A Heterogeneously Integrated Double-Sided Cooling Silicon Carbide Power Module

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Outline

- Introduction to double-sided cooling (DSC) power modules and motivation for heterogeneous integration
- Proposed power module design
- Thermal simulation
- Process flow
- SOI based gate driver chip integration
- GMR current sensor integration
- System level integration
- Conclusion
**Introduction and Motivation**

- **Conventional power module package drawbacks:**
  - Single-side cooling provides less heat removal
  - Vertical power loop not possible
  - Top-side wire bonds increase failure risk

- **DSC power module benefits:**
  - Better heat dissipation capability
  - Low parasitic inductance
  - No wire bond failure risk
# State-of-the-Art DSC Power Modules for EV Applications

<table>
<thead>
<tr>
<th>Specification</th>
<th>294 A/1200 V module</th>
<th>-</th>
<th>600 V</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Integrated features</strong></td>
<td>Decoupling capacitors</td>
<td>NTC thermal resistors, integrated heatsink solution</td>
<td>-</td>
<td>On chip current and temperature sensor</td>
</tr>
<tr>
<td><strong>Architecture for double-sided cooling</strong></td>
<td>Copper molybdenum post as spacers</td>
<td>Metal spacers to enable double-sided cooling</td>
<td>Electroplated copper and solder mask to device’s top side</td>
<td>Metal spacer on device top</td>
</tr>
<tr>
<td>$L_{\text{power}}$ (nH)</td>
<td>10.6</td>
<td>-</td>
<td>-</td>
<td>13</td>
</tr>
<tr>
<td>$R_{\text{th}}$ (K/W)</td>
<td>0.146, Huazhong University, China [23]</td>
<td>0.0899, Power Semiconductor, UK [13]</td>
<td>0.14, University of Maryland, USA [12]</td>
<td>0.11, Infineon Technologies [9]</td>
</tr>
</tbody>
</table>
### State-of-the-Art Volumetric System Power Density (PD)

<table>
<thead>
<tr>
<th>Organization</th>
<th>PD (kW/ L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hitachi Ltd., Japan [18]</td>
<td>35</td>
</tr>
<tr>
<td>University of Nottingham, UK [19]</td>
<td>30</td>
</tr>
<tr>
<td>Chinese Academy of Sciences, China [20]</td>
<td>14.8</td>
</tr>
<tr>
<td>NCSU, USA [21]</td>
<td>12.1</td>
</tr>
</tbody>
</table>
Proposed DSC Power Module Design

- **Key features:**
  - Pyramidal or 45-degree connection blocks:
    - Maximum heat dissipation path
  - LTCC based interposer:
    - Electrical isolation
    - Mechanical strength
    - Aligning top and bottom substrates

- **Integrated features:**
  - Decoupling capacitors
  - Temperature sensors
  - Current sensor
  - Gate driver boards
Thermal Simulation and Design Specification

- **Software:**
  - SolidWorks Thermal Simulator

- **Contact sets:**
  - Thermal contact resistance modeled:
    - Attachment silver sinter paste (T.C.= 60 W/mK, 50 um)
    - Thermal interface material (T.C.= 9.6 W/mK, 0.5 mm)

- **Boundary conditions:**
  - Convection co-efficient: 10,000 W/m²K

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of paralleled devices</td>
<td>Two</td>
</tr>
<tr>
<td>Key integrated parts</td>
<td>Decoupling capacitors, Temperature sensors, Current sensor, Two gate drivers</td>
</tr>
<tr>
<td>Dimension (mm)</td>
<td>66<em>63</em>10</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>1200</td>
</tr>
<tr>
<td>Current (A)</td>
<td>164 @ T&lt;sub&gt;j&lt;/sub&gt;=175°C</td>
</tr>
<tr>
<td>Power loop inductance (nH)</td>
<td>1.5</td>
</tr>
<tr>
<td>Junction-to-ambient thermal resistance (K/W)</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Integrated SOI Based Gate Drivers

- XFAB's 180 nm silicon-on-insulator (SOI) CMOS process
- Can safely operate up to 175°C
- System protection features:
  - Active Miller clamping
  - Over-current detection
  - Under-voltage lockout circuits
- Die area is ~ 3.14 mm x 3.14 mm
- Pad area of ~ 100µm x 100µm

- Very low gate loop inductance due to the integrated gate driver
Problem Statement:
- Integration of current measurement method inside power modules:
  - Small and accurate
  - Low or no power loss
  - High bandwidth and capable of measuring both AC and DC currents
  - No saturation problem
  - Low in cost
- GMR sensors
  - Small, accurate and high bandwidth
  - Contactless sensors
  - No power loss

Challenges:
- Sensitivity of GMR sensors to stray magnetic fields and temperature fluctuation

Solution:
- Implementation of Two GMR Sensors (TGS) method [5]
Fabrication Flow

1st sinter on bottom DBC:
Devices, terminals, $C_{dec}$, connection blocks, temp. sensor

2nd sinter on top DBC:
Devices, terminals, connection blocks, temp. sensor

1st wire-bonding on bottom DBC:
Devices, temp. sensor

2nd wire-bonding on top DBC:
Devices, temp. sensor, current sensor routing to DBC

3rd sinter:
Bottom DBC, interposer, top DBC

1st solder:
Current sensor on AC terminal

2nd solder:
Bottom DBC, interposer, top DBC

1st glue:
Assembly, bottom housing, top switch gate driver board

2nd glue:
Assembly, housing part 2, bottom switch gate driver board

3rd glue:
Housing part 3

3rd wire-bonding:
Device gate-source connections to PCB; Encapsulation

4th wire-bonding:
Device gate-source, temp. and current sensor routing to PCB; Encapsulation
Volumetric System Power Density (PD)

Segmented two-level three-phase inverter with PM traction motor in EV systems [17]

- Better than most state-of-the-art inverter (system) power densities for EV applications

<table>
<thead>
<tr>
<th>Proposed Volumetric System PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed DSC Module System</td>
</tr>
<tr>
<td>System power= 200 kW</td>
</tr>
<tr>
<td>Volume</td>
</tr>
<tr>
<td>188 mm (L) * 102 mm (H) * 77 mm (W)</td>
</tr>
<tr>
<td>Power density</td>
</tr>
<tr>
<td>136 kW/L</td>
</tr>
</tbody>
</table>
## Summary and Conclusion

<table>
<thead>
<tr>
<th>Module rating</th>
<th>1.2 kV/ 164 A</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical Configuration</strong></td>
<td>Half- bridge</td>
</tr>
<tr>
<td><strong>Key integrated parts</strong></td>
<td>Two gate driver boards, thermal sensors, decoupling capacitors, current sensor</td>
</tr>
<tr>
<td>$L_{\text{power}}$ (nH)</td>
<td>1.5</td>
</tr>
<tr>
<td>$R_{\text{th,j-a}}$ (K/W)</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>System volume (L<em>B</em>H)</strong></td>
<td>188 mm(L) * 102 mm(H)* 77 mm(W) = 1.4 L</td>
</tr>
<tr>
<td><strong>Volumetric system power density (kW/L) for a 200-kW system</strong></td>
<td>136</td>
</tr>
</tbody>
</table>

- Double-sided cooling enabling high current rating
- Highly integrated power module
- Very high system power density
Future Work and Acknowledgment

- Fabrication of the power module
- Test the power module

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References


References


Thank you for your attention!

Questions?

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