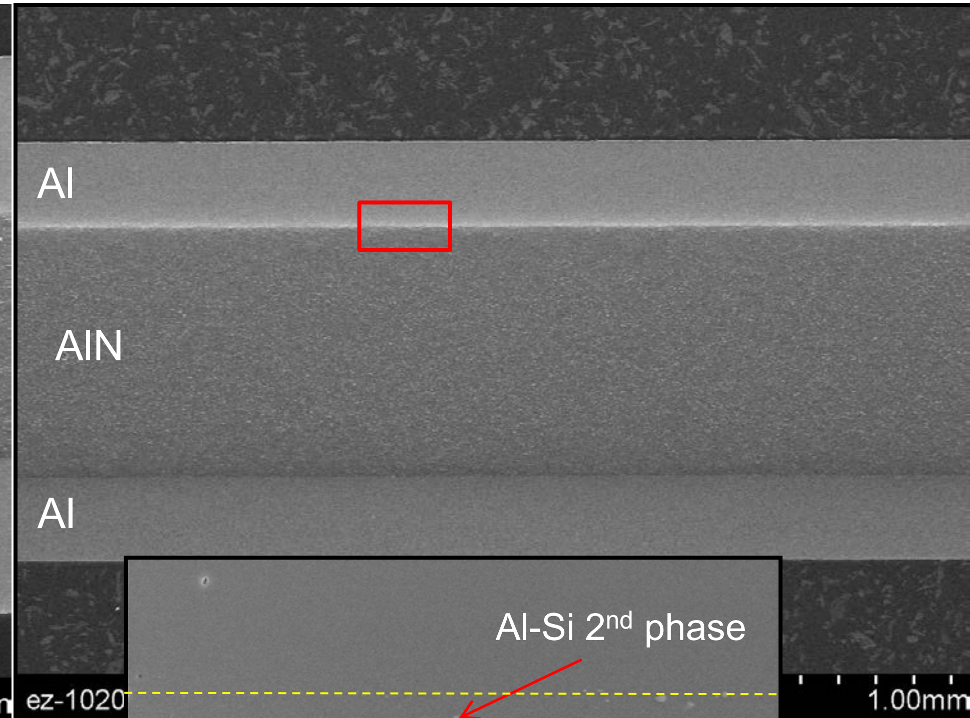
SEM micrographs of polished cross-section of commercial DBA substrates

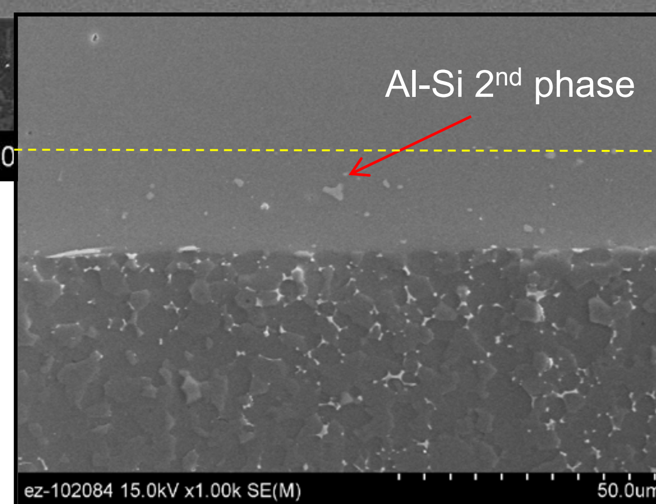
Commercial A - DBA





Commercial B - DBA

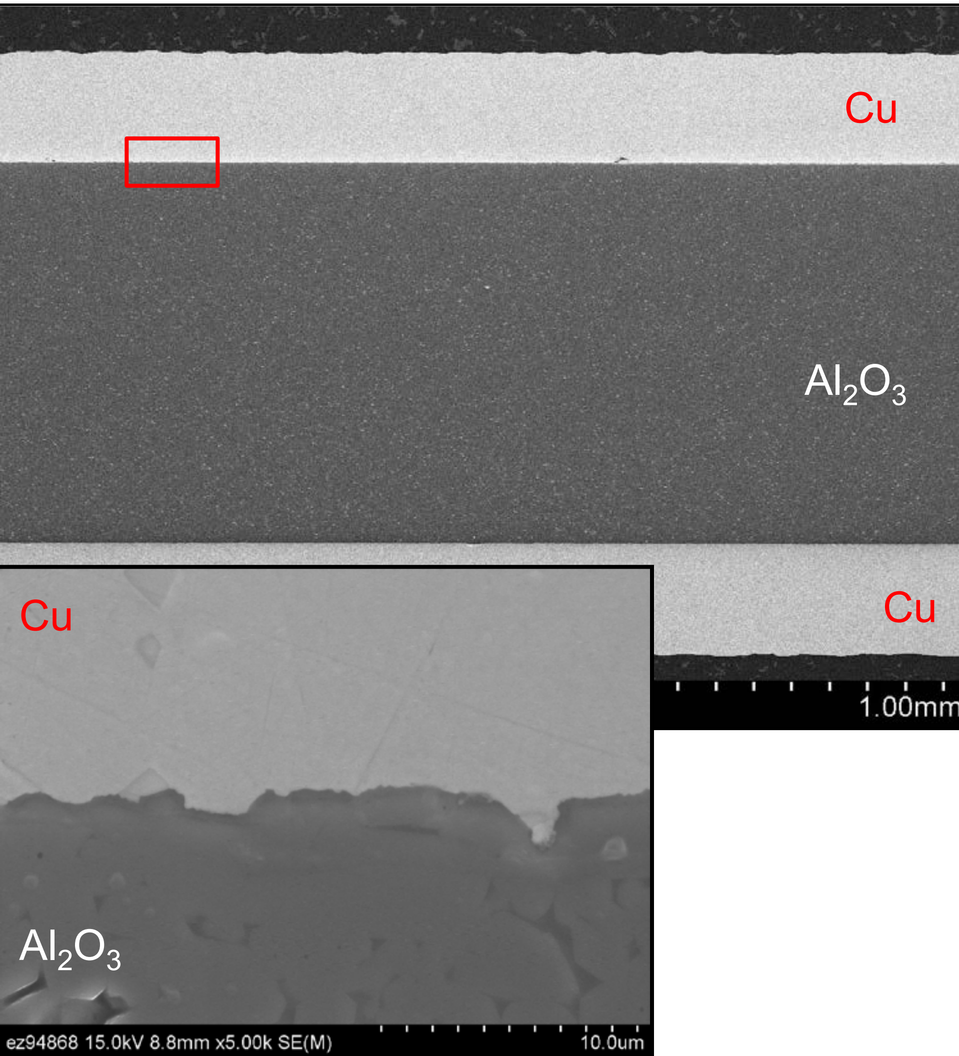




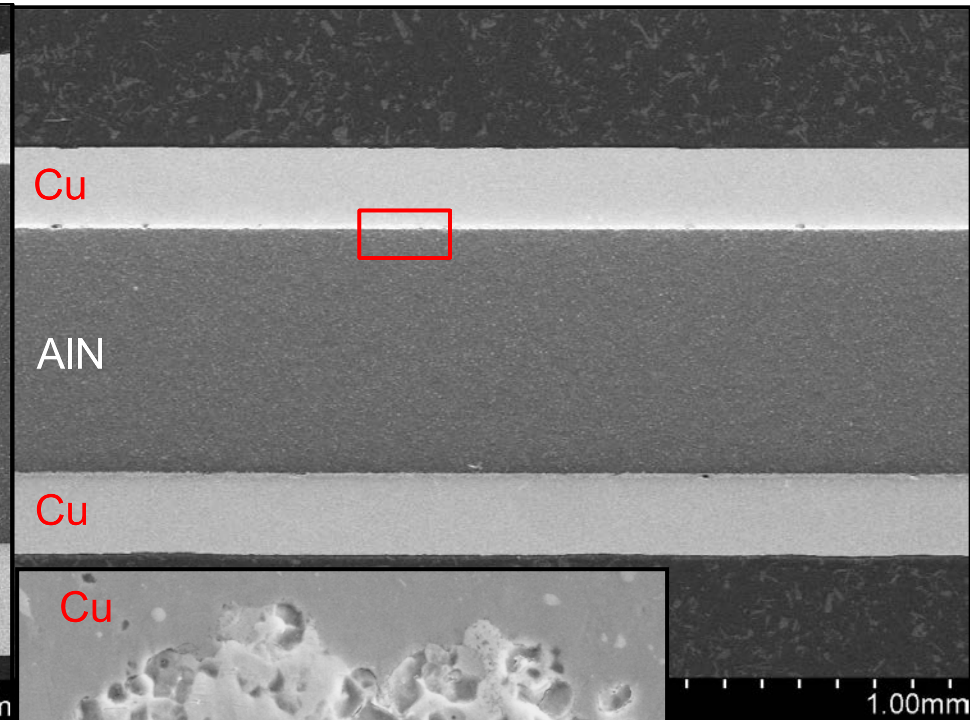
Accomplishments (continued)

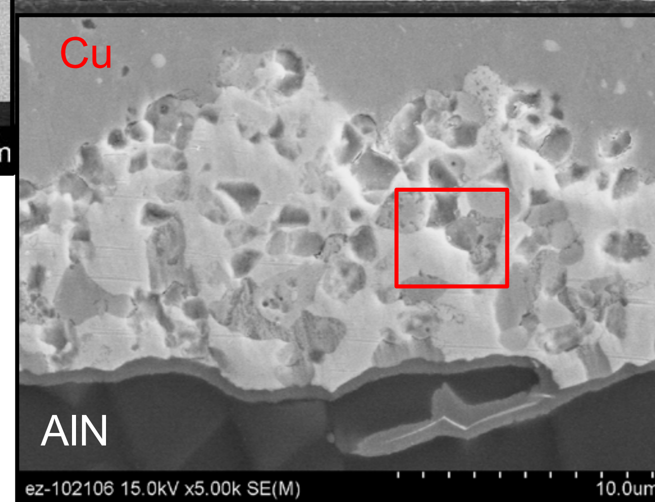
SEM micrographs of polished cross-section of commercial DBC substrate

Commercial A - DBC



Commercial B - DBC

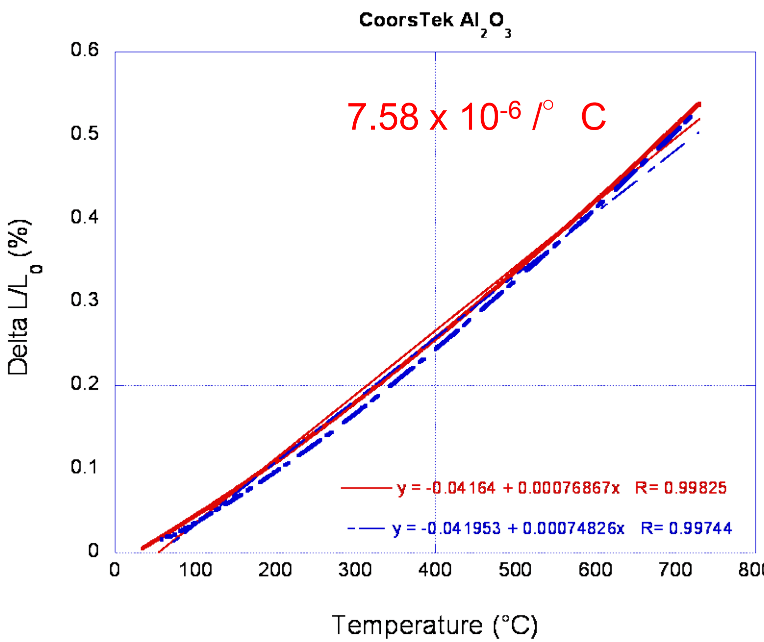


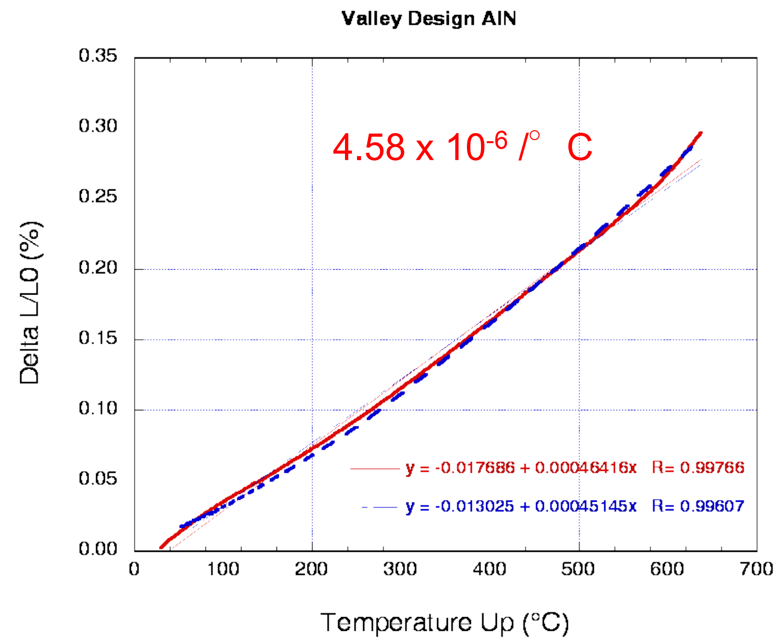


Chemical elements: Cu-Ag-Al-S-Mg

Accomplishments (continued)

Measurement of physical properties (CTE and Young's modulus) of commercial Al_2O_3 and AlN ceramic substrates





Measured by resonant ultrasound spectroscopy (RUS)

	Length (mm)	Width (mm)	Thickness (mm)	Mass (g)	Density (g/cm^3)	Young's modulus (GPa)	Possion's ratio
Al_2O_3 CoorsTek	10.066	9.995	0.776	0.2902	3.7170	328.3083	0.2424
Valley Design AlN	10.076	9.999	0.890	0.2930	3.2676	314.4820	0.2441

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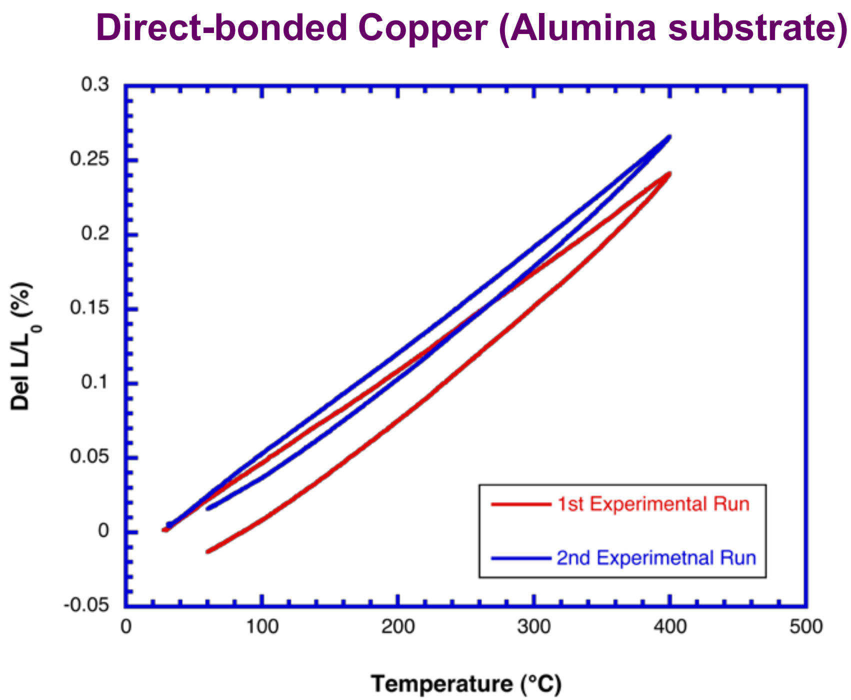
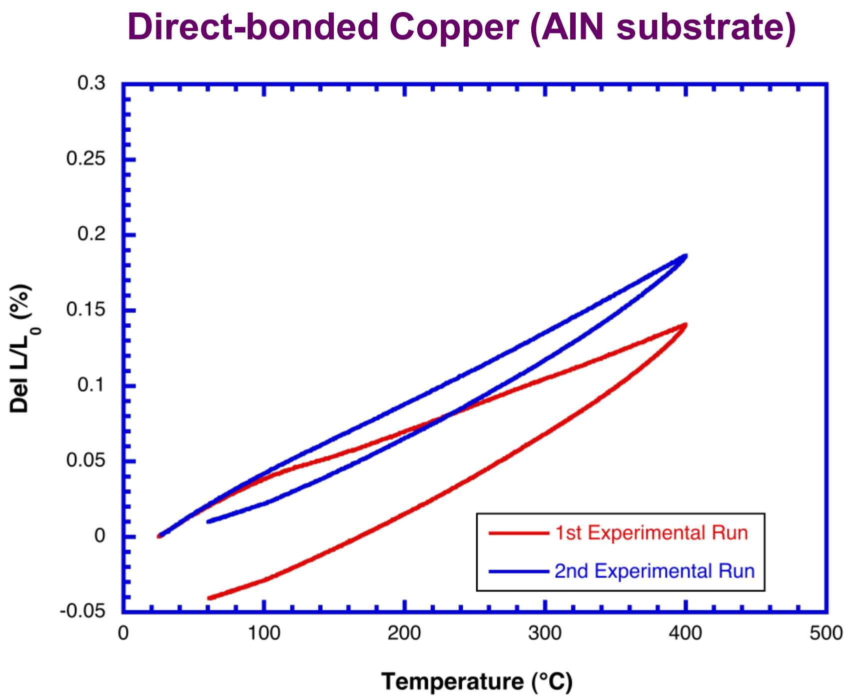
Accomplishments (continued)

Measurement of coefficient of thermal expansion of commercial DBC with Al_2O_3 and AlN ceramic substrate





Feature of a hysteresis loop of strain-temperature observed after the heating cycle, presumably resulting from the residual stress state present in the substrate

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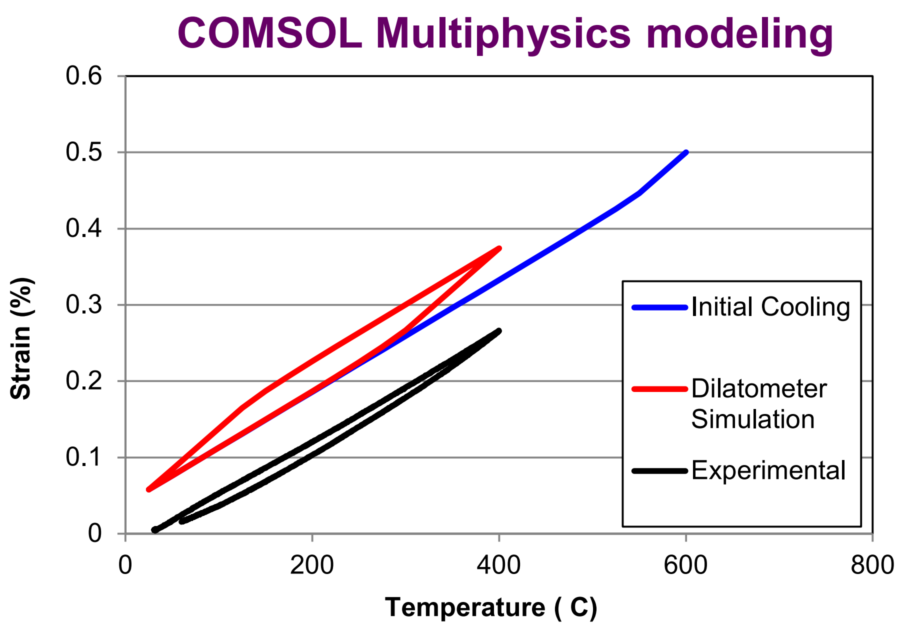
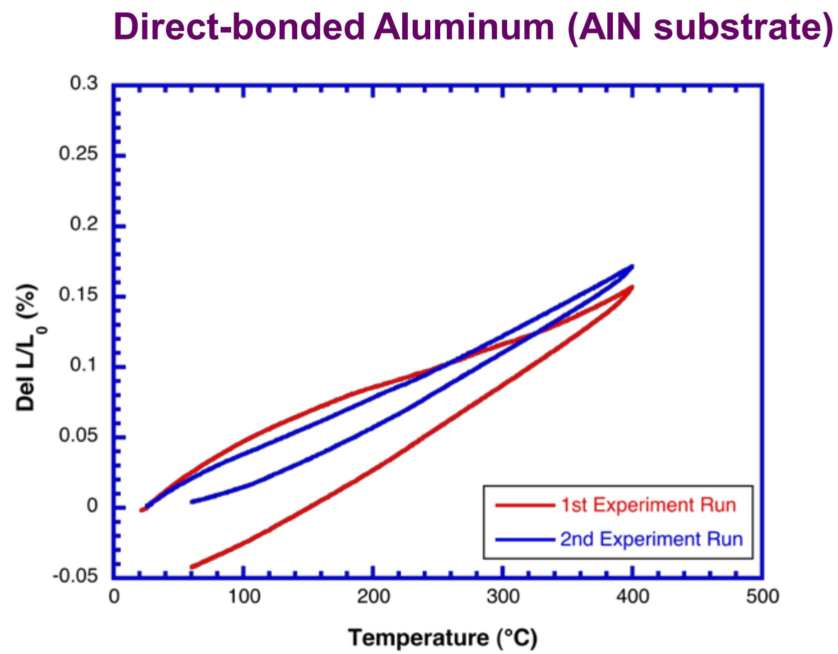
Accomplishments (continued)

A COMSOL Multiphysics program was used to model the hysteresis strain-temperature loop of DBA substrate



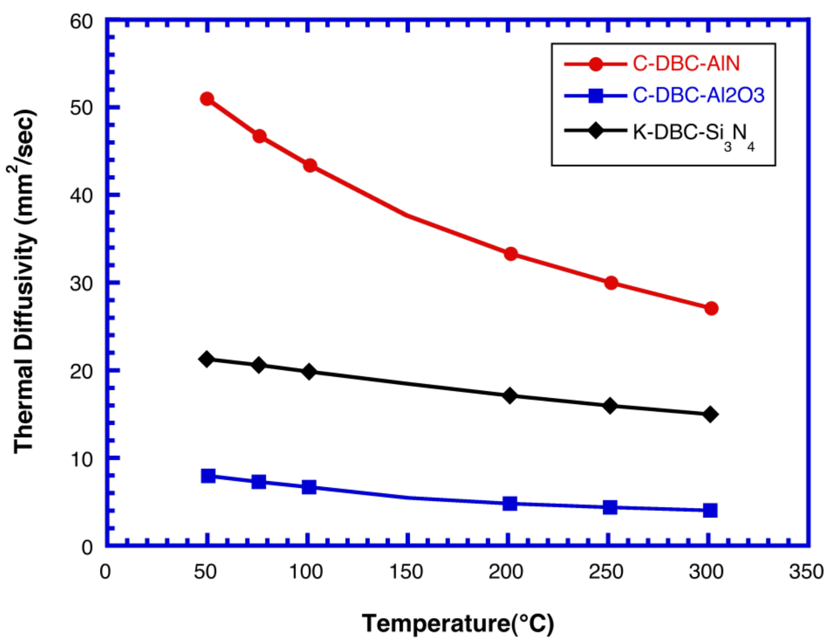


- Assumptions: constant CTE and yield strength of Al metal
- Plastic (permanent) deformation of Al metal could result in the residual stress and strain
- Externally applied stress during processing could augment the level of residual stress and strain

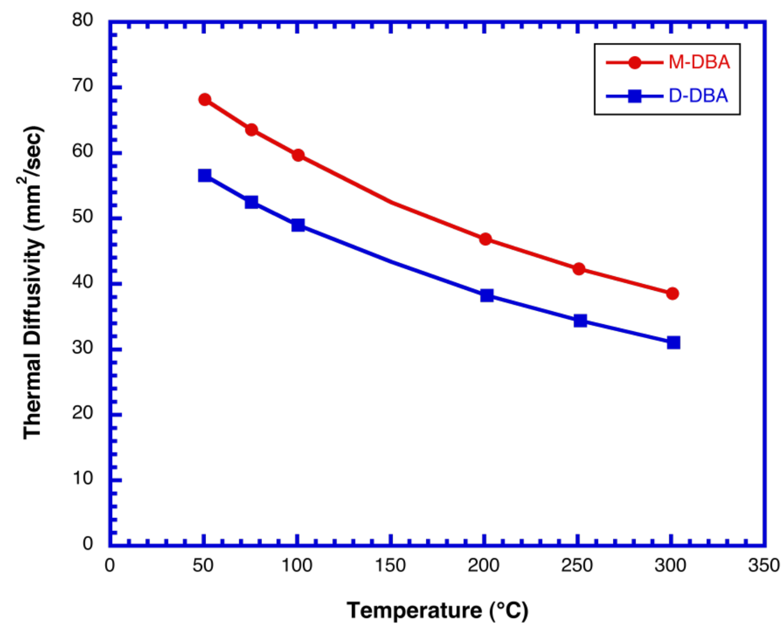
Accomplishments (continued)

Measurement of thermal diffusivity of commercial DBC and DBA substrates

Direct-bonded Copper Substrate



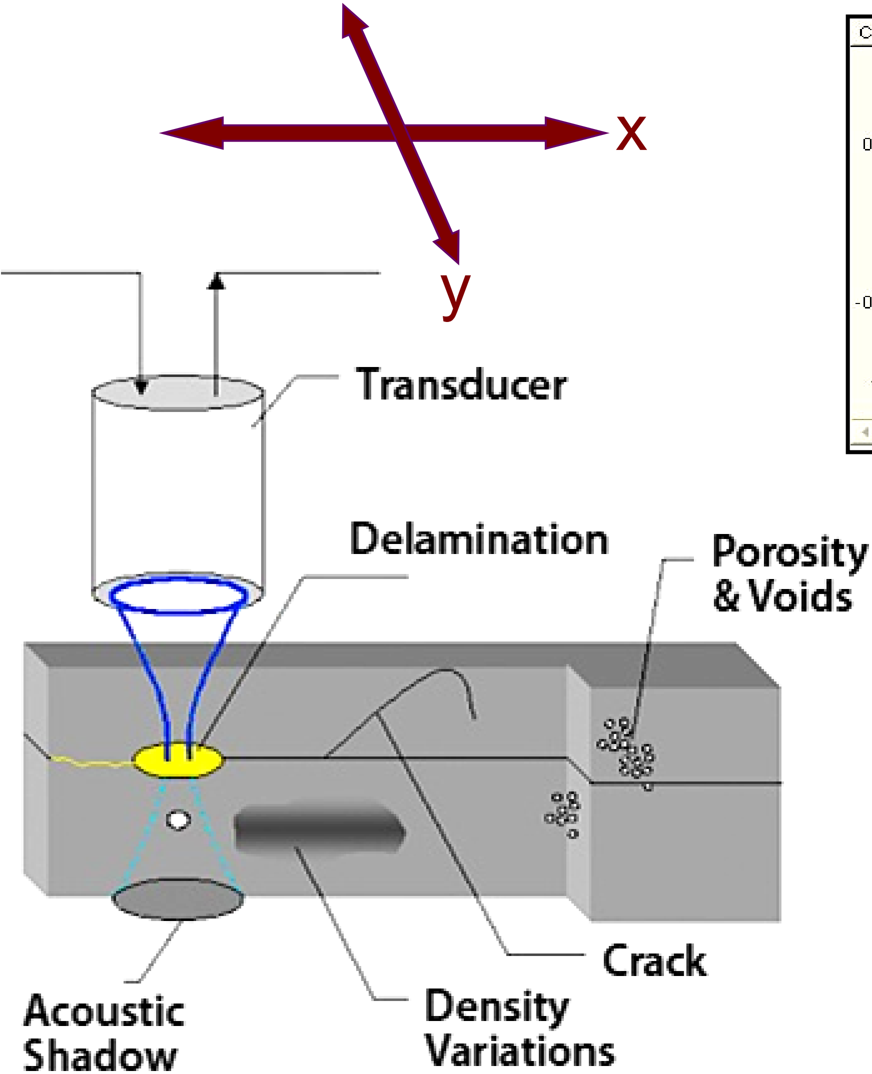
Direct-bonded Aluminum Substrate

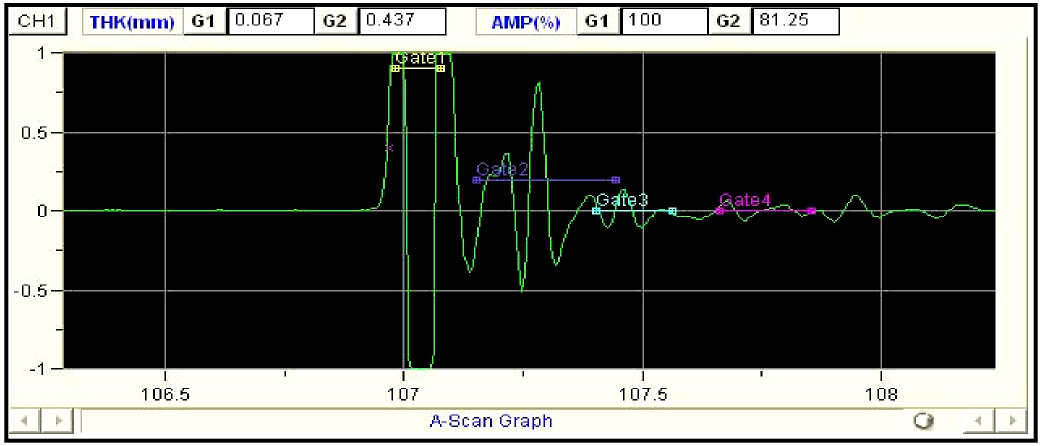


- **Method: using laser flash technique in argon**
- **Thermal conductivity of ceramics governs the (composite) substrate thermal property**
- **Interfacial microstructure (and chemistry) could also impact thermal property**

Accomplishments (continued)

Scanning Acoustic Microscopy (SAM) can be used for detection of voids, cracks, and delaminations



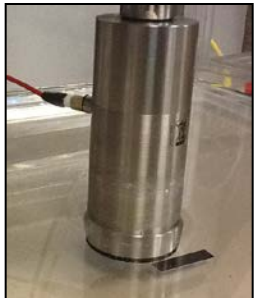


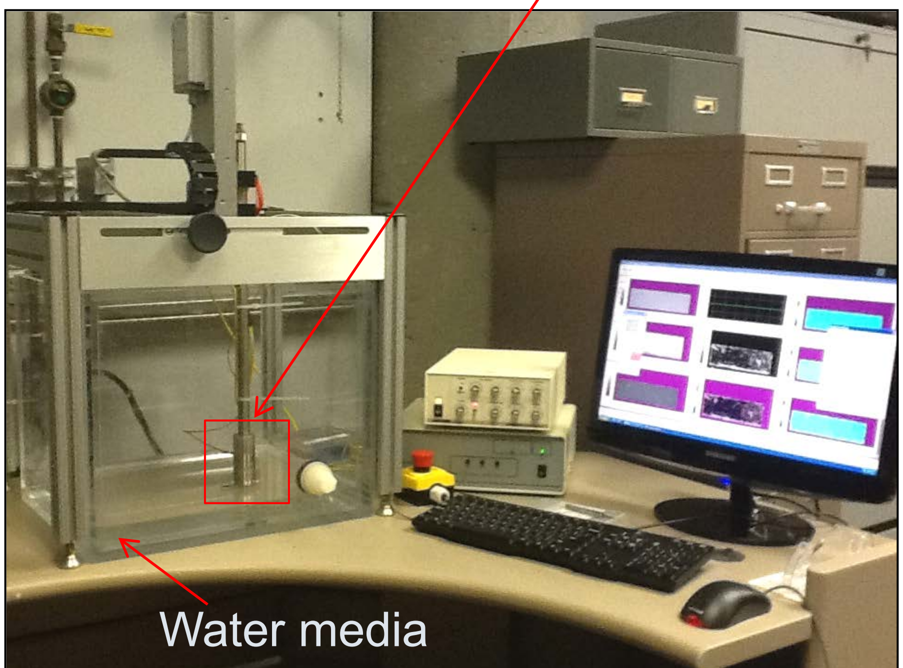
1. A pulse of ultrasound, which is focused to a pinpoint spot, is sent into a sample and reflected off of interfaces.
2. In the reflection mode of operation the same transducer is used to send and receive the ultrasonic pulse.
3. Return echoes arrive at different times based upon the depth of the reflecting feature and the velocity of sound in the materials.
4. The amount of ultrasound reflected at the interface is based on the differences in the materials at the interface.

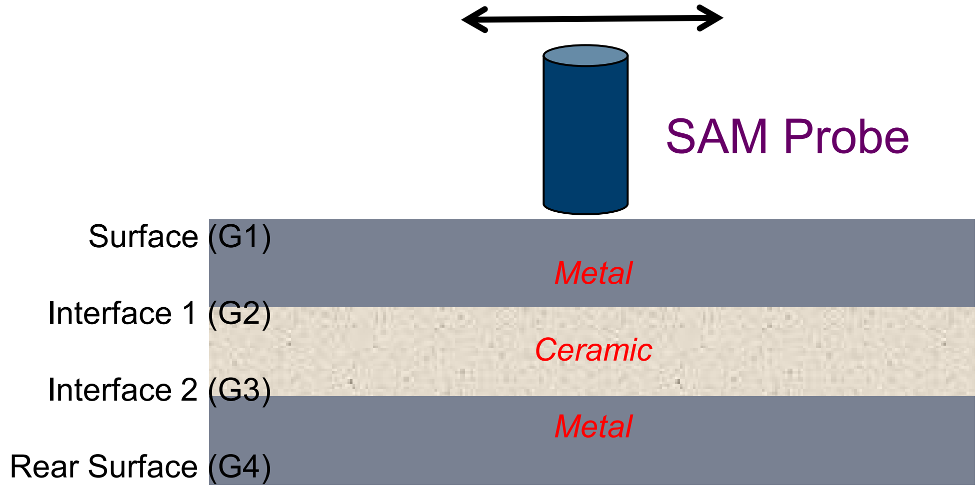
Accomplishments (continued)

Direct Bonded Metal on Ceramics Examined

SAM Probe







Notes:
1. Specimen immersed in water
2. Transducer is scanned over surface to create 2D image
3. Time gating used to select specific regions to examine

Issues:
1. Surface roughness leads to trigger errors
2. Water compatibility
3. Data interpretation complicated multiple reflections

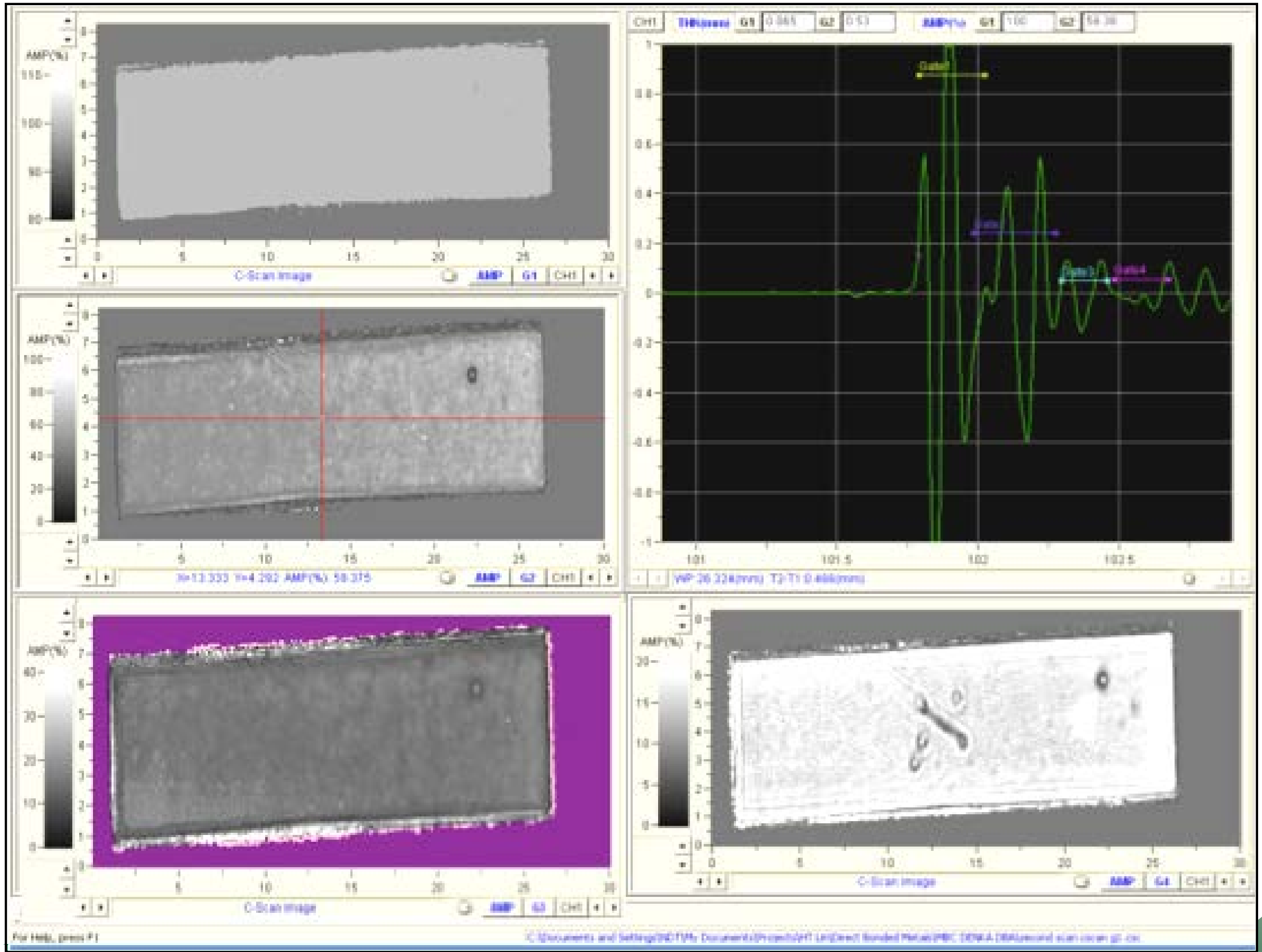
Accomplishments (continued)

SAM of Commercial DBA - 1

G1 – top surface

G2 – 1st interface

G3 – 2nd interface



G4 – bottom surface

Accomplishments (continued)

SAM of Commercial DBA - 2

G1 – top surface

G2 – 1st interface

G3 – 2nd interface

G4 – bottom surface

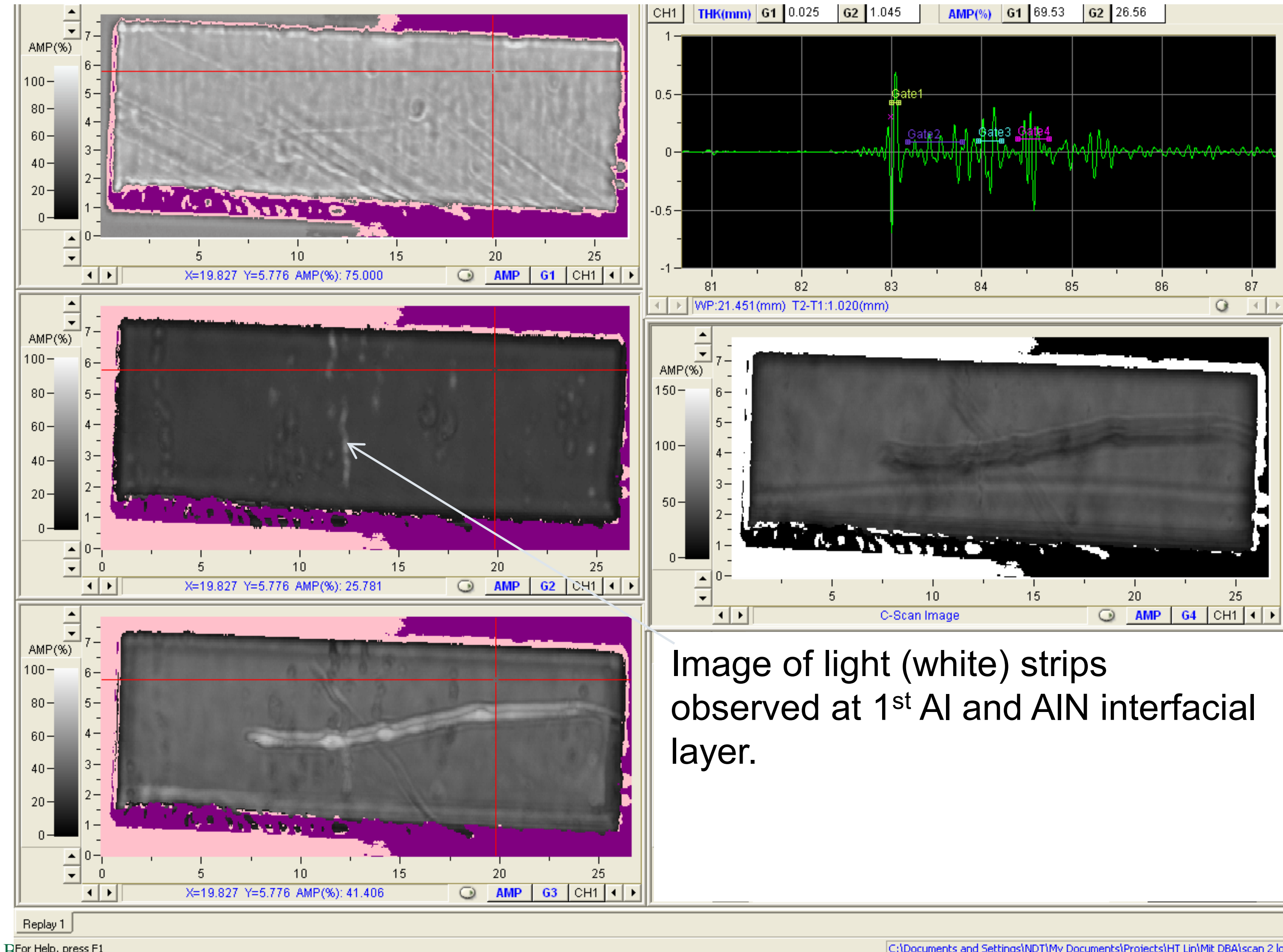
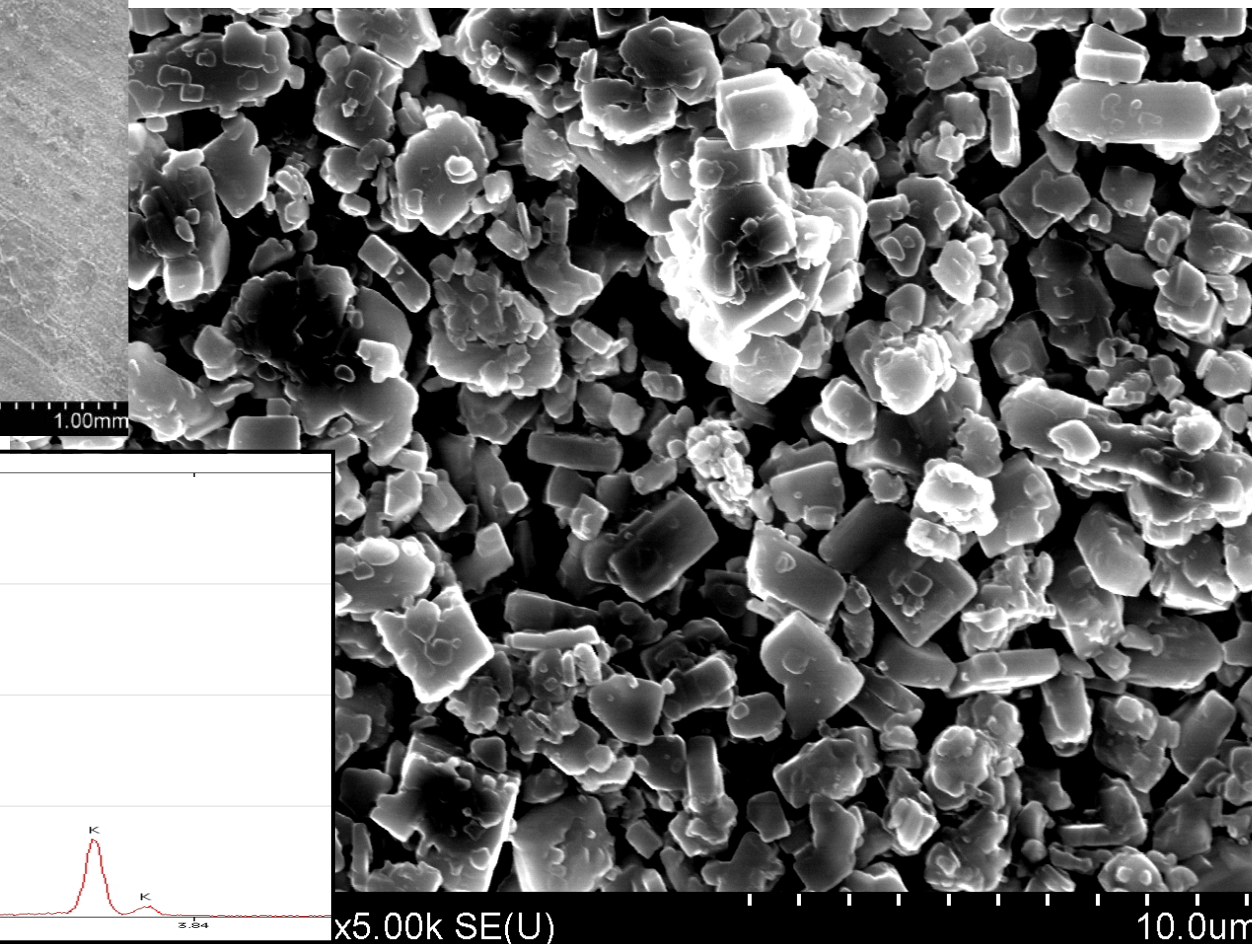


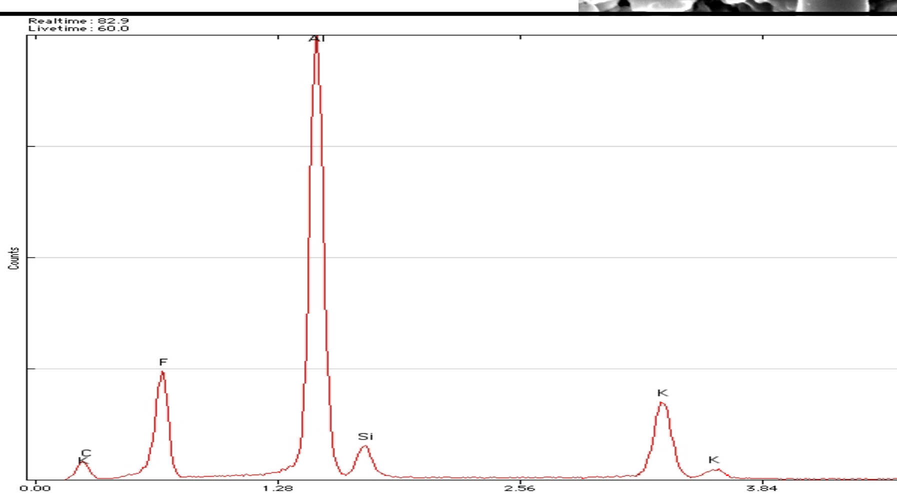
Image of light (white) strips observed at 1st Al and AlN interfacial layer.

Accomplishments (continued)

- **Analysis of commercial Al-Si brazing paste**

The paste chemical elements: Al, Si, K, and F

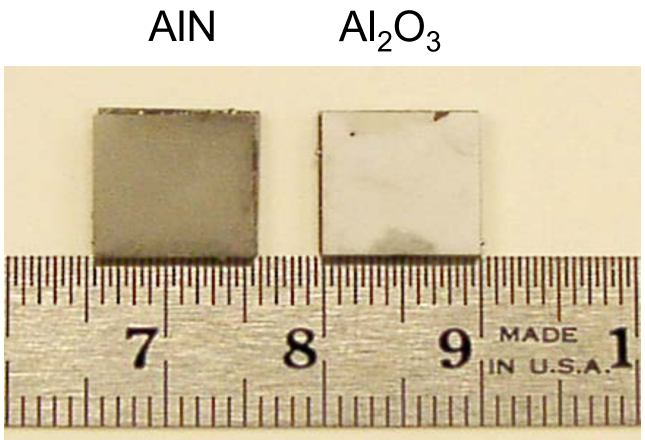


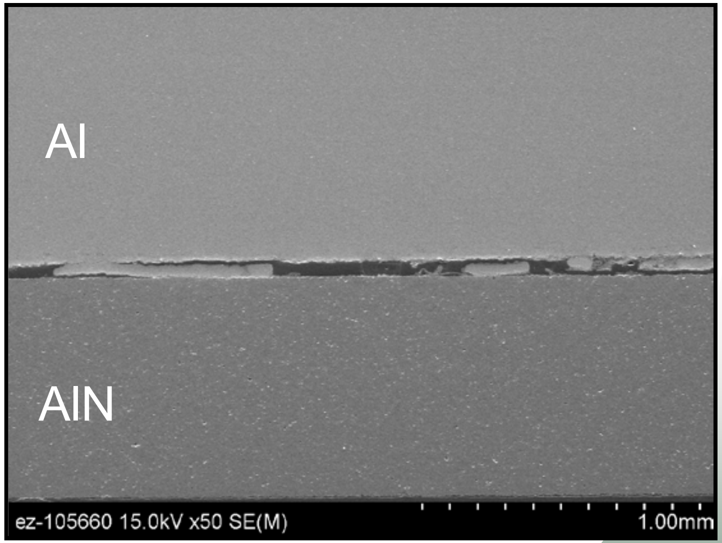


Accomplishments (continued)

Processing procedures:

1. Acid clean of Al substrate to remove Al_2O_3 thin film formed
2. Ultrasonically clean both Al and ceramic substrate in aceton
3. Apply ~ 0.5mm thick Al-Si commercial paste
4. Sintered at 620° C in hot-press furnace in flowing argon or in gas-pressure sintering furnace for 30 minutes



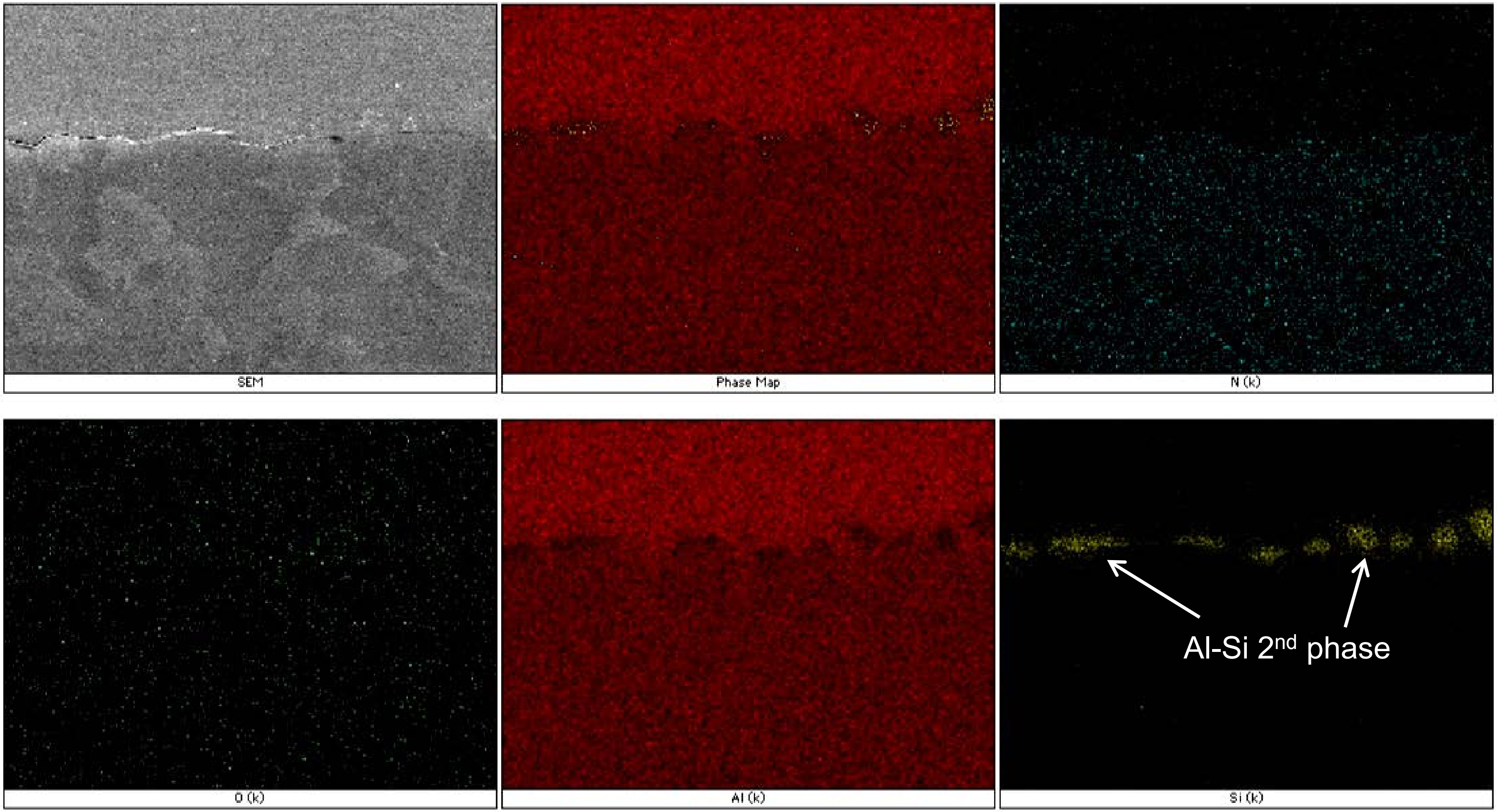


Issues/findings:

- Need high vacuum to < 10^{-5} torr (at least).
- Presence of oxygen would inhibit the bonding reaction process
- Need to apply external load during sintering
- Construction of high vacuum furnace is in progress

Accomplishments (continued)

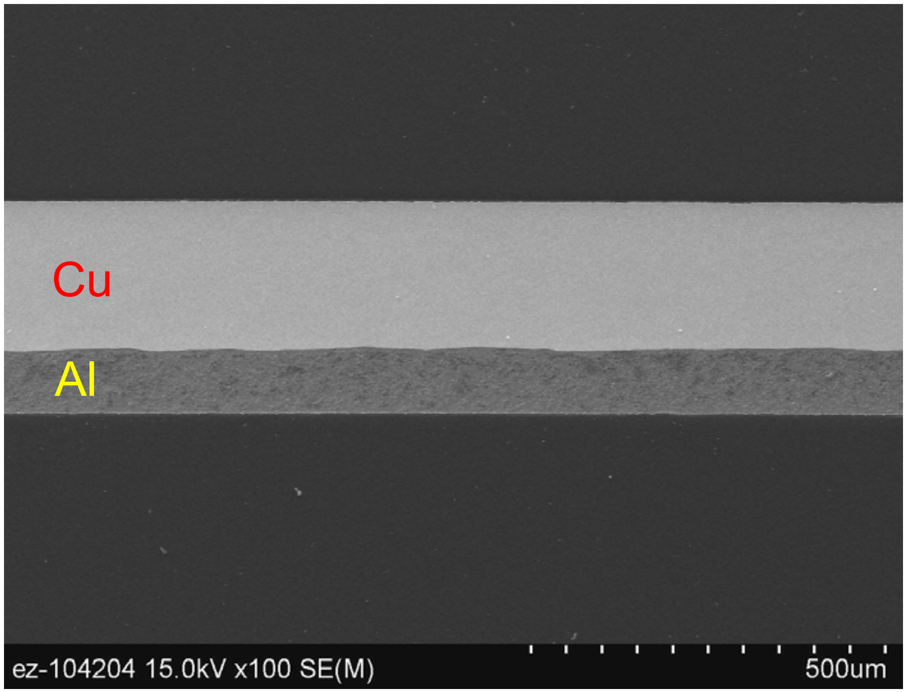
Microstructure analysis of DBA substrates via the use of Al-Si brazing paste

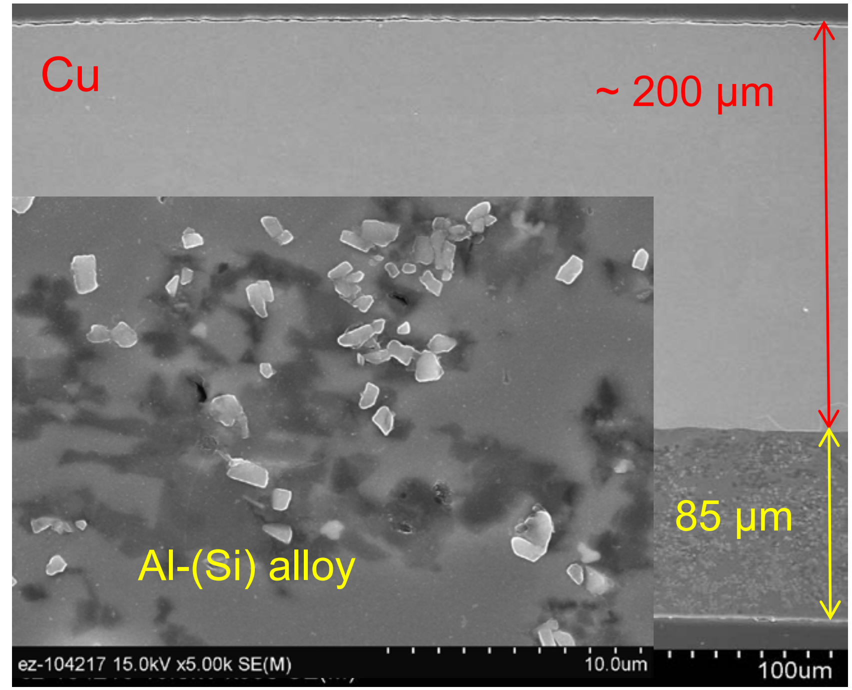


Distribution of Si element is not uniform across the interface

Accomplishments (continued)

SEM of polished cross section of Cu-clad Al ribbon provided by Materion





Proposed alternative approach:

- **The use of Cu-clad Al material could eliminate the need of interfacial brazing layer.**
- **Cu-clad Al material exhibits 45% higher thermal conductivity and 30% higher current density.**

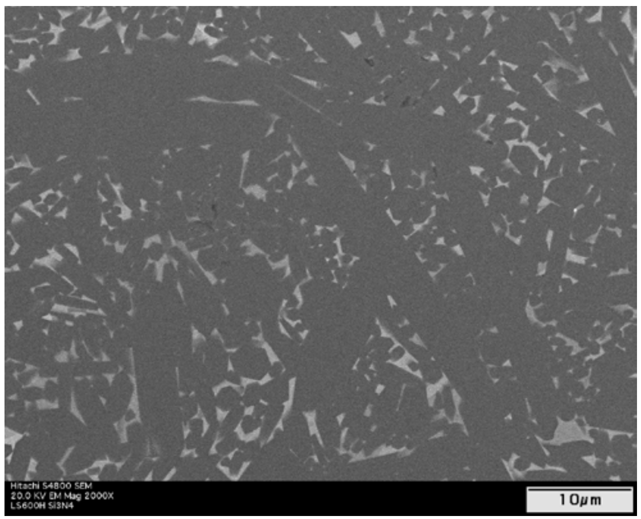
Accomplishments (continued)

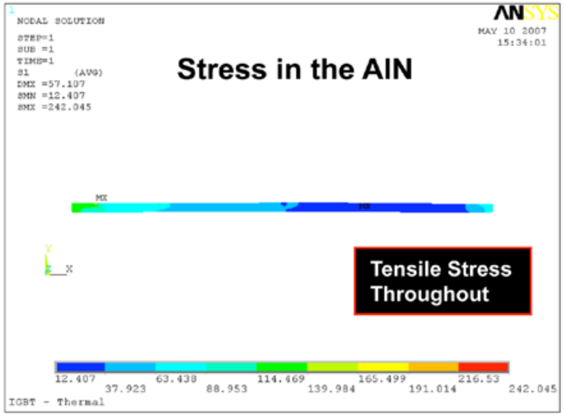
SEM of Si_3N_4 substrate employed in Toyota Lexus Hybrid (LS600H) IGBT component

✓Current market of Si_3N_4 substrate: USD $10M.

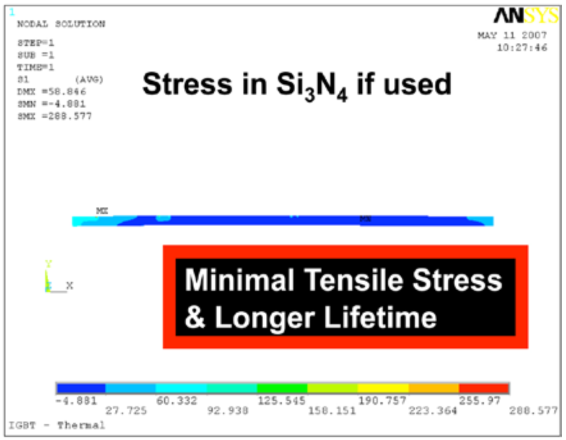
✓A new and large national project on Si_3N_4 electronic substrate to be initiated in FY13 in Japan.

Si_3N_4 substrate in LS600H





σ = 450 MPa
m = 13
K_{IC} = 3 MPa•m$^{0.5}$



σ = 1090 MPa
m = 18
K_{IC} = 6 MPa•m$^{0.5}$

- No commercial DBA substrate with Si_3N_4 available in the market (only DBC with Si_3N_4)

Proposed alternative approach:

Al or Cu-cladding Al strip

SRB Si3N4

Al or Cu-cladding Al strip

The use of Si_3N_4 ceramic substrate with high thermal conductivity combined with excellent mechanical performance provides key solution of high temperature and high power electronics component

Collaborations

➢ Partners

- ✓ PI has kept continuous communications with Advanced Power Electronics and Electric Motors R&D team members at NTRC of ORNL.
- ✓ PI has been proactively engaging in communications with Electric and Electronic Tech Team that provides very constructive inputs to the project.
- ✓ Marlow has expressed interest in conducting the bench mark test for DBA substrates
- ✓ Materion would provide Cu-clad Al ribbon with tailored thermal and electric property to meet specific substrate application.

➢ Technology transfer

- ✓ Continue to seek potential research collaboration with GM and/or Delphi on the development of high performance DBA substrate with Cu-clad Al ribbon or with reaction Si_3N_4 ceramic substrate.
- ✓ Development of high performance DBA substrate with Si_3N_4 ceramic susbtrate would provide key a constituent to meet the high-power and high-temperature challenge for IGBT with SiC or GaN wide band gap material.

Summary

- Complete microstructure characterization and physical properties database for commercial DBA and DBC substrates. Benchmarking of commercial DBA substrates provides better understand bonding characteristics of Al-ceramic interface.

- Hysteresis strain loop observed in commercial DBA and DBC substrates. *A proper thermal het treatment (annealing) process could be devised to reduce the residual thermal stress prior to application.*

- Process and sintering conditions need to be refined to prepare DBA substrates with good and coherent interfacial bonding. High vacuum and externally applied load are needed to achieve proper bonding strength.

- It is proposed to use the Cu-clad Al ribbon for DBA substrate to achieve both high thermal and electric conductivity performance.

- It is proposed to develop DBA substrate with reaction-bonded Si3N4 ceramic for high power and high temperature devices.

Future Work

- Bench mark the thermal cycle performance on commercial DBA and DBC between -40° C and +150° C in air .
- Modify ORNL's in-house unique sintering facilities (microwave or electric-field assisted furnace) to achieve high vacuum to fabricate innovative DBA substrates with high adhesive strength of the ceramic-metal interfaces.
- Consider to fabricate tape-cast Al-Si thin film using plasma spray Al-Si alloy powders for joining application.
- Fabricate DBA substrates using Cu-clad Al ribbon and evaluate the interfacial microstructure and properties.
- Fabricate DBA substrates using reaction-bonded Si_3N_4 ceramics via Ti-containing active brazing element.