Thermal Management of Power Semiconductor Packages – Matching Cooling Technologies with Packaging Technologies

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Kevin Bennion
Gilbert Moreno

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1. Efficient heat transfer technologies can enable increased power density and specific power.

2. Thermal management is a path to reduce cost and maintain robust operation.

3. Thermal management should not be an afterthought but should involve an integrated systems approach.

4. Cost-effective solutions require integration of capabilities for cooling, packaging (materials/geometry), and reliability prediction.

Relevance of Thermal Management

Thermal management directly relates to improvements in cost, power density, and specific power.

**Impacts: Lower cost, volume, and weight**
“Easy ways to increase output power are paralleling more silicon chips and/or step-up the die size to increase current capacity. But this strategy is unaffordable in terms of both increased chip cost and packaging space.”

**Concern: Heat**
“The most significant concern for increasing current is intensified heat dissipation.”

*Source: Yasui, H., et al, “Power Control Unit of High Power Hybrid System” – EVS23*
Outline

Background
• Department of Energy’s Advanced Power Electronics and Electric Machines (APEEM) activity.
• Thermal management for power electronics cooling.

Problem
• Quantify trade-off interaction between packaging configuration and cooling technology.
• Identify effective packaging and cooling combinations.

Approach

Results
Background

DOE’s Advanced Power Electronics and Electric Machines (APEEM)

National Renewable Energy Laboratory (NREL)
Lead: APEEM Thermal Control R&D

Oak Ridge National Laboratory (ORNL)
Lead: Power Electronics & Electric Machines R&D

Other Industry Partners and Universities

Industry and Academia
Background

- NREL Advanced Power Electronics Thermal Overview

Industry Collaboration

Research Community

Performance Targets

- Heat load
- Heat flux
- Thermal resistance

System Impacts

- Cost
- Weight
- Volume
- Efficiency
- Robustness

APEEM Technology Development

Advanced Vehicle Systems

APEEM Thermal Control Subsystem integration, performance, reliability

Potential Thermal Management Technologies

NREL Advanced Power Electronics Thermal Overview
Background

- NREL Advanced Power Electronics Thermal Focus Areas
Background

- Defines thermal requirements
- Links thermal technologies to electric traction drive systems
Problem

How do developments in APEEM technologies influence cooling technology selection?

How do developments in cooling impact APEEM technology selection?

Advanced Vehicle Systems

APEEM Technology Development

APEEM Thermal Control Subsystem integration, performance, requirements

Potential Thermal Management Technologies

\[ \delta_t \]

\[ S \]

\[ T \]

\[ \text{heater diameter} \]

\[ L \]
Approach

Quantify interaction between package configuration and cooling technology on total thermal performance.

- Cooling Technologies
  - Fins & Jets
- Cooling Performance
  - Experimental Correlations, CFD Results, & Analytical
- Heat Exchanger Characterization
  - Effectiveness – NTU Method
    \[ R_{NTU} = \frac{1}{\frac{1}{\varepsilon m c_p}} \]
Quantify interaction between package configuration and cooling technology on total thermal performance.

\[ R_{NTU} = \frac{1}{\varepsilon \dot{m} c_p} \]

- **Heat Transfer & Fluid Flow Characterization**
- **Cooling Technologies**
- **Experimental Correlations, CFD Results, & Analytical**
- **Cooling Performance**
- **Heat Exchanger Characterization**
- **Effectiveness – NTU Method**
- **Thermal Characterization**
- **Heat Flux vs. Heat Exchanger Thermal Resistance**
- **3D Parametric FEA**
- **PE Package Thermal Characterization**
- **3D Package Configuration**

**System Performance Trade-offs**

- **IGBT Flux (W/cm^2)**
- **Heat Exchanger Thermal Resistance, \( R_{hx} (K/W) \)**
- **Package A**
- **Package B**
Quantify interaction between package configuration and cooling technology on total thermal performance.
Approach

Applied process to range of package configuration examples approximated from in-use commercial packages with different geometries.

- Semikron SKM
- Toyota Camry
- Toyota Prius 2004
- Lexus LS 600h

IGBT and diode pair
## Approach

### Baseline Package Configurations

<table>
<thead>
<tr>
<th>Layer</th>
<th>SKM</th>
<th>SKAI</th>
<th>Prius</th>
<th>Camry</th>
<th>Ls 600H</th>
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<tr>
<td>IGBT/Diode (Si)</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
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<td>x</td>
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<tr>
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<td>x</td>
<td>x</td>
<td>x**</td>
<td>x**</td>
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<td>Substrate</td>
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<tr>
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<td>x</td>
<td>x</td>
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</tr>
<tr>
<td>Al2O3</td>
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<td>Solder</td>
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<td>x</td>
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<tr>
<td>Heat Spreader</td>
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</tr>
<tr>
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<tr>
<td>Cu-Mo-Cu</td>
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<td>x</td>
<td>x</td>
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<tr>
<td>TIM</td>
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<td>x*</td>
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<tr>
<td>Heat Sink</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

**Cooled Surface Footprint Area: [cm²]** 15.34 3.90 16.86 7.68 15.00**

* Included additional model variation with AlN.
+ Modeled with reduced thermal interface material thickness of 0.05 mm.
** Assumed copper metallization layer.
++ Listed area is for one side of the package, and it is the same on each side of the package.

### Reference:

**Results**


Results

- All curves flatten as the heat exchanger performance improves ($R''_{th,h-a}$ decreases).
- Package becomes thermal limitation.
- Difference in total thermal performance ($R''_{th,j-a}$) is affected by the footprint area available for cooling.


• Weight the total thermal performance ($R_{th,j-a}$) by the total footprint area available for cooling.

• Curves collapse onto a single curve as the heat exchanger resistance increases.

• Removes effect of different package footprint areas.
Results

Package geometry, material, and cooling trade-offs

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**Results**

- **Baseline Direct Cooled Baseplate (DCB)**
- **Direct Cooled Baseplate (DCB)**
- **Direct Cooled DBC (DCD)**

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**Graph:**

- x-axis: \( R_{th,h-a}^{in} \) (mm²·K/W)
- y-axis: \( R_{th,j-a} \) (K/W)

- **Symbols:**
  - Open symbol: Baseline
  - Gray symbol: DCB
  - Black symbol: DCD
  - AIN

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**Legend:**

- AIN
- DCB
- DCD

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**Image:**

- Baseline
- Direct Cooled Baseplate (DCB)
- Direct Cooled DBC (DCD)
Results

Baseline
- At low $R_{th,h-a}$, the separation between Al$_2$O$_3$ and AlN package resistance is more significant.
- Trade-off between material cost and heat exchanger performance cost.
- At about 100 mm$^2$-K/W, switching to AlN would have a similar benefit to a 10X heat exchanger improvement.

Direct Cooled DBC (DCD)
- At high $R_{th,h-a}$, the cooling area footprint and heat exchanger resistance dominate thermal performance.
- As the cooling technology improves, the thermal characteristics of the package become more important.
Results

- Weight the total thermal performance ($R_{th,j-a}$) by the total footprint area available for cooling.

- Curves collapse onto a single curve as the heat exchanger resistance increases.

- Removes effect of different package footprint areas.

- Highlights impact of package.
Results

![Graph showing the relationship between $R_{th,j-a}$ ($Al_2O_3$) and $R_{th,j-a}$ (AlN). The graph includes data points for baseline, DCB, and DCD conditions.](image)
Results

- The impact of a material with improved thermal conductivity depends on the package configuration and heat exchanger performance.

- The cost/benefit trade-off improves for more aggressive cooling and packages with fewer thermal bottlenecks.

- Relationship between package thermal performance and cooling technology can lead to a more expensive system than necessary if the relationship is not used properly.
Results

Matching package geometry and cooling technology

![Graph showing thermal resistance values for Lexus and Camry (DCD)]

- **Lexus**
- **Camry (DCD)**

Results

Matching package geometry and cooling technology

- To maximize the thermal performance, the package and heat exchanger technology should be investigated together.
- Identify appropriate cooling methods for a given package technology.
- Identify appropriate packaging options for a given cooling approach.

Conclusion

- Thermal management plays an important part in the cost of electric drives in terms of power electronics packaging.
- Cost-effective solutions require an appropriate balance between package and thermal management design.
- Appropriate cooling technology depends on
  - Package application
  - Reliability
- **Integration** of capabilities for **cooling**, **packaging** (materials/geometry), and **reliability** prediction provide a system view of technology developments.