Thermal Management and Reliability of Automotive Power Electronics and Electric Machines

Sreekant Narumanchi
National Renewable Energy Laboratory
Email: sreekant.narumanchi@nrel.gov; Phone: 303-275-4062

Team: Kevin Bennion, Emily Cousineau, Doug DeVoto, Xuhui Feng, Bidzina Kekelia, Ram Kotecha, Joshua Major, Gilbert Moreno, Paul Paret, Jeff Tomerlin

International Workshop on Integrated Power Packaging
Toulouse, France
April 26, 2019
Research Pathway to Electrification

- Vehicle architecture change
  - Driven by long-range BEVs and need for commonality for production scale

- Greater fleet applications of BEVs
  - Mobility as a Service
  - Driving increase in reliability (15 years/300K miles)

- Long-range BEVs
  - Driving need for high-rate power transfer – high-power charging

- Innovations to overcome gaps
  - Understanding the physics of new materials
  - Quantifying the impact of new designs

BEV: Battery Electric Vehicle


Significant volume reduction (factor of 10)
Improved reliability (factor of 2)
Lower cost (50% lower)
Future Power Electronics Designs – Gaps and Challenges

- Planar power electronics construction
- Reduction in volume/size by a factor of 10 – thermal and reliability challenges
- Materials innovations needed (electrical, thermal, mechanical, and magnetic properties)
NREL APEEM Research Focus Areas

Power Electronics
Thermal Management

Advanced Packaging
Designs and Reliability

Electric Motor
Thermal Management

APEEM: Advanced Power Electronics and Electric Motors
Power Electronics Thermal Management

- Compact, power-dense wide-bandgap (WBG)-device-based power electronics require
  - Higher-temperature-rated components and materials
  - Advanced heat transfer technologies
  - System-level thermal management

Advanced cooling

Component-level and system-level heat transfer

Photo by Gilbert Moreno, NREL
Thermal Strategy to Reach a Power Density of 100 kW/L

Define the thermal target to achieve 100 kW/L

- Heat load (100 kW inverter): 2,150 W
- Maximum device temperature: 250°C
- Module and cold plate volume: < 240 mL

Volumetric thermal resistance target: 21 cm³-K/W

Design the cooling strategies

Convective cooling

Cooling fluid

Dielectric cooling (single-phase heat transfer) planar package concept

Device packaging

Photo by Gilbert Moreno, NREL
Dielectric Cooling Concept

- Cooling of the bus bars/electrical interconnects to lower capacitor and gate driver temperatures
- Improved cooling (single-phase) via jet impingement and finned surfaces
- Eliminates expensive ceramic materials
- Improved performance over conventional direct-bond-copper (DBC)-based designs

Dielectric fluid

Electrical lead

MOSFET: metal–oxide–semiconductor field-effect transistor
Designed fluid manifold to distribute flow to 12 devices

- Reduced size: 120 mL total cold plate and power module volume
- Total flow rate: 4.1 Lpm at 0.33 psi pressure drop
- Reduced pumping power: 80% lower parasitic power compared to 2014 Honda Accord Hybrid

Results using Alpha 6 fluid at $T_{\text{inlet}} = 65^\circ\text{C}$
Experimental Validation

**Designed the heaters**
- To simulate devices and dissipate >700 W/cm²

**Cartridge heater design-temperature contours**

**Completed cold plate fabrication**
- 3D printed using inexpensive, lightweight plastic to test prototype
- Cold plate can be fabricated using conventional manufacturing methods

**Nylon cold plate manifold prototype**

**Cold plate size compared to cell phone**
Advanced Power Electronics Packaging Performance and Reliability

- Improve reliability of new (high-temperature/WBG) technologies
- Develop predictive and remaining lifetime models
- Package parametric modeling

Crack Propagation in Pressure-Assisted (30 – 40 MPa) Sintered Silver

Photo by Paul Paret, NREL
High-Temperature Bonded Material

Cu/Al, Cu/Sn

Georgia Tech

Virginia Tech

Hybrid-silver

Low pressure-assisted

NREL

Nano-silver

Pressureless

Cu-Al bond – SEM image¹

AIN

Cu-Al

ALSiC

Cu-Al bond – SEM image¹

Photo by Darshan Pahinkar, Georgia Tech

Photo by G.-Q. Lu, Virginia Tech

SEM: scanning electron microscope

¹ Photo by Darshan Pahinkar, Georgia Tech

² Photo by G.-Q. Lu, Virginia Tech

Cu: copper, Al: aluminum, Sn: tin

AIN: aluminum nitride

ALSiC: aluminum silicon-carbide

Hybrid-silver – SEM image²
Sintered Silver Reliability Evaluation

- Subject CTE-mismatched samples bonded with the material of interest to thermal cycling from -40°C to 200°C
- Obtain C-SAM images of the bond material at periodic cycling intervals
- Estimate crack growth rate from C-SAM images through image analysis

C-SAM: C-mode scanning acoustic microscope
CTE: co-efficient of thermal expansion
Thermal Cycling of Pressure-Assisted Sintered Samples (3 MPa)

- Four samples were cycled for each diameter case.
- Failure (> 20% crack growth) may have occurred within 50 cycles.
- Crack growth rate was higher on the Invar side.
Mode of crack propagation was found to be a combination of cohesive and adhesive failure mechanisms.

Presence of different crack modes possibly indicates the strong impact of both global (Cu and Invar) and local (silver and Invar) CTE mismatch.

Multiple cracks observed explain the difference in C-SAM images/crack percentage calculations from Cu and Invar side.
Organic Direct-Bond-Copper Substrate Thermal Performance

- Substrates were placed between diode and cold plate.
- A transient power pulse was applied to the package, and the decay of the temperature in the diode was monitored over time to establish the resistance-capacitance network for the package.
- ODBC thermal performance is similar to AlN.

### Thermal Resistance of Sample Package

<table>
<thead>
<tr>
<th>Material</th>
<th>RTH (K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu 5.0 mm</td>
<td>0.917</td>
</tr>
<tr>
<td>Si₃N₄ AMB 0.8/0.32/0.8 mm</td>
<td>1.045</td>
</tr>
<tr>
<td>AlN 0.3/0.38/0.3 mm</td>
<td>1.071</td>
</tr>
<tr>
<td>ODBC 1.0/0.025/1.0 mm</td>
<td>1.082</td>
</tr>
<tr>
<td>Al₂O₃ 0.3/0.38/0.3 mm</td>
<td>1.112</td>
</tr>
<tr>
<td>HPS 9% 0.3/0.32/0.3 mm</td>
<td>1.118</td>
</tr>
</tbody>
</table>

ODBC: Organic Direct-Bond-Copper
Si₃N₄ AMB: Silicon nitride atomic metal brazing
AlN: Aluminum nitride
Al₂O₃: Aluminum oxide
HPS: High-performance substrate

Photo by Douglas DeVoto, NREL
ODBC Reliability

- Thermal Shock: -40°C to 200°C, 5-minute dwells
- Thermal Aging: 175°C
- Power Cycling: 40°C to 200°C
- ODBC substrates have reached 5,000 thermal shock cycles, 1,900 thermal aging hours, and 2,200 power cycles
- No significant decrease in electrical or thermal performance has been observed.
Electric Motor Thermal Management

- Increase current density, power density
- Increase reliability
- Higher voltages and switching frequencies
- Understand material properties as a function of temperature and material lifetime
- Advanced cooling strategies

Photos by Doug DeVoto, Emily Cousineau, Kevin Bennion and Bidzina Keklia, NREL
• Quantify impact of new or alternative cooling approaches for ATF cooling of motors.
• Characterize impact of new cooling fluids.

ATF: automatic transmission fluid
Photos by Kevin Bennion and Bidzina Kekelia, NREL
ATF Orifice Jet Impingement

Heat transfer coefficients (HTC) for ATF at $T_{\text{fluid}} = 70^\circ\text{C}$

- Temperature of the cooled surface affects HTC values:
  \[ T_{\text{surface}} \uparrow \Rightarrow h \uparrow \]

- Experiments ongoing to evaluate impact of varying other parameters on HTC:
  - incidence angle
  - nozzle distance from target surface
Material/Interface Thermal Characterization

- Stator-to-case thermal contact resistance
- Liner-to-stator thermal contact resistance
- Winding-to-liner thermal contact resistance
- Cross-slot winding thermal conductivity
- Slot windings
- Slot liner or ground insulation

Illustration by Kevin Bennion, NREL
• Validated model with experimental data using multiple materials.
### Multiple Research Activities and Projects

<table>
<thead>
<tr>
<th>DOE VTO Electrification R&amp;D</th>
<th>Thermal management and reliability of electric-drive vehicle power electronics and electric machines; high-power fast charging Advanced WBG power electronics and thermal management techniques</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ARPA-E</strong></td>
<td>Advanced WBG power electronics and thermal management techniques</td>
</tr>
<tr>
<td><strong>DOE AMO PowerAmerica</strong></td>
<td>Manufacturing WBG power electronics</td>
</tr>
<tr>
<td><strong>AMO Next-Generation Electric Machines</strong></td>
<td>Energy-efficient, high-power-density, high-speed integrated medium-voltage-drive systems for critical energy applications</td>
</tr>
<tr>
<td><strong>AMO Medium-Voltage Power Electronics</strong></td>
<td>Grid-tied power electronics</td>
</tr>
<tr>
<td><strong>AMO Traineeship in Power Engineering</strong></td>
<td>Traineeship and curriculum development leveraging WBG power electronics</td>
</tr>
<tr>
<td><strong>Technology Commercialization</strong></td>
<td>Bringing lab-developed technology closer to commercialization/production</td>
</tr>
<tr>
<td><strong>DOD and Industry-Funded</strong></td>
<td>DOD agency and industry-funded projects in the broad areas of thermal management and reliability</td>
</tr>
<tr>
<td><strong>NREL Laboratory Directed Research and Development</strong></td>
<td>Projects in the areas of power electronics prognostics and ultra-WBG power electronics packaging</td>
</tr>
</tbody>
</table>
Summary

• Low-cost, high-performance thermal management technologies are helping meet aggressive power density, specific power, cost, and reliability targets for power electronics and electric machines.

• NREL is working closely with numerous industry and research partners to help influence development of components that meet aggressive performance and cost targets through:
  - Development and characterization of cooling technologies
  - Thermal characterization and improvements of passive stack materials and interfaces
  - Reliability evaluation, lifetime, and physics-of-failure models.

• Thermomechanical reliability and lifetime estimation models are important enablers for industry in cost- and time-effective design.
Acknowledgments:

Susan Rogers  
Electric Drive Technologies Program  
Vehicle Technologies Office  
Advanced Manufacturing Office  
U.S. Department of Energy

For more information, contact:

NREL APEEM Team Leader  
Sreekant Narumanchi  
sreekant.narumanchi@nrel.gov  
Phone: 303-275-4062

<table>
<thead>
<tr>
<th>Industry and Research Partners</th>
<th>Industry Original Equipment Manufacturers</th>
<th>Suppliers/Others</th>
<th>Agencies</th>
<th>National Laboratories</th>
<th>Universities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ford, General Motors, Fiat-Chrysler Automobiles, John Deere, Tesla, Toyota, Caterpillar</td>
<td>3M, NBETech, Curamik, DuPont, Energetics, GE Global Research, GE Aviation, Indian Integrated Circuits, Semikron, Kyocera, Sapa, Delphi, Btechcorp, ADA Technologies, Remy/BorgWarner, Heraeus, Henkel, Wolverine Tube Inc., Wolfspeed, Kulicke &amp; Soffa, UQM Technologies, nGimat LLC</td>
<td>DARPA, U.S. Army Research Laboratory</td>
<td>Oak Ridge National Laboratory, Ames Laboratory, Argonne National Laboratory, Sandia National Laboratories</td>
<td>Virginia Tech, University of Colorado Boulder, University of Wisconsin, Carnegie Mellon University, Texas A&amp;M University, North Carolina State University, Ohio State University, Georgia Tech, University of Missouri Kansas City, North Dakota State University, University of Maryland</td>
</tr>
</tbody>
</table>