Advanced Power Modules & Packaging Technology

Scott Leslie
Chief Technologist
Advanced Power Module Technology - Outline

• Voltage & Frequency Limitations of Silicon Based Devices
  • Device Conduction & Switching Losses

• Alternatives to Silicon-Based Power Modules
  • Si IGBT / SiC FW Diode Hybrid Modules
  • All SiC Power Modules

• Technical Challenges for HV / HF Modules
  • Voltage Strike & Creep
  • Dielectrics
  • Inductance
  • Cooling

• Commercial Challenges For SiC Based Power Modules
Present IGBT Module Ratings: 250V to 6.5kV

Si IGBT Switching Frequency Capability Decreases Rapidly with Voltage Rating Due to Increased Losses

4.5 kV, 60A IGBT (3-Level diode-clamp)

6.5 kV, 600A IGBT

Operating Frequency Range For Si IGBT / Si FWD Modules

<table>
<thead>
<tr>
<th>IGBT Voltage Rating (kV)</th>
<th>Switching Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High Frequency</td>
</tr>
<tr>
<td>1.2</td>
<td>56</td>
</tr>
<tr>
<td>1.7</td>
<td>50</td>
</tr>
<tr>
<td>2.5</td>
<td>45</td>
</tr>
<tr>
<td>3.3</td>
<td>40</td>
</tr>
<tr>
<td>4.5</td>
<td>35</td>
</tr>
<tr>
<td>6.5</td>
<td>30</td>
</tr>
</tbody>
</table>
Power Module Technology Trends

- Silicon Power Modules Rated to 6.5kV
  - Switching Frequency Limited for Modules Rated Above 1200V
  - Low Operating Frequency Does Not Permit Reduction of Passive Components

- Hybrid Silicon IGBT/SiC FW Diode Can Extend Switching Frequency
  - “Zero” Recovery Charge of HV SiC Schottky Diodes Reduce IGBT Switching Losses

- Shift to HV, HF SiC-Based Majority Carrier Switches
  - 1.2kV & 10kV SiC MOSFETs Developed
  - Higher Temperature Capability of SiC Can Lead to Higher Converter System Power Densities & Relaxed Cooling Requirements
  - Higher Frequency Reduces Passive Component Sizes
SiC Shottky FW Diodes Reduce Si IGBT Switching Losses

1st Annual Ground - Automotive Power & Energy Symposium
July 20-22, 2005, Hilton, Detroit/Troy

SiC SBD - Hybrid Module
(Cree 25 amp SiC SBD)

Si Diode - Standard Module
(Ultra Fast Si Diode)

Silicon IGBT

SiC Shottky Diode

300A -1200V Dual Si/SiC Hybrid Module

High-Megawatt Power Converter Technology Workshop: Apr 08 2008
Si IGBT / SiC FW Diode Dual & 3 F Bridge Modules

1200V/50 A SiC Schottky Diodes

1200V Silicon IGBT

1200A -1200V Dual Si/SiC Hybrid Module

75A -1200V 3-F Si IGBT / SiC FW Diode Module
10kV, 50A SiC MOSFET/ SiC Schottky Half H-Bridge Module

**HPE Phase II Module**
- 15kV Isolation
- Capable of 200C Operation
- Liquid Cooled

<table>
<thead>
<tr>
<th>Test</th>
<th>Q1</th>
<th>Q2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{gs} @ Vgs = 15V$</td>
<td>2 uA</td>
<td>2 uA</td>
</tr>
<tr>
<td>$I_{ds} @ Vd = 3kV$</td>
<td>0.6 uA</td>
<td>0.1 uA</td>
</tr>
<tr>
<td>$I_{ds} @ Vd = 5kV$</td>
<td>2.6 uA</td>
<td>0.6 uA</td>
</tr>
<tr>
<td>$I_{ds} @ Vd = 6kV$</td>
<td>5.1 uA</td>
<td>1.3 uA</td>
</tr>
<tr>
<td>$V_{ds} @ Id = 50A$</td>
<td>6.3 V</td>
<td>6.1 V</td>
</tr>
<tr>
<td>$V_{ds} @ Id = 50A$</td>
<td>5.6 V</td>
<td>5.5 V</td>
</tr>
<tr>
<td>JBS Diode $V_{F} @ If = 50A$</td>
<td>3.8 V</td>
<td>3.9 V</td>
</tr>
</tbody>
</table>

All Tests @ 25C
1.2kV, 100A SiC MOSFET/ SiC Schottky Half H-Bridge Module

Capable of 200C Tj Operation

D1 S1D2 S2

Cree 1.2kV, 20A SiC MOSFET
Cree 1.2kV, 50A SiC JBS Diode

Cree 1.2kV, 100A SiC MOSFET Module: Avg JBS Diode Vf vs If

Cree 1.2kV, 100A SiC MOSFET Module: Avg Vds vs Ids
Vgs = 20V

Capable of 200C Tj Operation
Technology Challenges for HV, HF Power Modules

- External Voltage Strike & Creep
- Internal Dielectrics
  - Reliability & Losses
  - Corona/Partial Discharge
  - High Temperatures
- Low Inductance
  - Power Loop
  - Gate Loop
- Efficient Cooling
  - High Chip Power Densities
- Package Reliability

HPE Phase III SiC MOSFET Module: 10kV, 120A Half H-Bridge
Internal Package Dielectric Material Challenges for HV/HF Modules

Start of HTRB Life Test

Gel Breakdown Failures Due to Bubble Formation

Program to Investigate & Improve Encapsulant Reliability Currently Funded by Navy MANTECH
Cooling Challenges– Reducing the Heat Flow Path

**Standard Heatsink**

- IGBT Die
- Solder
- DBC Copper
- Aluminum Nitride
- Ceramic
- DBC Copper
- Solder
- Baseplate/Heatsink
- Thermal Interface Material
- Heatsink

**Built-In Heatsink**

- IGBT Die
- Solder
- DBC Copper
- Aluminum Nitride
- Ceramic
- DBC Copper
- Solder
- Baseplate/Heatsink

**Integrated Heatsink**

- IGBT Die
- Solder
- DBC Copper
- Aluminum Nitride
- Ceramic
- DBC Copper

High-Megawatt Power Converter Technology Workshop: Apr 08 2008
# Thermal Resistivity Comparison of Paths to Cooling Medium

<table>
<thead>
<tr>
<th>Path to Cooling Medium</th>
<th>Thermal Resistivity J-S (C·cm²/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Module / External Chill Plate</td>
<td>0.45</td>
</tr>
<tr>
<td>Built-In Chill Plate</td>
<td>0.40</td>
</tr>
<tr>
<td>Integrated Chill Plate</td>
<td>0.35</td>
</tr>
</tbody>
</table>

1200V IGBT Module Design:
- External Chill Plate
- Thermal Compound
- Cu Baseplate
- Substrate Solder
- Bottom DBC Cu
- AlN
- Top DBC Cu
- Die Solder
- Silicon Die

Programs Funded by DARPA, ONR, AFRL & DOE to Extend the State of the Art in Module Air & Liquid Cooling

Fins

Microchannels
Commercial Challenges For SiC-Based Modules

- SiC Chip Costs
  - High Material Cost
  - Low Yield

- Power Module Costs
  - Small SiC Die Sizes Leads to Lower Power Densities & Larger Modules
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