An Advanced Power Converter System Based on High Temperature, High Power Density SiC Devices

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Outline

1. Introduction
2. Objective
3. Approach
4. Work scope (Design, Modeling and Simulation)
5. Summary

• Acknowledgment: DOE STTR Phase I (DE-FG02-05ER86234), supervised by Stanley Atcitty (Sandia National Lab.), Imre Gyuk (DoE)

• Aegis Technology Inc.: Power electronics and thermal management for wide bandgap semiconductor
1. Introduction – Advantages and Challenges

• Si technology is approaching its theoretical limits.
• SiC devices are superior to present Si devices.
  – High temperatures, breakdown voltages, frequency and thermal conductivity
  – High efficiency, light weight, small size in SiC conversion system
• Challenges in utilizing SiC power devices.
  – High cost (expensive material, low yield) and limited availability (Schottky diodes, JFET)
  – New circuits, passive components, gate drivers and thermal management (high temperature, high power density package)
2. Objectives

- Develop an innovative power converter using high temperature, high power density SiC devices.
  - High efficiency, small size, and light weight
  - High power density, high temperature, and high frequency
  - Scalable current ratings for various motor controls

- Insert the technology for the applications in electric energy storage, motor control, and others.
3. Approach

- Circuit design and modeling of converter to evaluate the effects of SiC devices on power loss and efficiency.

- High temperature, high power density packages for the thermal management of SiC power devices.

- Gate drive that enables SiC power devices under high temperature.
4.1 Design – Converter

- **Battery**: Lead acid battery
- **Converter**: SiC devices (JFET, Schottky diode)  
  Bi-directional conduction
- **Utility grid**: 3-phase, 60Hz, 480 V line-line voltage

![Converter Design for Battery System](image)
4.1 Design – Power Module

Power module circuit

- Feed throughs of 1 - 5 for the power input (1,2) and output (3,4,5).
- Feed throughs of 9 -17 for the circuit control.
4.1 Design – Thermal Management

High temperature, high power density package

High temperature AlN package
High efficiency graphite (carbon foam) heatsink
4.1 Design – Thermal Management (cont.)

- AlN package substrate
  - High thermal conductivity
  - Low CTE matchable with SiC
  - High thermal shock resistance and insulation

<table>
<thead>
<tr>
<th>Property</th>
<th>AlN</th>
<th>Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (W/m K)</td>
<td>200</td>
<td>20</td>
</tr>
<tr>
<td>Dielectric strength (kV/cm)</td>
<td>140 - 170</td>
<td>100</td>
</tr>
<tr>
<td>CTE ($x10^{-6/°C}$) (25 ~ 400 °C)</td>
<td>4.5</td>
<td>7.3</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>3.3</td>
<td>3.9</td>
</tr>
<tr>
<td>Flexure strength (MPa)</td>
<td>300 - 500</td>
<td>240 - 260</td>
</tr>
</tbody>
</table>

- Carbon foam heatsink
  - High thermal conductivity
  - Interconnected pores acting like network microchannel
  - High convective heat transfer (100% enhancement over Al heatsink).
4.2 Circuit Modeling

- Compute power losses of SiC devices /power module/converter.
- Evaluate junction temperatures of the SiC devices and the energy efficiency of the converter.
- Demonstrate the advantages of the SiC inverter compared to its Si counterpart quantitatively.
- Investigate the effects of important parameters (package, heatsink etc.).
4.2 Circuit Modeling – Methodology

Single device model:
On-state resistance switching characteristics

Converter system power loss model:
Averaging technique

Thermal model:
Equivalent circuit

Temperature Loop

Parameters

Device tests

Control Strategy
4.2 Circuit Modeling – SiC Power Devices

Modeling and testing: Static/switching characteristics

- SiC diode I-V, on-resistance, voltage drop (Vd) at different ambient temperatures
- SiC switch I-V, on-resistance, voltage drop (Vd) at different temperatures

Forward Voltage of SiC Schottky Diode

I-V characteristics of JFET
4.2 Modeling – Power Module

- Power loss: Sum of power loss in VJFET and diode
  - Conduction loss
  - Switching loss

- Thermal model

Thermal equivalent circuit of the power module
4.3 Simulation

Implement model using Matlab Simulink

Simulation flow chart

Battery model, power loss model, and system thermal model
4.3 Simulation – Results

A periodical input was modeling to compute the junction temperature increase of devices

Junction temperature after 20 cycles

Heatsink 1

Heatsink 2

(a) JFET

(b) Diode
## 4.3 Simulation – Results (cont.)

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum temperature for 1st cycle (°C)</th>
<th>Ave. temperature rise per cycle (°C)</th>
<th>Maximum power loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>JFETs</td>
<td>Diodes</td>
<td>JFETs</td>
</tr>
<tr>
<td><strong>Heatsink 1:</strong> R&lt;sub&gt;ch&lt;/sub&gt;=0.0026, t&lt;sub&gt;ch&lt;/sub&gt;=0.01; R&lt;sub&gt;ha&lt;/sub&gt;=1, t&lt;sub&gt;ha&lt;/sub&gt;=900;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>38.025</td>
<td>38.639</td>
<td>0.041</td>
</tr>
<tr>
<td>Si</td>
<td>71.844</td>
<td>111.773</td>
<td>0.548</td>
</tr>
<tr>
<td><strong>Heatsink 2:</strong> R&lt;sub&gt;ch&lt;/sub&gt;=0.0026, t&lt;sub&gt;ch&lt;/sub&gt;=0.01; R&lt;sub&gt;ha&lt;/sub&gt;=0.01, t&lt;sub&gt;ha&lt;/sub&gt;=60;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiC</td>
<td>38.021</td>
<td>38.612</td>
<td>0.007</td>
</tr>
<tr>
<td>Si</td>
<td>71.748</td>
<td>111.276</td>
<td>0.104</td>
</tr>
</tbody>
</table>

Maximum temperature, average temperature and maximum power loss
### 4.3 Simulation – Results (cont.)

<table>
<thead>
<tr>
<th>Material</th>
<th>Average power input (W)</th>
<th>Average power loss (W)</th>
<th>Average temperature for 1st cycle (°C)</th>
<th>Inverter efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiC</td>
<td>1131.21</td>
<td>5.92</td>
<td>Heatsink 1: ( R_{ch} = 0.0026, t_{ch} = 0.01; ) ( R_{ha} = 1, t_{ha} = 900; )</td>
<td>37.090 37.228 99.48%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heatsink 2: ( R_{ch} = 0.0026, t_{ch} = 0.01; ) ( R_{ha} = 0.01, t_{ha} = 60; )</td>
<td>37.066 37.205</td>
</tr>
<tr>
<td>Si</td>
<td>1131.21</td>
<td>77.69</td>
<td>Heatsink 1: ( R_{ch} = 0.0026, t_{ch} = 0.01; ) ( R_{ha} = 1, t_{ha} = 900; )</td>
<td>38.777 44.730 93.13%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heatsink 2: ( R_{ch} = 0.0026, t_{ch} = 0.01; ) ( R_{ha} = 0.01, t_{ha} = 60; )</td>
<td>44.110 57.808</td>
</tr>
</tbody>
</table>

Average power loss and efficiency of a SiC inverter and a Si inverter
5. Summary

- SiC power converters are expected to provide higher efficiency and reduced size/weight.

- Feasibility demonstration a SiC converter through
  - Circuit design
  - System modeling
  - Packaging and thermal management

- Integration of circuit design and thermal management will enable SiC converters and their applications.

- System prototype including high-temperature gate drive is under investigation.