Low-Cost Direct Bonded Aluminum (DBA) Substrates

H. –T. Lin, A. A. Wereszczak, and S. Waters
Oak Ridge National Laboratory

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Project ID #: PM036

Overview

Timeline

- Project start: October 2010
  (actual funding starts: Jan 2011)
- Project end: September 2013
- Percent complete: 75%

Budget

- Total project funding
  - DOE 100%
- FY11: $200k
- FY12: $200k
- FY13: $130k ($80k allocated to-date)

Barriers*

- 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

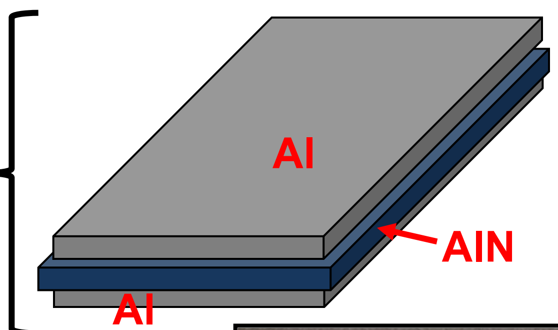
- NTRC – ORNL
- Marlow (thermoelectric manuf.)
- Materion (metal cladding supplier)

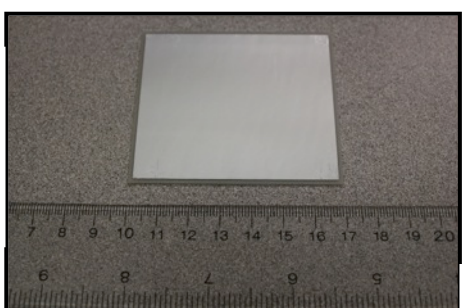
* VTP Multi-Year Program Plan 2011-2015

Objectives

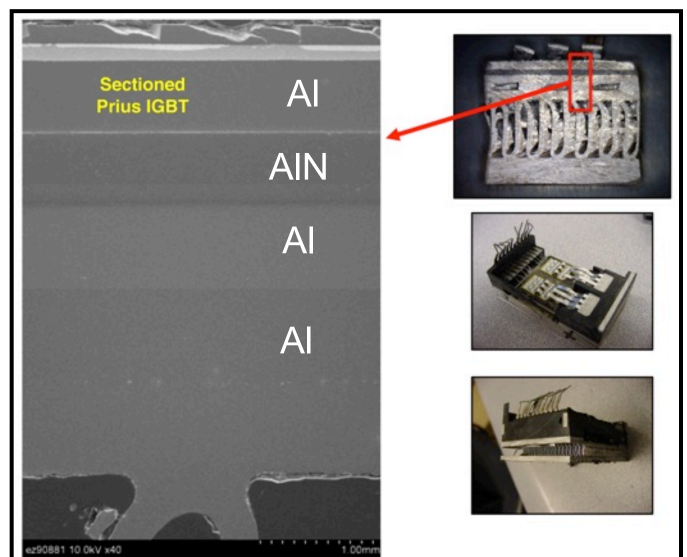
- **Develop low-cost, high quality, and thermomechanically robust direct-bonded aluminum (DBA) substrates.**
- **Use ORNL's in-house unique processing capabilities to fabricate innovative DBA substrates using a process that is amenable for mass production and that produces high adhesive strength of the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

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

- **FY13 - 1: Complete optimization of fabrication processing parameters for DBA substrates with alumina (Al_2O_3) and aluminum nitride (AlN) ceramic.**

- **FY13 - 2: Complete fabrication of silicon nitride (Si_3N_4) ceramic substrates with both high mechanical properties and thermal conductivity.**

- **FY13 – 3: Complete development of DBA and/or direct bonded copper (DBC) substrates with high performance silicon nitride ceramics (may not be completed due to budget changes).**

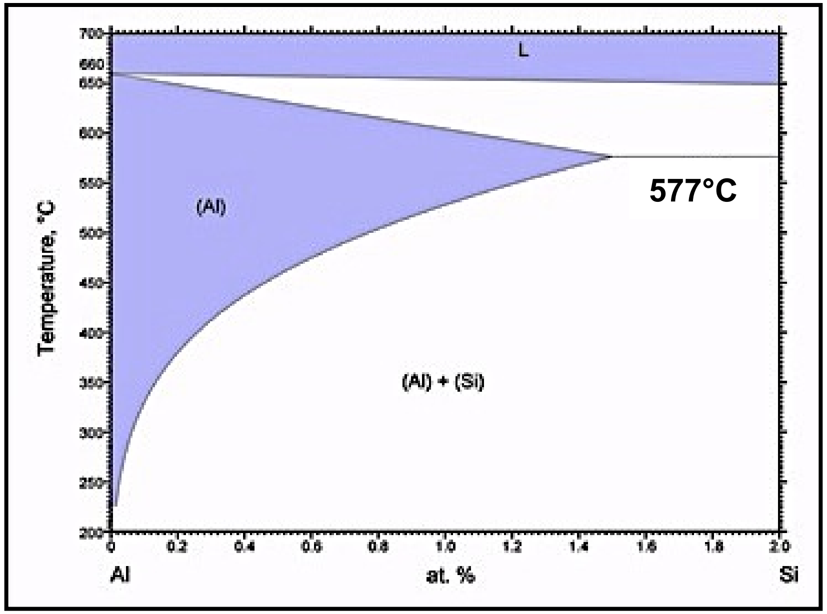
Technical Approach

- 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.
- Benchmark existing commercial DBA substrates for eventual comparison against DBA substrates fabricated in this project. Also, benchmark select commercially available DBC substrates.
- Develop Si_3N_4 material with both high mechanical and thermal properties for ceramic substrate fabrication.
- Develop test method to measure interfacial shear strengths of the Al-ceramic interface.

Accomplishments

Many Bonding Methods Were Considered

Al-Si phase diagram



Al-Si exhibits an eutectic phase at ~577°C

- **Transient Liquid Phase (TLP) process via CVD Si film**
- **Brazing process via Al-Si alloy film**

➢ **Approaches taken in this subtask:**

- **Commercial Al-11Si brazing paste (DayBraze 729, Johnson Manufacturing Co.)**
- **Al-Si alloy foil (All Foils, Inc.)**
- **Al-Si tape prepared from powders via atomization process (READE Advanced Materials)**
- **Si tape prepared from powders (Vesta Si)**

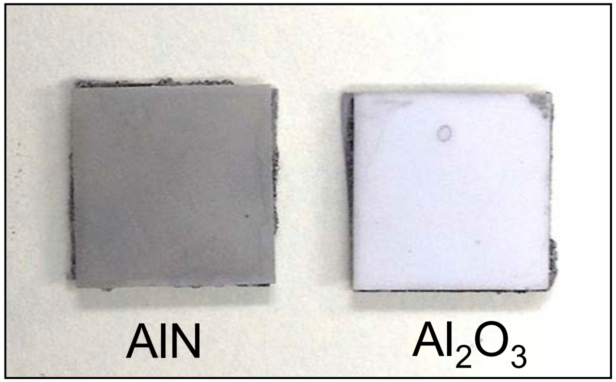
➢ **Hot press conditions:**

- **580 – 600°C**
- **5 MPa**
- **Argon or N_2**

Accomplishments (continued)

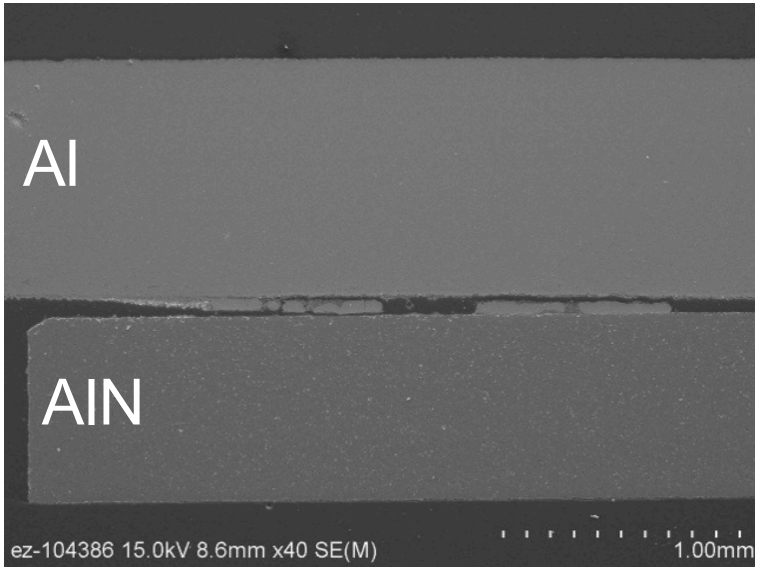
Insufficient Bonding Resulted in Early Trials

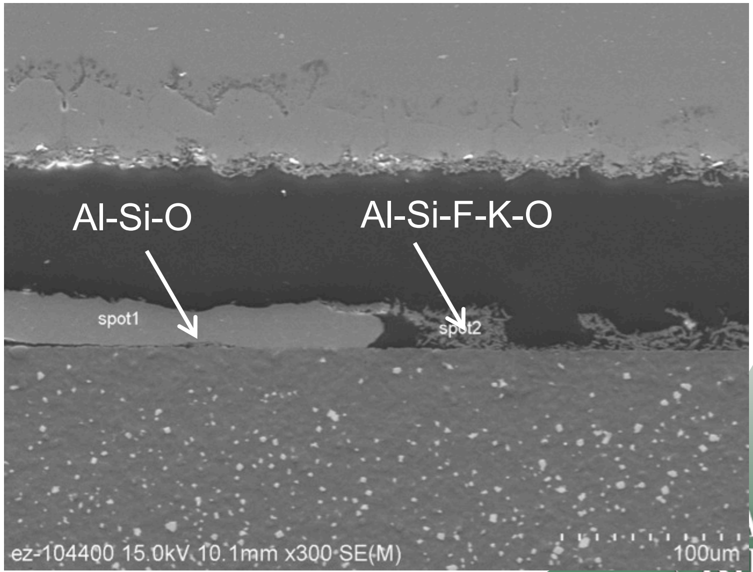
ORNL DBA substrates via Al-11Si brazing paste



Visual inspection looked sound, but they could be readily peeled off by hand, indicative of poor bonding.

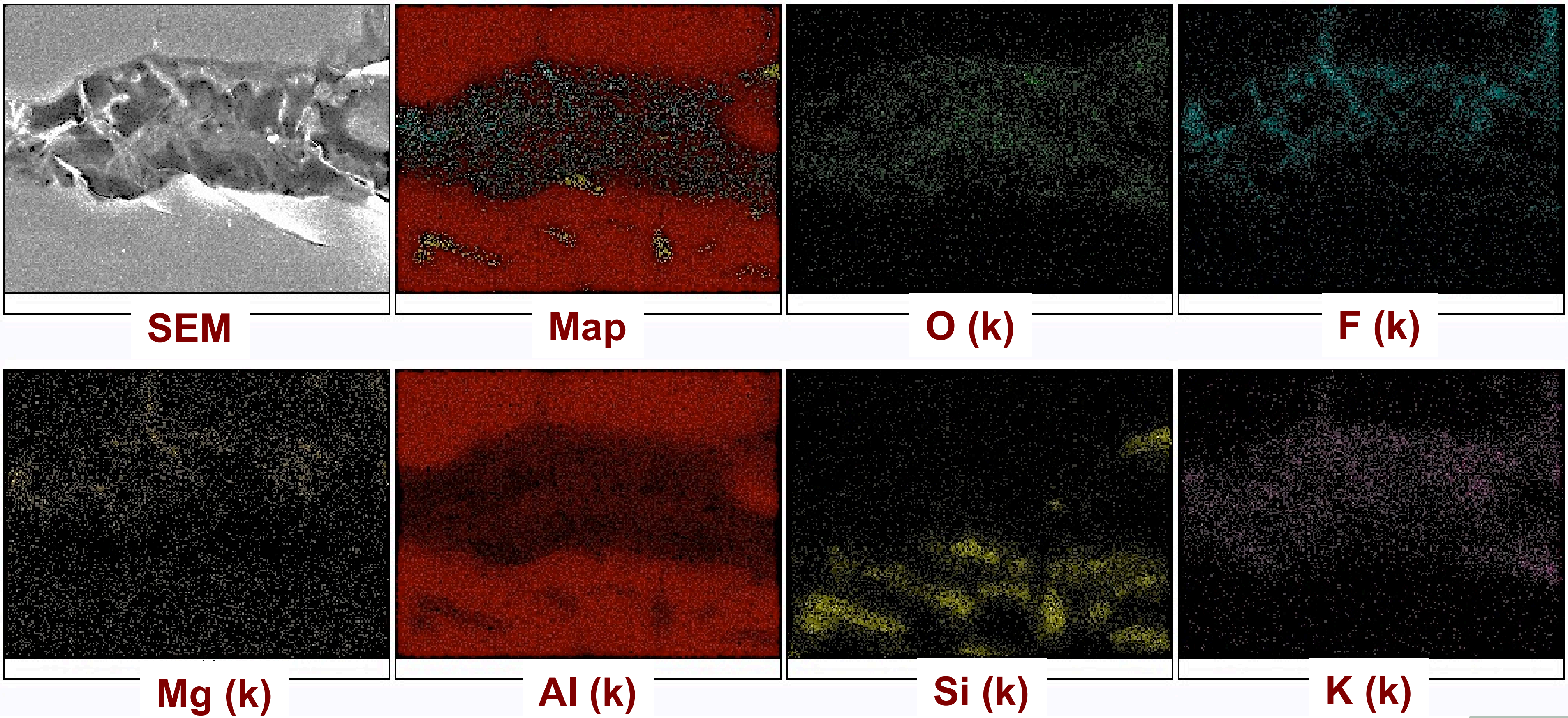
- **Low vacuum in the hot-press could cause oxidation of Al plate and paste prior to joining.**
- **Completed instrumentation of a mechanical testing system with high vacuum furnace.**





Accomplishments (continued)

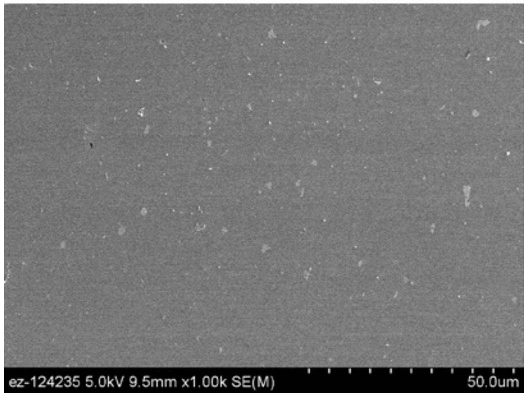
Uncompleted Reaction of Al-Si Paste Combined with High Oxygen Content Were Probably the Cause of Poor Bonding



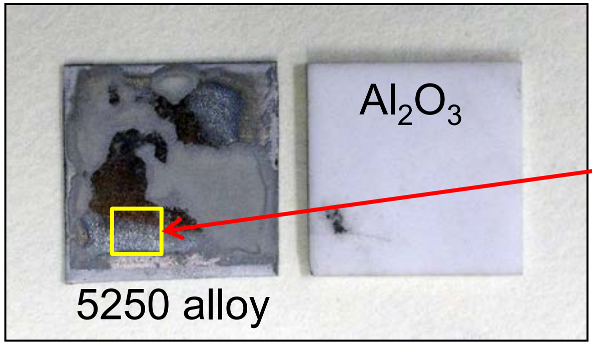
SEM EDAX element map of ORNL DBA substrate bonded with commercial Al-11Si brazing paste

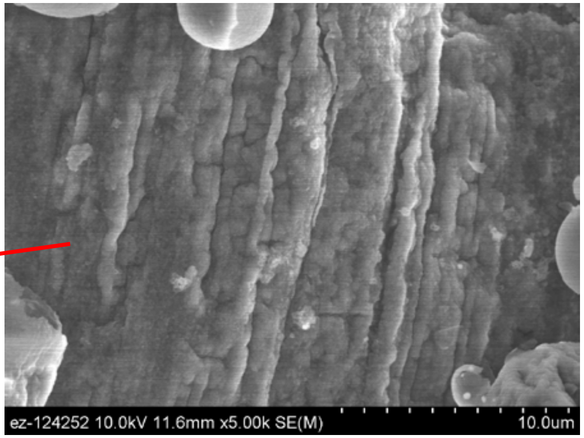
Accomplishments (continued)

Poor Wettability Existed Between Both Grades of Al-Si Foil and Ceramic Substrate

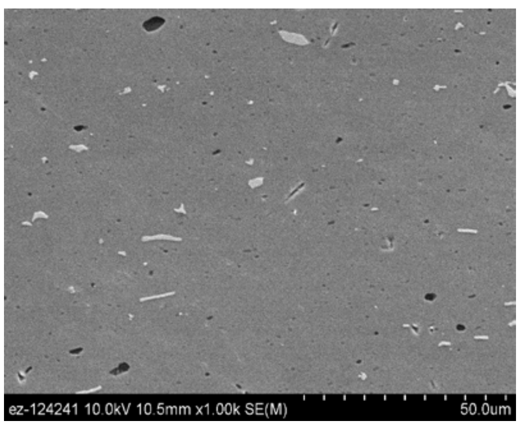


5250 alloy (Al-Mg-Mn-Si)

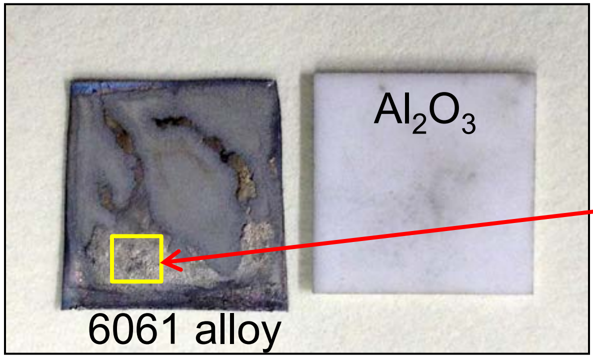


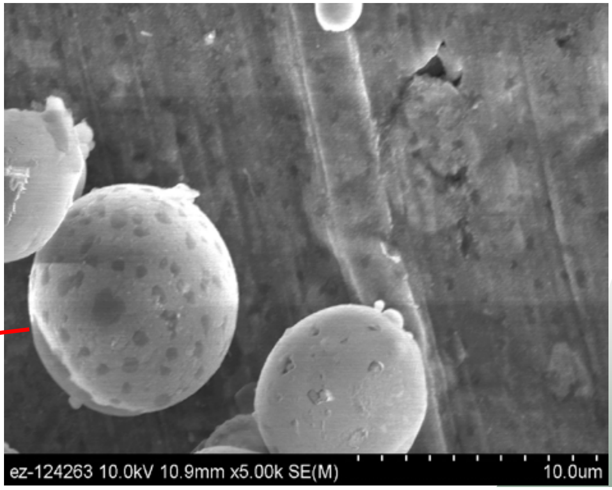


Hot press at 610°C in N_2



6061 alloy (Al-Si-Cu-Cr)





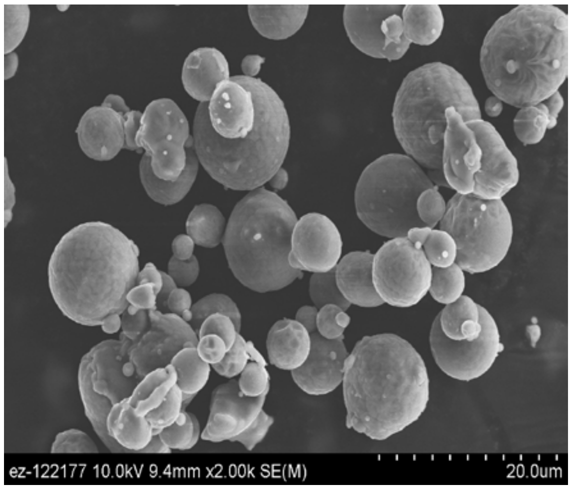
SEM micrographs of polished cross section of as-received Al-Si alloy foils

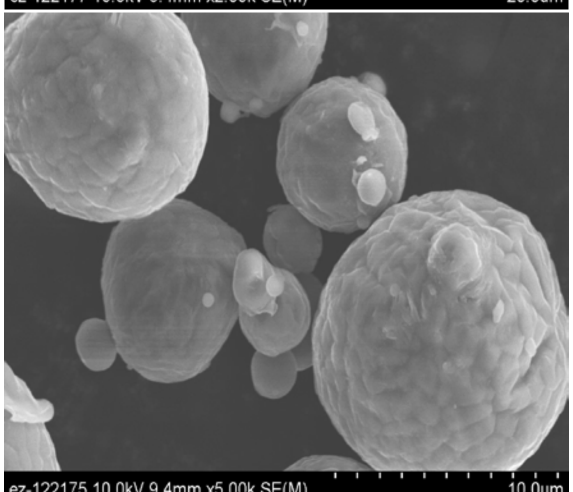
SEM micrographs of Al plate surface after bonding

Accomplishments (continued)

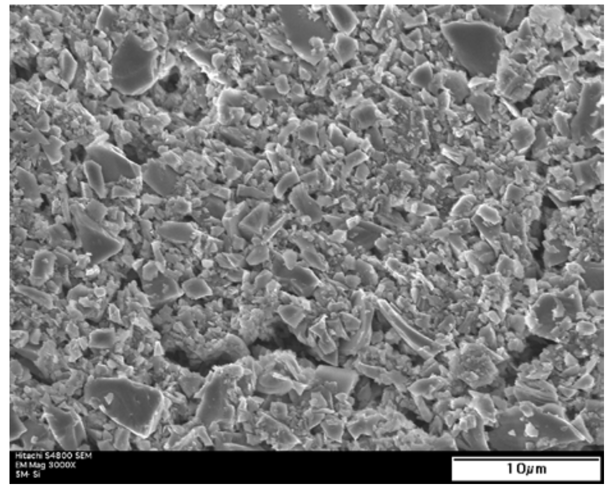
Microstructure of Al-Si-Mg and Si Powders

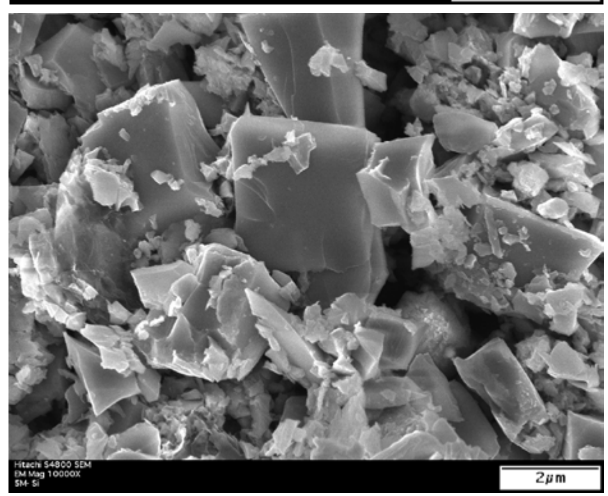
READE Advanced Materials





SicoMill® Si powder (Vesta Si)





Al-Si and Si film prepared by tape casting will be used to bond Al and Al_2O_3 (AlN) ceramic in the remaining FY13.

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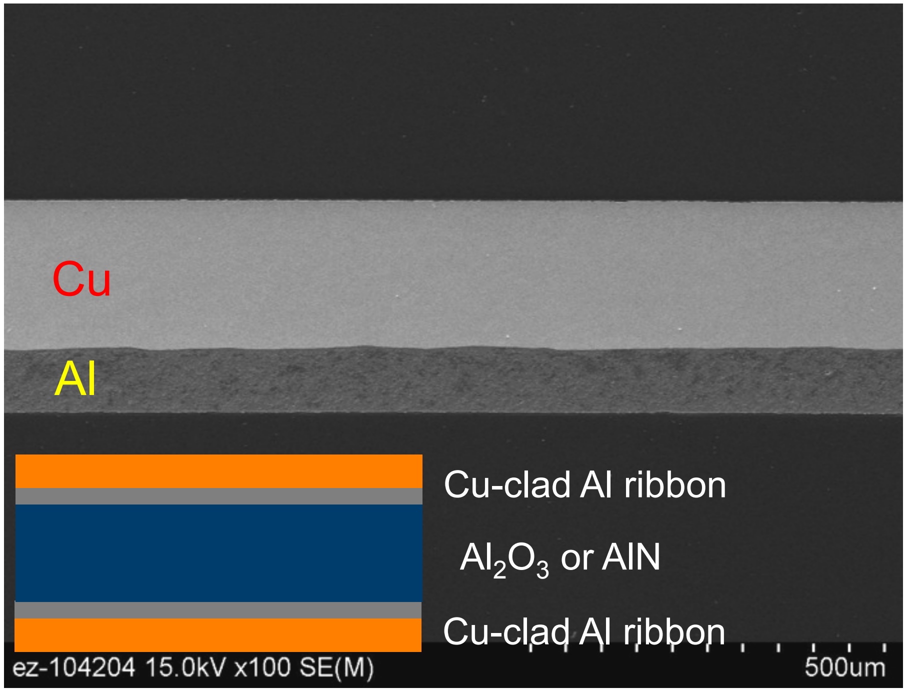
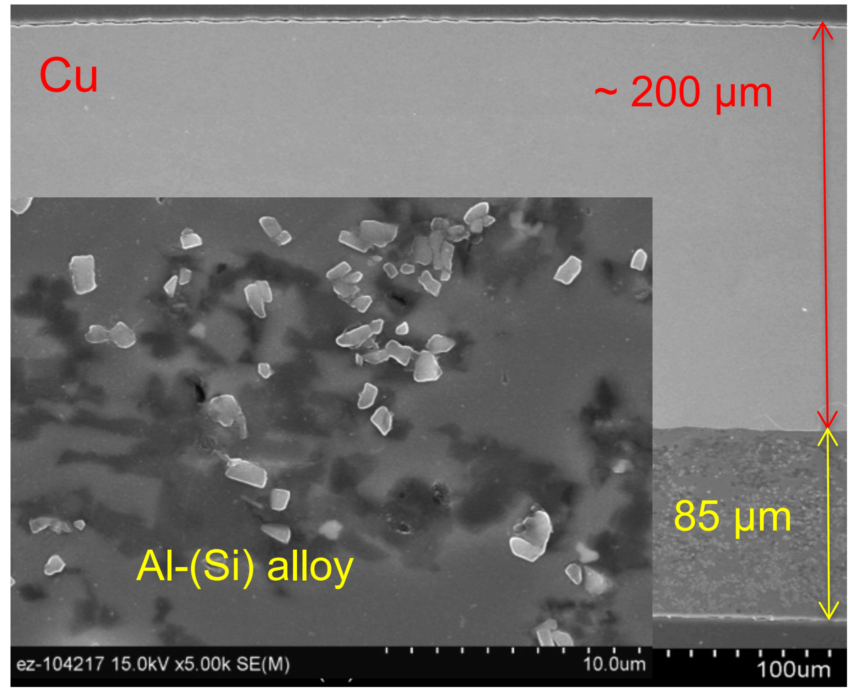
Accomplishments (continued)

Cu-clad Al foil was Evaluated as a Candidate Cladding



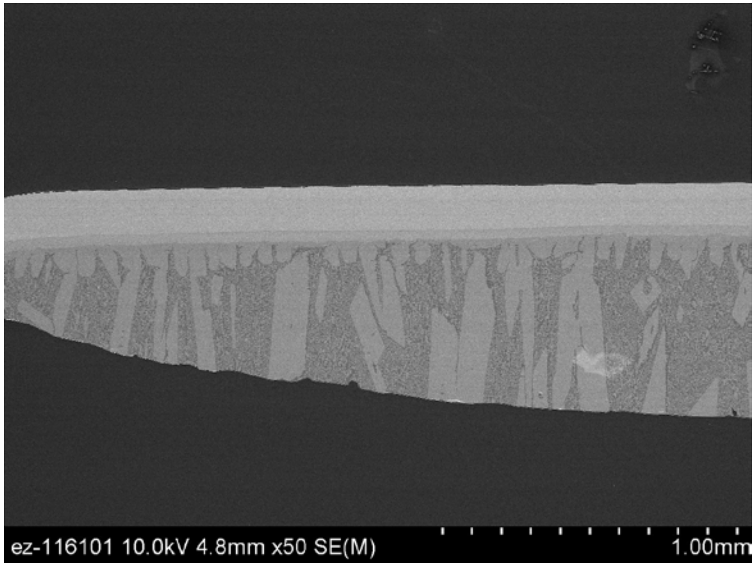


Developmental Cu-clad Al foil was acquired from Materion Corp., Cleveland, OH.

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

Accomplishments (continued)

Poor Bonding Resulted Between Cu-Clad Al Foil & Ceramic



1: 100% Cu

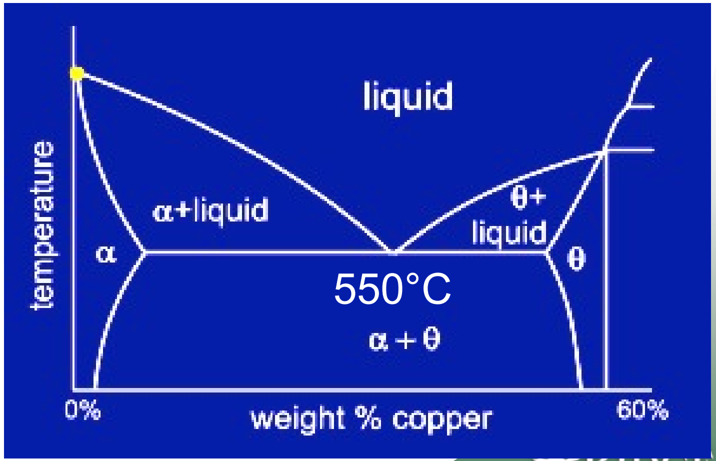
2: 79%Cu-21%Al

3: 75%Cu-25%Al

4: 53%Cu-47%Al

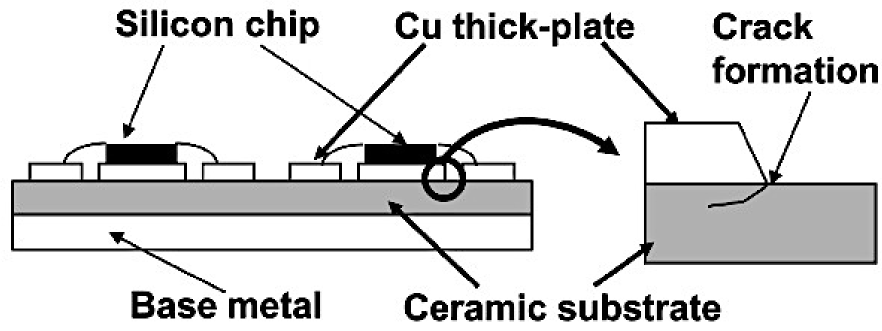
Polished cross section of Cu-clad Al foil after joining

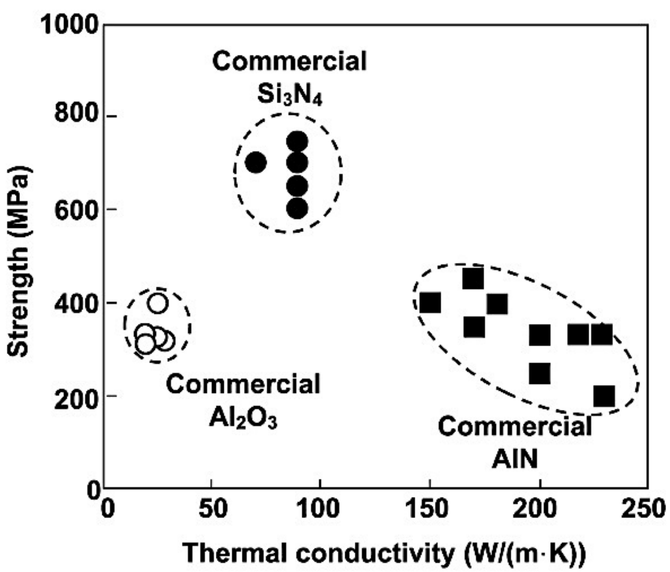
- **Cu-Al exhibits an eutectic point at 550°C lower than Al-Si eutectic point of 577°C**
- **Active brazing alloy might be needed to prevent early Al-Cu eutectic formation**



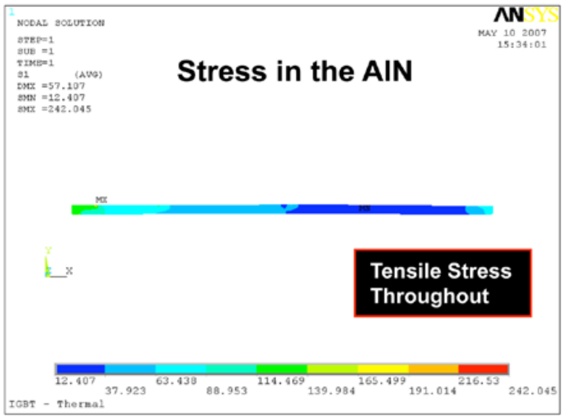
Accomplishments (continued)

Wide Band Gap Technology (GaN or SiC) Requires High Performance Substrates Such as Si_3N_4 DBC Substrates

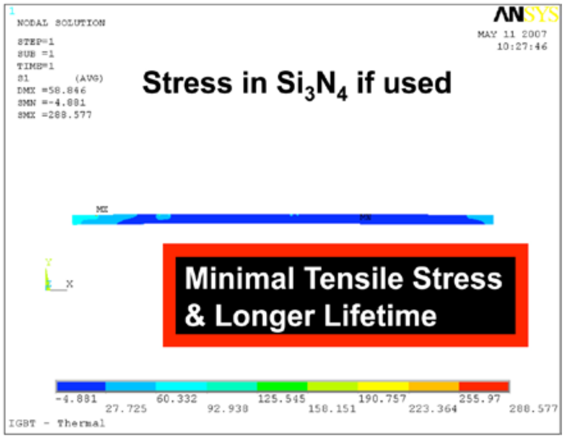




Courtesy of Hirao Kiyoshi, AIST, Japan



σ = 400 MPa
m = 13
K_{IC} = 3 MPa•m$^{0.5}$



σ = 800 MPa
m = 18
K_{IC} = 6 MPa•m$^{0.5}$

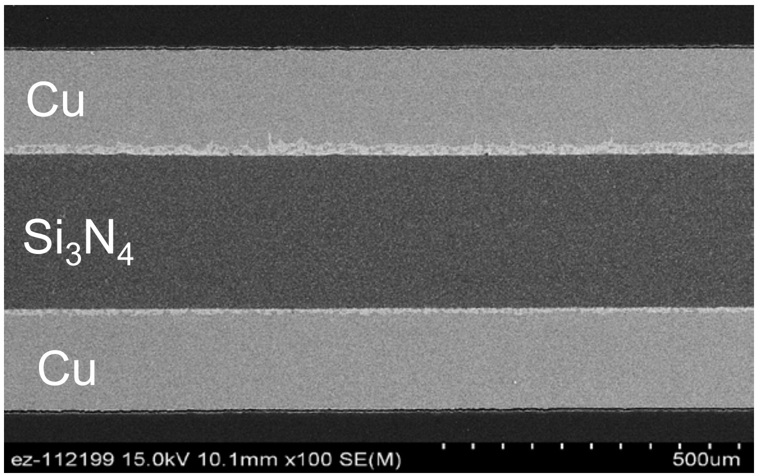
FEA Wereszczak

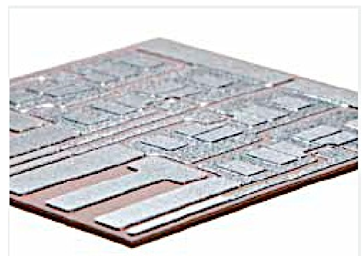
The use of Si_3N_4 ceramic substrate (1/2 of AlN thickness) with excellent mechanical performance could minimize tensile stress and thus improve mechanical reliability

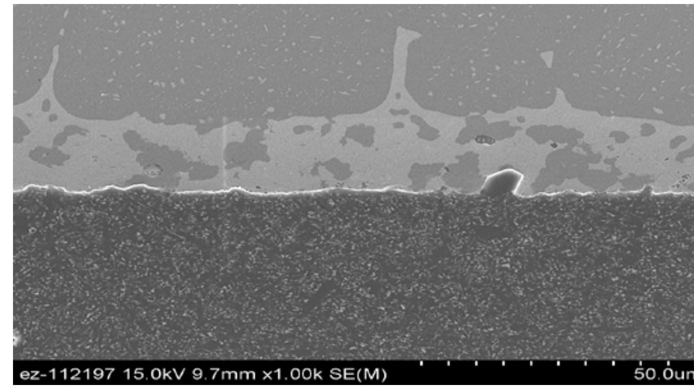
Accomplishments (continued)

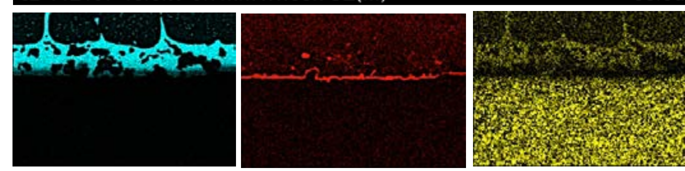
Si_3N_4 DBC Substrates Have Better Mechanical Reliability Than Traditional Substrates

Kyocera AMT DBC









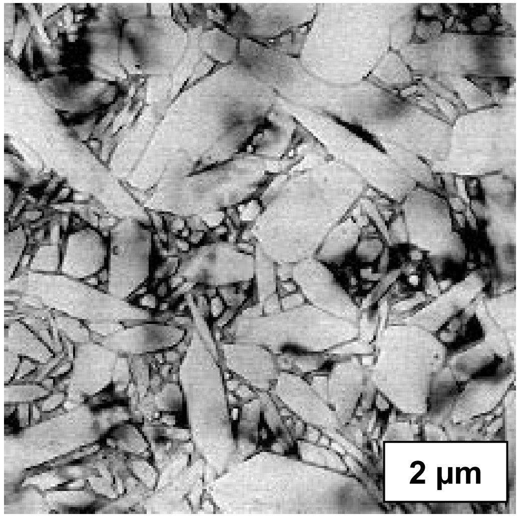
Ag Ti Mg

Supplier	Flexure Strength (MPa)	Fracture Toughness (MPa•√m)	Thermal Conductivity (W/m•k)
Commercial AIN	400	5	150 - 200
Kyocera SN460	850	5	60
Toshiba SN90	650	6.5	90
Curamic SN*	650	6.5 - 7	90

*Curamic (Rogers Corp.) officially demonstrated new Si_3N_4 DBC substrates at eCarTech, Munich, Oct 2012

Accomplishments (continued)

ORNL Si_3N_4 Ceramics Exhibit Comparable or Superior Mechanical Properties to Commercial Ones



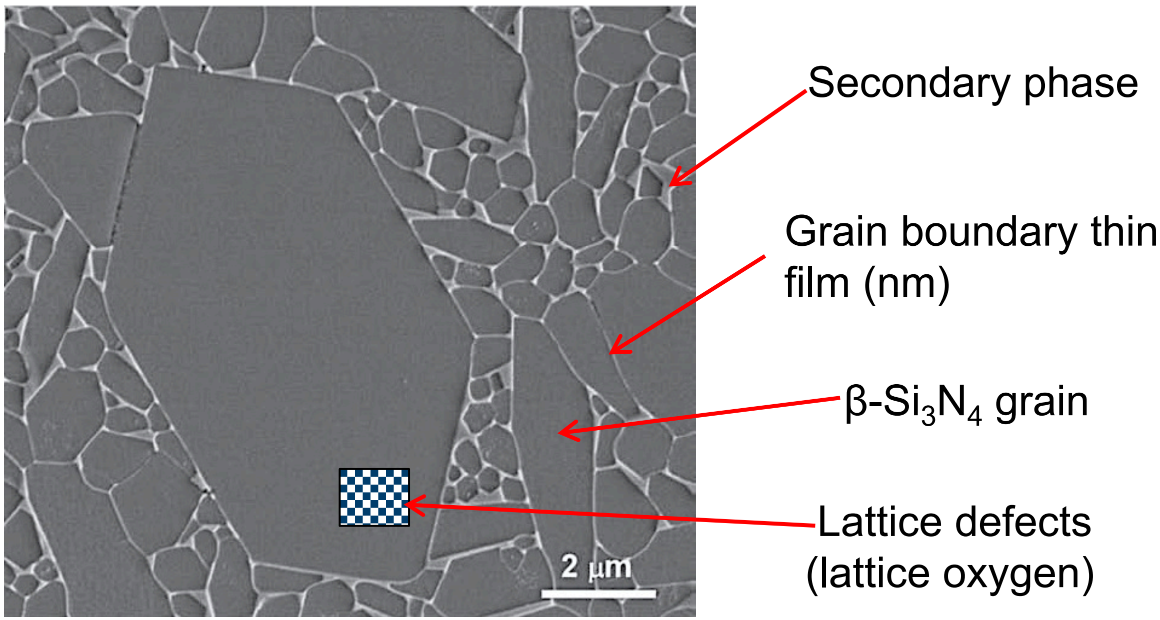
Composition	Flexure Strength MPa @ 22°C	Flexure Strength MPa @ 1200°C	Fracture Toughness MPa•√m
SN8La2Mg	1140	832	10-13
SN8Gd2Mg	1226	906	11
SN8Lu2Mg	1040	894	11-13
SN8La2Si	947	-	10
SN8Gd2Si	997	803	8
SN8Lu2Si	942	-	10
NT154	950	-	6
SN147	700-800	-	6
SN240	1000	-	10

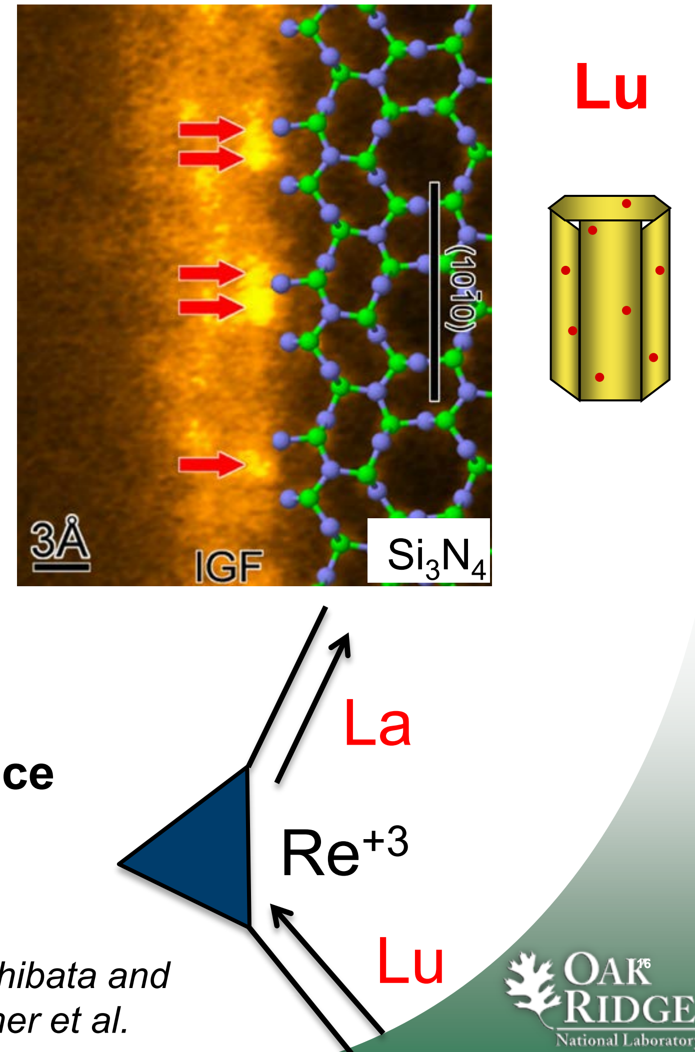
US patent: US 7,968,484 B2
Becher and Lin

- **SN – developed by ORNL**
- **NT154 – Saint-Gobain**
- **SN147 – Ceradyne**
- **SN240 - Kyocera**

Accomplishments (continued)

Thermal Conductivity of Si_3N_4 Can be Tailored by Grain Boundary Microstructure and Chemistry



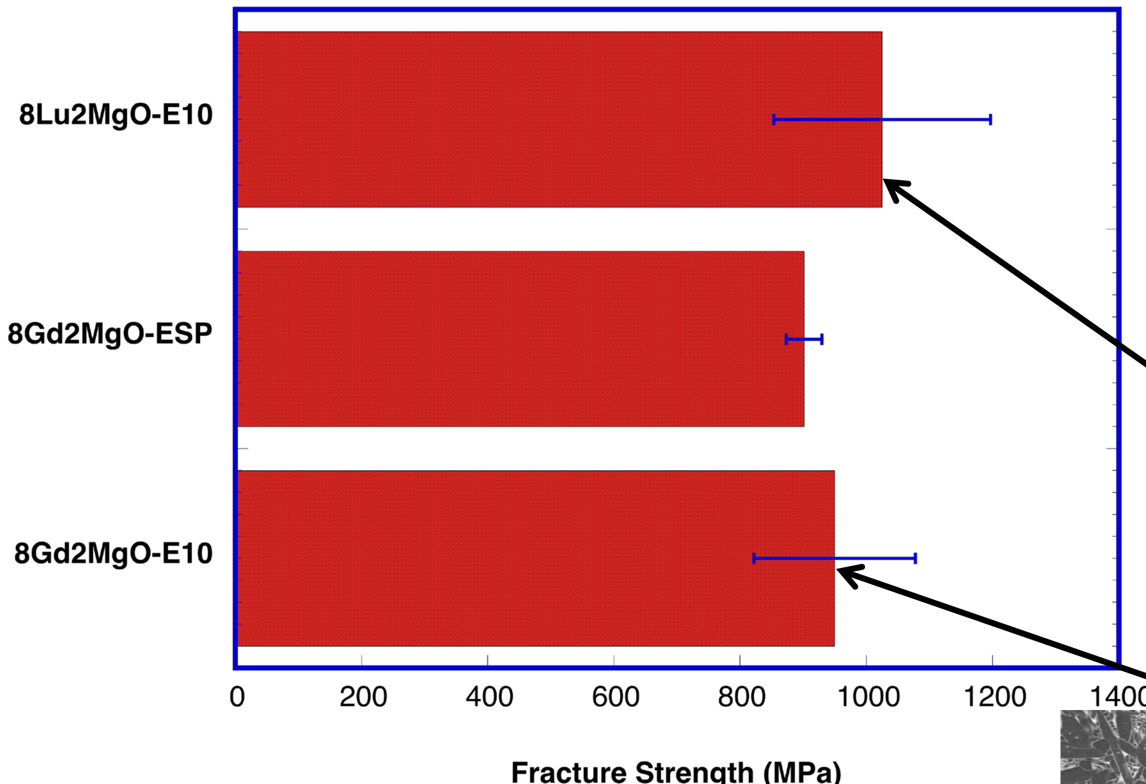


2^{nd} phases, GB film (low thermal property) and lattice oxygen (more phonon scattering) could lower the thermal conductivity of Si_3N_4 ceramics

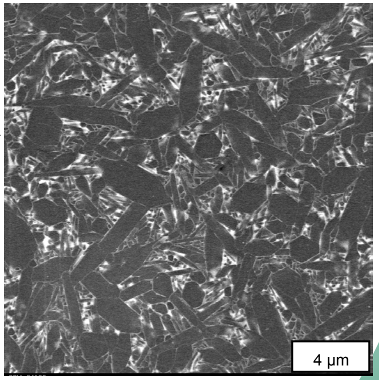
by Shibata and Becher et al.

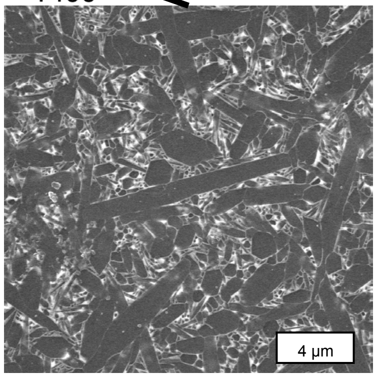
Accomplishments (continued)

Mechanical Strength of ORNL Si_3N_4 Ceramics Confirmed



- **Composition:**
- **8wt% Lu_2O_3-2wt% MgO**
- **8wt% Gd_2O_3-2wt% MgO**
- **Si_3N_3 powder:**
- **Ube E-10 and ESP**
- **Processing conditions:**
- **Hot-press @ 1800°C, 20MPa, N_2**

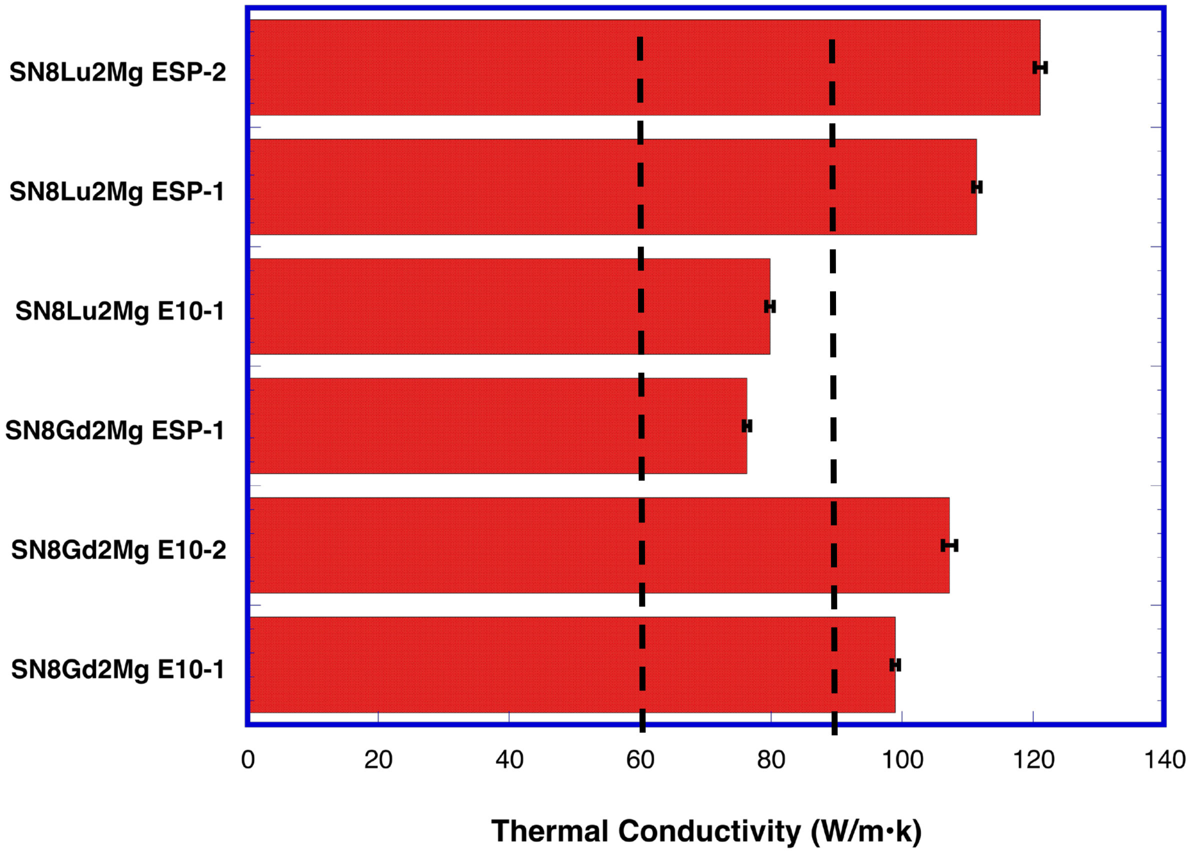




950-1100 MPa: flexure strength of ORNL specimens fabricated in 2010; *JACS, 93 [2] 570–580 (2010)*

Accomplishments (continued)

ORNL Si_3N_4 Ceramics Exhibit Comparable or Superior Thermal Conductivity to Commercial Si_3N_4



- Kyocera SN460: 60 W/mk

- Toshiba SN90: 90 W/mk

- Curamic SN: 90 W/mk

Manufacturers reported data

Measured by laser flash method

Thermal property could be further enhanced by engineering control of Si_3N_4 grain size, oxygen content, and crystallinity of 2nd phase

Collaborations

- **Partners**
  - ✓ Advanced Power Electronics and Electric Motors R&D team members at NTRC of ORNL.
  - ✓ Electric and Electronic Tech Team provided constructive input.
  - ✓ Marlow (established thermoelectric manufacturer) provided their DBA substrate for ORNL to assess and conduct bench mark test.
  - ✓ Materion provided the Cu-clad Al ribbon with tailored thermal and electric property.

- **Technology transfer**
  - ✓ Potential with Marlow, GM or Delphi on the development of high performance DBA/DBC substrates with Si_3N_4 ceramic substrate.
  - ✓ Development of high performance DBA substrate with Si_3N_4 ceramic substrate would provide the high-power and high-temperature challenge for IGBT and MOSFET with SiC or GaN wide band gap material.

Future Work

- Complete fabrication of tape-cast Al-Si thin film using atomization Al-Si powders for bonding Al-AlN (and Al_2O_3) substrates. (FY 13)
- Complete fabrication of tape-cast Si thin film using commercial Si powders for bonding Al-AlN (and Al_2O_3) substrates. (FY13)
- Complete optimization of Si_3N_4 ceramic with both high mechanical and thermal properties for power electronic ceramic substrates. (FY14)
- Develop low-cost Si_3N_4 ceramic using high purity Si powders via sinter-reaction bonded process. (FY14)
- Fabricate DBC (and DBA) substrates using reaction-bonded Si_3N_4 ceramics via Ti-containing active brazing element, and tech transfer and commercialize the products. (FY15)

Summary

- **Relevance:** low cost and robust DBA substrates to improve reliability of power electronic device.
- **Approach:** develop low cost and reliable DBA substrates with AlN and Si_3N_4 ceramic via brazing and/or metallurgical process.
- **Collaboration**: EETT, substrate manufacturers, and materials suppliers.
- **Technical Accomplishments:**
  - ✓ Results confirm compromise between low cost and reliability must be struck.
  - ✓ Processing and characterization of DBA substrates with Al-Si paste and Al-Si foil.
  - ✓ Characterizations of Al-Si and Si powders
  - ✓ Re-produce ORNL Si_3N_4 ceramics with consistent excellent mechanical strength
  - ✓ Thermal property measurements of ORNL Si_3N_4 ceramics
- **Future Works**:
  - ✓ Optimization of Si_3N_4 ceramic with both high mechanical and thermal properties.
  - ✓ Development low-cost Si_3N_4 ceramic using high purity Si powder
  - ✓ Fabrication of DBC (and DBA) substrates using reaction-bonded Si_3N_4 ceramics and tech transfer and commercialize the products.