Thermal Management of Power Electronics and Electric Motors for Electric-Drive Vehicles

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Session SS1
September 15, 2014
Importance of Thermal Management

- Excessive temperature degrades the performance, life, and reliability of power electronics and electric motors.

- Advanced thermal management technologies enable
  - keeping temperature within limits
  - improved reliability
  - higher power densities
  - lower cost materials, configurations and system.
DOE APEEM Program Mission

- Department of Energy Vehicle Technologies Office (VTO)
  - Develop more energy-efficient and environmentally-friendly highway transportation technologies that enable America to use less petroleum.
- Advanced Power Electronics and Electric Motors (APEEM)
  - Develop APEEM technologies to enable large market penetration of electric-drive vehicles.

Research Laboratories
- Oak Ridge National Laboratory
  - Lead: Power Electronics and Electric Motors
- Lead: APEEM Thermal Management
- Others: Argonne National Laboratory, Ames Laboratory

Industry, Automotive Suppliers and University Interactions
VTO APEEM Electric Drive System Targets

- Discrete Components
- Silicon Semiconductors
- Rare-Earth Motor Magnets
- Fully Integrated Components
- Wide-Bandgap (WBG) Semiconductors
- Non Rare-Earth Motors

2012 Electric Drive System
$30/kW, 1.1 kW/kg, 2.6 kW/L
90% system efficiency
(on-road status)

2022 Electric Drive System
$8/kW, 1.4 kW/kg, 4.0 kW/L
94% system efficiency

4X Cost Reduction
35% Size Reduction
40% Weight Reduction
40% Loss Reduction
NREL APEEM Research Focus Areas

Power Electronics Thermal Management

Advanced Packaging Reliability

Electric Motor Thermal Management

Enabling Materials

Research Focus Areas Will Reduce Cost, Improve Performance and Reliability
Power Electronics Thermal Management Strategy

• Packages based on WBG devices require advanced materials, interfaces, and interconnects
  • Higher temperature capability
  • Higher effective thermal conductivity

• Low-cost techniques to increase heat transfer rates are required
  • Coolants – water-ethylene glycol (WEG), air, transmission coolant, refrigerants
  • Enhanced surfaces
  • Flow configurations
Thermal Resistance of Various Non-Bonded TIMs

- Red dashed line in the two figures above is the target thermal resistance (3 to 5 mm²K/W).
- Most non-bonded TIMs do not come close to meeting thermal specification of 3 to 5 mm²K/W thermal resistance at approximately 100-μm bond line thickness.
Thermal Resistance of Sintered Silver and Solder

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 silver and lead-free solder both showed promising results.

- Bonded interface resistance in the range of 1 to 5 mm²K/W is possible.
  - Materials developed in the DARPA nTIM Program are in this range.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Thickness (µm)</th>
<th>Resistance (mm²K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silvered Cu-Cu sintered interface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>5.4</td>
<td></td>
</tr>
<tr>
<td>Cu-Cu soldered interface (SN100C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>3.7</td>
<td></td>
</tr>
</tbody>
</table>
Thermal Resistance of Thermoplastics

<table>
<thead>
<tr>
<th></th>
<th>Thermoplastic film HM-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bondline thickness (µm)</td>
<td>60</td>
</tr>
<tr>
<td>Bulk thermal conductivity (W/m·K)</td>
<td>44.5 ± 8.0</td>
</tr>
<tr>
<td>Contact resistance (mm²·K/W)</td>
<td>3.1 ± 1.1</td>
</tr>
<tr>
<td>Total thermal resistance (mm²·K/W)</td>
<td>7.5 ± 1.9</td>
</tr>
</tbody>
</table>

- Thermoplastics with embedded carbon fibers show very good thermal performance.
- Thermal performance characterized via the transient thermoreflectance technique.

Photo: Courtesy of BtechCorp

Transient Thermoreflectance Technique Setup
Integrated Module Heat Exchanger

NREL integrated module heat exchanger
Patent No.: US 8,541,875 B2 (Kevin Bennion and Jason Lustbader)

• Up to 100% increase in power per die area
• Up to factor of 8 increase in coefficient of performance
Liquid Jet-Based Plastic Heat Exchanger

- Up to 12% increase in power density
- Up to 36% increase in specific power
Two-Phase Cooling for Power Electronics

<table>
<thead>
<tr>
<th>Fundamental Research</th>
<th>Module-Level Research</th>
<th>Inverter-Scale Demonstration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characterized performance of HFO-1234yf and HFC-245fa.</td>
<td>Reduced thermal resistance by over 60% using immersion two-phase cooling of a power module.</td>
<td>Dissipated 3.5 kW of heat with only 180 mL of refrigerant.</td>
</tr>
<tr>
<td>Achieved heat transfer rates of up to ~200,000 W/m²-K.</td>
<td>Quantified refrigerant volume requirements.</td>
<td>Predicted 58%-65% reduction in thermal resistance via indirect and passive two-phase cooling.</td>
</tr>
</tbody>
</table>
Air Cooling for High-Power Electronics

- Maximum Temperatures
- Device Efficiency

- Inverter Components
- Under-hood Location

- Parasitic Power (fan)
- Air Source (ducting)
Heat Dissipation for Optimized Case (6 modules)

Shows the potential for air cooling without inverter housing.
Bonded Interface Material Reliability

- Thermoplastics yield very good reliability.
- Reliability of sintered silver is better than solder.
Bonded Interface Material Reliability

- Thermoplastics yield very good reliability.
- Reliability of sintered silver is better than solder.
Three 400-µm wires can be replaced by a single 2,000-µm x 200-µm ribbon for equivalent current carrying capability.
Electric Motor Thermal Management Strategy

- Advanced materials and interfaces are required
  - Lower cost (less rare earth) materials
  - Higher effective thermal conductivity

- Low-cost techniques to increase heat transfer rates are required
  - Coolants – water-ethylene glycol (WEG), air, transmission coolant, refrigerants
  - Enhanced surfaces
  - Flow configurations
  - Reduce temperature
Transmission Oil Jet Heat Transfer Characterization

50°C Inlet Temperature

- Heat transfer coefficients on all target surfaces at 50°C inlet temperature.
- At lower impingement velocities, all samples achieve similar heat transfer.

Note: Heat transfer coefficient calculated from the base projected area (not wetted area)
Lamination Stack Effective Thermal Conductivity

- Measured Stack Thermal Resistance
- Lamination-to-Lamination Thermal Contact Resistance
- Effective Through-Stack Thermal Conductivity

Asymptotic Stack Thermal Conductivity [W/m-K]

Pressure [kPa]

Error bars represent 95% confidence level
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 motors.

• NREL is working closely with industry and research partners to help influence development of components which meet aggressive performance and cost targets
  – Through development and characterization of cooling technologies.
  – Passive stack materials and interfaces thermal characterization and improvements.

• Thermomechanical reliability and lifetime estimation models are important enablers for industry in cost-and-time-effective design.
Acknowledgments:
Susan Rogers and Steven Boyd  
Technology Managers  
APEEEM Program  
Vehicle Technologies Office  
U.S. Department of Energy

NREL APEEEM Team
Kevin Bennion, Justin Cousineau, Doug DeVoto,  
Xuhui Feng, Charlie King, Gilbert Moreno, Paul  
Paret, Caitlin Stack, Suraj Thiagarajan, Scot Waye

Industry and Research Partners
Ford, GM, Chrysler, John Deere, Toyota, Oak Ridge  
National Laboratory, DARPA, Virginia Tech,  
University of Colorado Boulder, University of  
Wisconsin, 3M, NBETech, Curamik, DuPont, GE  
Global Research, Semikron, Kyocera, Sapa, Delphi,  
Btechcorp, Remy, Heraeus, Henkel, Wolverine  
Tube Inc., Arkansas Power Electronics International,  
Kulicke & Soffa, UQM Technologies Inc.

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