Environmental Effects on Power Electronic Devices

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Oak Ridge National Laboratory

2009 Vehicle Technologies Annual Merit Review

and Peer Evaluation Meeting

Arlington, VA

21 May 2009

Project ID #: pmp_20_wereszczak

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Overview

Timeline

- Project start: October 2007
- Project end: September 2010
- Percent complete: 50%

Budget

- Total project funding
  - DOE 100%
- FY08: $200k
- FY09: $200k

Barriers*

- Barriers Addressed
  - Higher-temperature-capable IGBTs
  - Accurate life prediction not available
  - PE components not sufficient rugged
  - PE components need improved thermal management
- Targets:
  - DOE VTP 2015 target: 105°C Coolant
  - DOE VTP 2015 target: 12 kW/l

Partners

- ORNL/NTRC
- Powerex
- Cree
- Kyocera
- Saint-Gobain

* FCVT Multi-Year Program Plan

Objectives

- Understand the complex relationship between environment (temperature, humidity, and vibration) and automotive power electronic device (PED) performance through materials characterization and modeling.

- Identify alternative materials and architectures internal to PEDs that will improve reliability and enable higher temperature operation.

Milestones

- **FY08: Examine how temperature environment in a power electronic device affects thermomechanical stresses of its constituents.**

- **FY09: Compare cooling efficiencies in a hybrid inverter IGBT that contains contemporary and alternative ceramic DBC substrates.**

Technical Approach

- Evaluate environmental effects on PE devices though modeling and experimental analyses.
- Dissect PE devices as part of their postmortem and evaluate failure initiation location.
- Evaluate the thermal management effectiveness of PE devices and seek means to achieve improvements that will enable reliability improvement and higher temperature usage.

Technical Accomplishments – 1 of 8

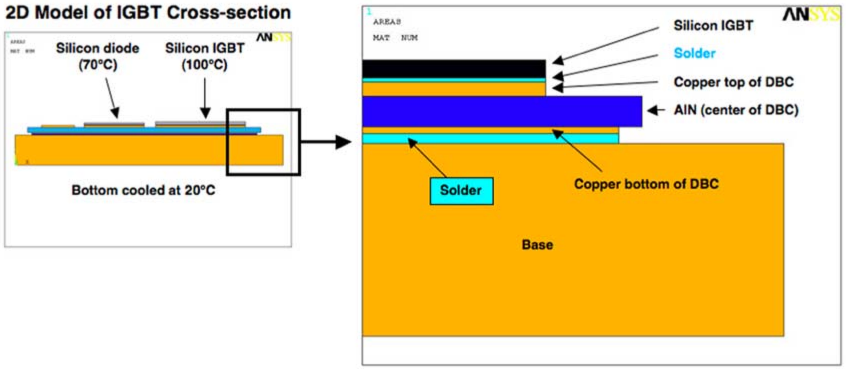
Overview of FY08 results

- **Modeling**
  - **100A-1200V IGBT module dissected, constituent dimensions measured, and thermomechanical stresses modeled**
  - **Direct-cooled ceramic substrate concept co-developed (patent filed)**
- **Experimental**
  - **Strength of several ceramic substrates measured**
  - **Strength of Si and SiC semiconductor chips measured**
  - **Alternative ceramic substrate material examined**

Technical Accomplishments – 2 of 8

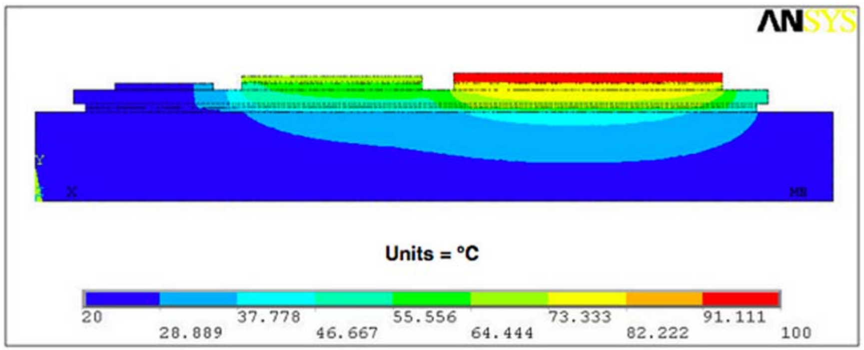
Dissection of IGBT enables modeling of stresses

IGBT model:

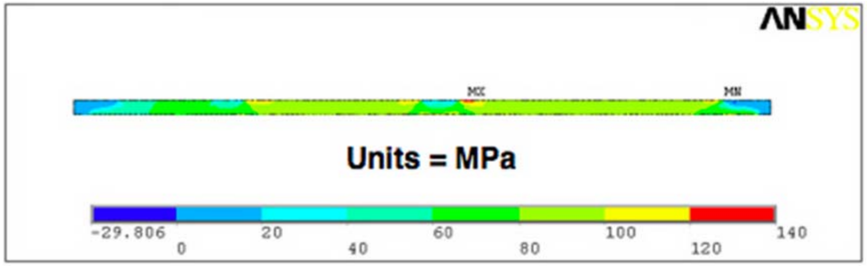


Material / Property	E (GPa)	v	CTE (ppm/°C)	TC (W/mK)	S_{yld} (MPa)
Silicon	130	0.28	4.1	150	∞ (Elastic)
Copper	135	0.34	17	400	∞ and 138 (Plastic)
AlN ceramic	300	0.24	4.5	150	∞
Solder	12.5	0.36	26	15	∞ and 22

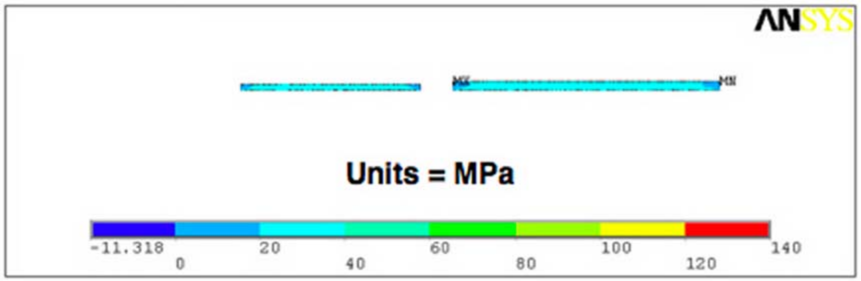
Representative thermal profile



Ceramic substrate stress field



Si or SiC stress field



Technical Accomplishments – 3 of 8

Stress analysis of direct-cooled ceramic substrate

- **Modeled the thermomechanical stress of a variety of designs (with NTRC/ORNL)**
- **Use CARES to estimate probability of survival of the ceramic substrate**
- **Patent filed for in early 2009**

Technical Accomplishments – 4 of 8

Strength of various ceramic substrates

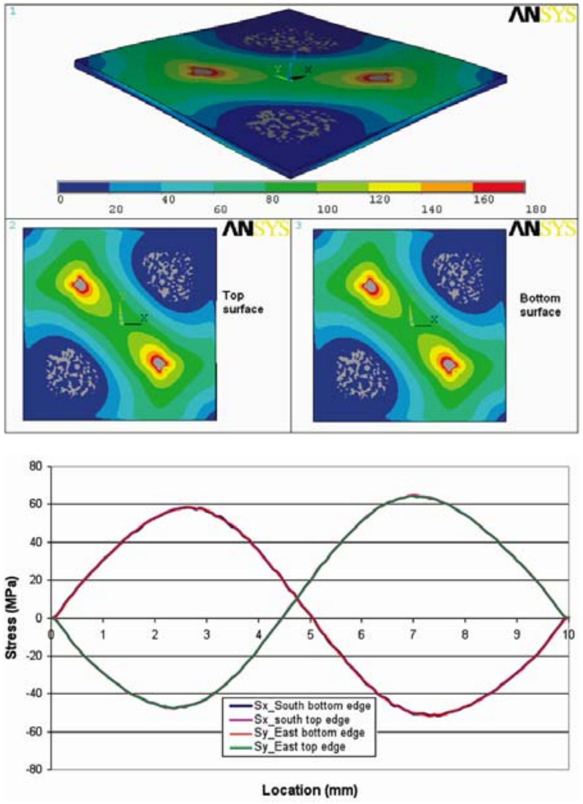
Material	Descriptor	Number of Specimens	Characteristic Equibiaxial Strength* (MPa)	Weibull Modulus
Aluminum Nitride	As Fired	15	665	33.0
Aluminum Nitride	Lapped	10	452	13.0
Aluminum Oxide	AD96	10	595	12.7
Aluminum Oxide	AD995	10	692	16.9
Boron Nitride		15	50	12.8
Silicon Carbide	Sintered Alpha	10	518	4.8
Silicon Nitride	SN460	15	1097	17.7

* Test Fixture: Ball on Ring (15mm Ring, 1/2" WC Ball, XHD=0.5 mm/min)

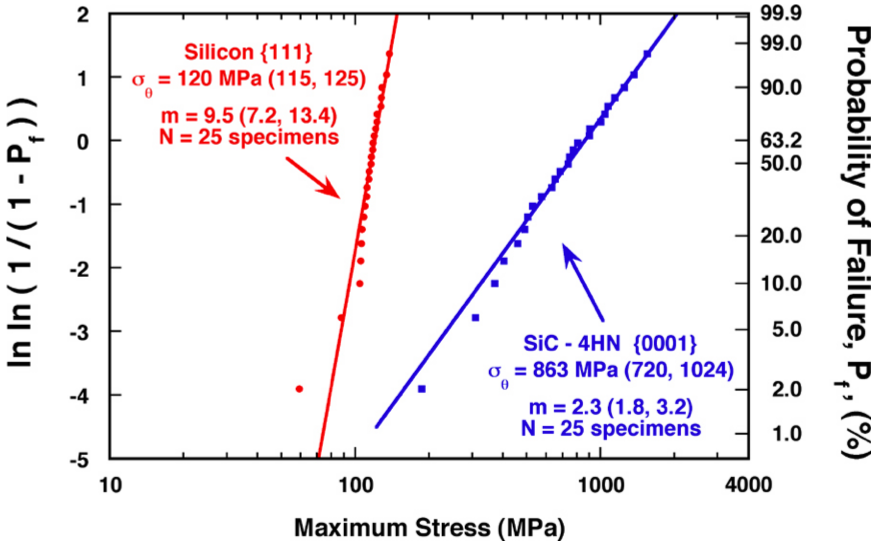
Technical Accomplishments – 5 of 8

Surfaces & edge-flaws limit strength of Si and SiC chips

Anticlastic bending



Strength of Si and SiC chips



Technical Accomplishments – 6 of 8

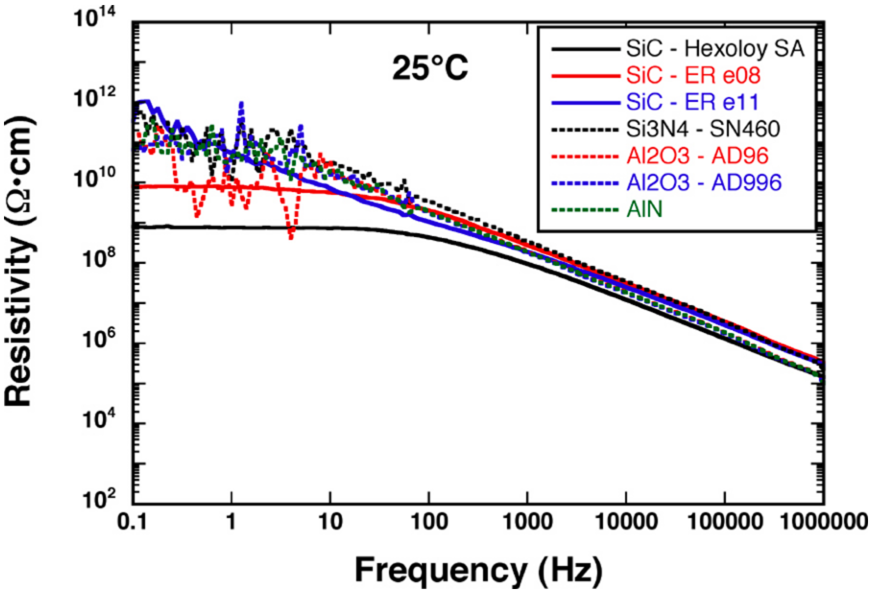
Issues with AlN (ceramic substrate)

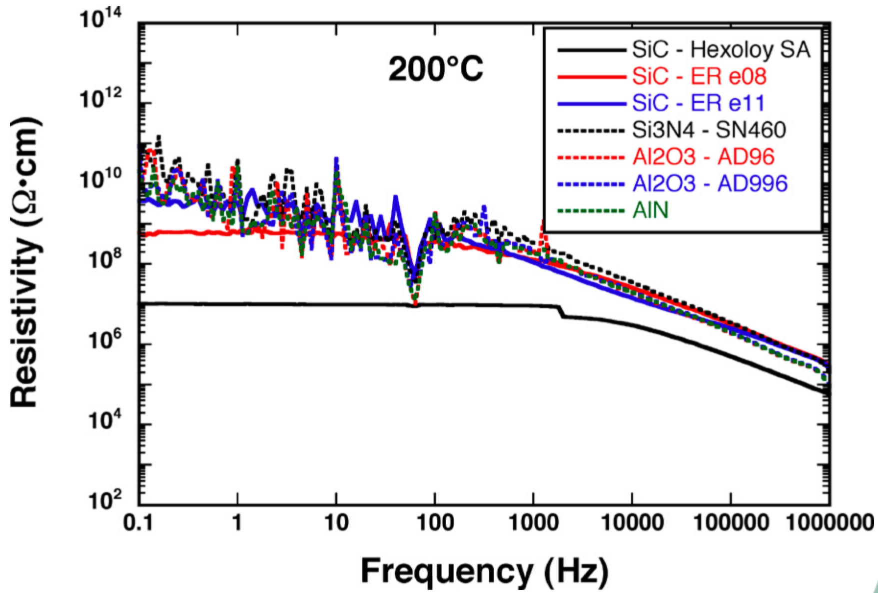
- **Expensive**
- **Decreasing list of manufacturers (too niche)**
- **Hydrophylic**
  - **"An intensive chemical reaction occurs between the AlN, H_20 and alkali, which causes a violent corrosion of AlN in alkaline aqueous solutions." Young and Duh, J. Mat. Sci., 30:185-195 (1995).**
  - **… "The hydrolysis of aluminum nitride (AlN) in these reactions is currently the major problem." Fukomoto et al., J. Mat. Sci., 35:2743-48 (2000).**

Technical Accomplishments – 7 of 8

Polycrystalline SiC as a substrate ceramic

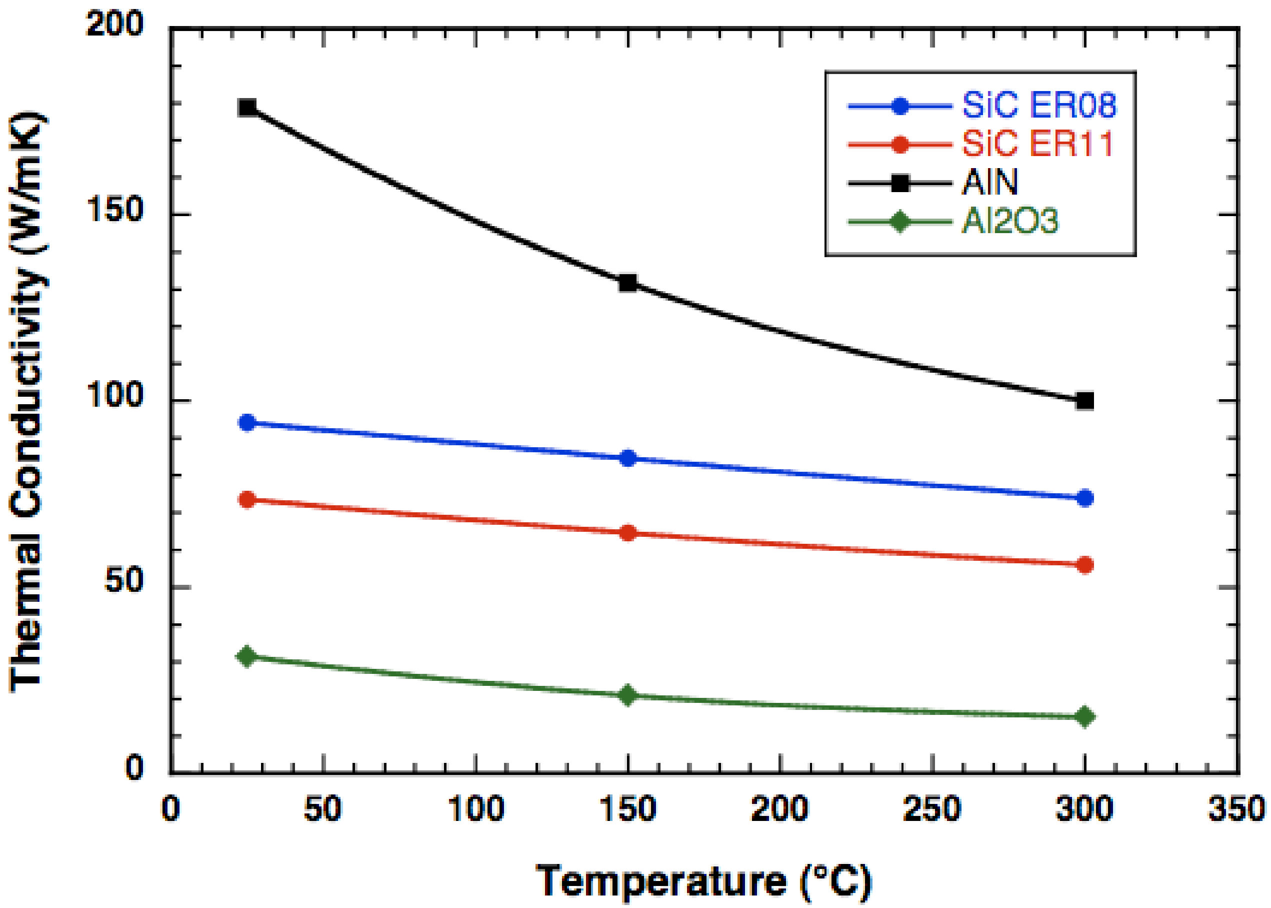
Resistivity as high as common substrate ceramics (e.g., Al_2O_3, AlN)





Technical Accomplishments – 8 of 8

The high TC of Polycrystalline SiC is attractive



Future Work

- Compare cooling efficiencies in a hybrid inverter IGBT that contains contemporary and alternative ceramic substrates. [FY09-FY10]

- Establish strength-size-scaling characteristics for {111} silicon and 4HN-silicon-carbide semiconductor chips and refine mechanical test methods that will enable the study of the effects of edge-type strength-limiting flaws. [FY09]

- Continue to model and interpret thermomechanical stress states of automotive PE devices in support of the APEEM Program and, where applicable, recommend alterative material constituents that will lessen stresses. [FY09-FY10]

- Continue to pursue the development of alternative electrically insulating ceramics having high thermal conductivity and prospects for low-cost production. [FY09-FY10]

Summary

- The thermomechanical stress state in an IGBT module was modeled, and the consideration of using alternative insulating ceramics began.

- A direct-cooled ceramic substrate concept was developed that is applicable to power electronic devices. *It will be able to reduce both weight and volume of inverters for hybrid vehicles.* A patent for this was applied for.

- The strength measurement of ceramic substrates occurred, and that for silicon and silicon carbide chips initiated. Test methods are under development to assess the effects of edge-type flaws on the strength of the silicon and silicon carbide chips.

- Electrically insulating polycrystalline silicon carbide is under consideration as an electronic substrate.