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

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
Motivation

• Most aggressive target of FreedomCAR program is the cost (2020 target is $8/kW for a 55 kW traction system).
• Meeting the cost target is critical for greater penetration of the vehicles market.
• NREL’s Advanced Power Electronics team is working on next-generation advanced cooling technologies (jets/sprays/micro-channels with single or two-phase) and novel packaging topologies.
• Advanced cooling technologies are used in conjunction with novel packaging topologies for identifying low-cost materials for cost (and weight) reductions while meeting the targets of performance and reliability.
Description of Technology

\[ Q = \frac{(T_H - T_B)}{R_{solder} + R_{DBC} + R_{TIM}} \]

\[ Q = h A (T_B - T_C) \]
Topologies

Baseline Topology

Topology 1 (very similar to the baseline topology, which uses Thermal Interface Material)

Topology 2 (Base plate cooling; does not involve Thermal Interface Material)

Topology 3 (Direct Cooling of Direct Bonded Copper)
Thermal Materials Exploration Study – Steps

Part 1: Exploring tradeoffs between thermal performance and cost for several topologies

Part 2: Evaluation of Thermal Stress and Reliability Aspects

Part 3: Emerging technologies:
1) LTCC substrates
2) Organic substrates

- Performance: Peak temperatures of the switching devices (IGBTs and diodes) need to be below 150°C.
- Reliability: Power electronics need to meet life-cycle target of 15 years.
Three layers that have potential opportunities for cost reduction are the substrate and the cold plate.

Today’s preferred substrate, Aluminum Nitride (AlN) is expensive.

Low-cost LTCC technology has been well demonstrated in automotive electronics applications. Several issues, notably thermal disadvantages have slowed down the spread of this substrate technology [1].

Silicon nitride (SiN) as a substrate would make economic sense if the cost is reduced to $5 per pound [2].


Materials Exploration – Topology 1

Alternate materials are explored for each layer.
Verification of CFD Model with Test

<table>
<thead>
<tr>
<th></th>
<th>CFD</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Heat Transfer Coefficient (W/m².K)</td>
<td>18,350</td>
<td>18,481</td>
</tr>
</tbody>
</table>
"What-If" option of Design Explorer in “ANSYS Workbench Thermal Simulation” is used to automate materials exploration studies

Heat Load per Diode = 35 W  Heat load per IGBT heat load = 85 W

Thermal Conductivity is varied for all the layers according to the material

Bulk material costs are assigned on a volumetric basis

Heat Transfer Coefficient = 18,350 W/(m\(^2\).K)

Coolant Temperature = 105 °C
Low-cost combination that meets the performance target (Cu-Mo, Graphite, SiN-Ideal)

Cost -> 842  Peak Temp -> 142 °C

Low-cost combination that meets the performance target (Cu-Mo, Graphite, Alumina, an LTCC substrate)

Cost -> 889  Peak Temp -> 149 °C
# Substrate Materials for Cost Reduction – Topology 1

## Maximum Temperature Vs Cost

<table>
<thead>
<tr>
<th>Material</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Nitride AIN</td>
<td>ALN, AL-501</td>
</tr>
<tr>
<td>AlN, AL-502</td>
<td></td>
</tr>
<tr>
<td>AlN, AL-503</td>
<td>AL-503</td>
</tr>
<tr>
<td>AlN, AL-504</td>
<td>AL-504</td>
</tr>
<tr>
<td>AN75W</td>
<td></td>
</tr>
<tr>
<td>Alumina, Al203</td>
<td>AL203, AL-600</td>
</tr>
<tr>
<td>Al2O3, AL-601</td>
<td>AL2O3, AL-601</td>
</tr>
<tr>
<td>Al2O3, AL-602</td>
<td>AL2O3, AL-602</td>
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<tr>
<td>Al2O3, AL-605</td>
<td>AL2O3, AL-605</td>
</tr>
<tr>
<td>Al2O3, AL-610</td>
<td>AL2O3, AL-610</td>
</tr>
<tr>
<td>Boron Nitride, BO-502</td>
<td></td>
</tr>
<tr>
<td>Silicon Nitride, S1-501</td>
<td></td>
</tr>
<tr>
<td>Silicon Nitride, Ideal</td>
<td></td>
</tr>
<tr>
<td>Beryllium Oxide (BeO)</td>
<td></td>
</tr>
</tbody>
</table>

**Alumina, an LTCC substrate**

**Silicon nitride, ideal**
Cu-Mo is a candidate base plate material (used in Prius)
Materials Exploration – Topology 2

Base Plate Cooling

- SnPb(63/37)
- SAC (lead-free)
- Copper
- Cu-Mo
- Cu-Tungsten
- AlSiC
- IGBT or Diode, 0.09mm
- Solder, 0.127mm
- Copper, 0.31mm
- Substrate, 0.625mm
- Copper, 0.31mm
- Solder, 0.127mm
- Trench IGBT, Silicon

Materials:
- Aluminum Nitride AlN
  - ALN, AL-501
  - ALN, aL-502
  - AL-503
  - AL-504
  - AN75W
- Alumina, Al2O3
  - AL2O3, AL-600
  - AL2O3, AL-601
  - AL2O3, AL-602
  - AL2O3, AL-603
  - AL2O3, AL-604
  - AL2O3, AL-605
  - AL2O3, AL-610
- Boron Nitride, BO-502
- Silicon Nitride, S1-501
- Silicon Nitride, Ideal
- Beryllium oxide (BeO)
Low-cost combination that meets the performance target (Cu-Mo, SiN-Ideal)
Cost -> 662  Peak Temp -> 132 °C

Low-cost combination that meets the performance target (Cu-Mo, Alumina, an LTCC substrate)
Cost -> 682  Peak Temp -> 148 °C
Cost with Topology 1 -> 889
Substrate Materials for Cost Reduction – Topology 2

Maximum Temperature Vs Cost

- Aluminum Nitride AIN
- ALN, AL-501
- ALN, AL-502
- AL-503
- AL-504
- AN75W
- Alumina, Al203
- AL203, AL-600
- AL2O3, AL-601
- AL2O3, AL-602
- AL203, AL-603
- AL2O3, AL-604
- AL203, AL-605
- AL2O3, AL-610
- Boron Nitride, BO-502
- Silicon Nitride, S1-501
- Silicon Nitride, Ideal
- Beryllium Oxide (BeO)

Silicon nitride, ideal

Alumina, an LTCC substrate
Materials Exploration – Topology 3

Direct Cooling of Direct Bonded Copper
Low-cost combination that meets the performance target (SnPb(63/37), SiN-Ideal)

Cost -> 339  Peak Temp -> 130 °C

Low-cost combination that meets the performance target (SnPb(63/37), Alumina, an LTCC substrate)

Cost -> 354  Peak Temp -> 149 °C

Topology 1 -> 889, Topology 2 -> 682
Substrate Materials for Cost Reduction – Topology 3

Alumina, an LTCC substrate

Aluminum Nitride AlN
ALN, AL-501
ALN, AL-502
AL-503
AL-504
AN75W
Alumina, AI203
AL203, AL-600
AL2O3, AL-601
AL2O3, AL-602
AL203, AL-603
AL2O3, AL-604
AL2O3, AL-605
AL2O3, AL-610
Boron Nitride, BO-502
Silicon Nitride, S1-501
Silicon Nitride, Ideal
Beryllium Oxide (BeO)

Maximum Temperature Vs Cost

Silicon nitride, ideal
Topography Effect on Junction Temperature

Effect of Topology on Performance

Baseline

Topology 1

Topology 2

Topology 3

Complex interaction between spreading and convection

Direct Backside Cooling

$h = 18,350 \text{ W/(m}^2\text{.K)}$
Thermal Resistances – Contributions

Opportunity for further reduction in thermal resistance through surface enhancement
Surface Enhancement

\[ U = h \cdot A \]

Targeted surface area enhancement is about 3

\[ U = h \cdot 3A \]

Effective area would be less than 3. Let’s assume it’s about 2.2:

\[ U = h \cdot (2.2A) \]

(in the test)

\[ U = (2.2h) \cdot A \]

(for modeling purposes)

The assumption above might be all right for a first order approximation:

Baseline, \( h = 18, \ 350 \ \text{W/(m}^2\text{.K)} \)

Enhanced, \( h = 2.2 \times h = 2.2 \times 18, \ 350 = 40,000 \ \text{W/(m}^2\text{.K)} \)
Combined Effects of Topology and Cooling Technology on Junction Temperature

Combined Effects of Topology and Cooling Technology on Performance

Baseline

Topology 1, $htc = 18,350$

Topology 2, $htc = 18,350$

Topology 3, $htc = 18,350$

Topology 1, $htc = 40,000$

Topology 2, $htc = 40,000$

Topology 3, $htc = 40,000$

Backside Cooling with surface enhancement
Conclusions and Future Studies

• Advanced thermal control (advanced cooling technologies and novel packaging topologies) helps to meet FreedomCAR program’s key target of cost.
• Direct Backside Cooling (Topology 3) has the greatest potential for cost reduction.
• Using Advanced Thermal Control, low-cost LTCC substrate (alumina) has the potential to replace the traditional, more expensive HTCC substrate, AlN.
• Surface enhancement provides further opportunity for performance enhancement.
• Future studies would involve reliability aspects and emerging substrate technologies (LTCC and Organic).
Acknowledgements

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