High Temperature, High Performance SiC Power Modules for Next Generation Vehicles

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CAD Modeling Techniques

Simulation Process

Example Simulation Results

Hermetic Power Module

Packaging Overview

Inverter Testing

High Performance Modules

Packaging Overview

Characterization & Switching Loss

JFET, DMOS, TMOS

Introduction & Outline
Why High Temperature?

What if temperature was not a limitation?

- Cooling Systems
- Thermal Shielding
- Design Tradeoffs
- Extreme Environments

- Efficiency
- Power Density
- Size & Weight
- Complexity
- Cost
Wide Band Gap Semiconductors

**Band Gap (eV)**
- Si: 1.1
- GaN: 3.4
- 4H-SiC: 3.2

**Breakdown Electric Field (MV/cm)**
- Si: 0.25
- GaN: 5
- 4H-SiC: 3

**Thermal Conductivity (W/cm*K)**
- Si: 1.6
- GaN: 1.3
- 4H-SiC: 3.7

**Larger band gaps mean...**
- Intrinsic Carriers
- Operating Temperature

**Higher critical fields result in...**
- Blocking Voltages
- On-Resistance
- Switching Speed

**Increased thermal cond. allows...**
- Heat Dissipation
- Power Density
Military Vehicle Applications
More Electric Aircraft Applications

Inverter / Converter / Controller
- Conditioned power to flight critical actuation system

Emergency Generator
- Independent source of electrical power

DC Battery
- Uninterruptible, flight critical power

Starter / Generator
- Source for redundant, flight critical power

Power Drive Electronics
- Modulated power to flight control actuators

Electro-Hydrostatic Actuators
- Redundant control power at each control surface

More Electric Aircraft (MEA) such as the F-35 could find SiC power electronics usage in or with:
Design

philosophy and processes
Adaptive CAD Modeling

Technique which allows for rapid configuration of a design with minimal user input.

Reference Sketches
Geometry is driven by relationships, equations, and named variables.

Assembly
Components are defined in context and driven by the referenced design variables.

Configurations
Thousands of variations may be rapidly analyzed with this process.
Adaptive Simulation

Using an adaptive CAD model and FEA simulation software, thousands of configurations may be investigated.

**Base Plate**
- material
- geometry

**Power Substrate**
- ceramic type
- ceramic thickness
- metal type
- metal thickness

**Die Attach**
- material
- thickness

**Spacing**
- die to die
- die to edge
- substrate to base plate
- substrate etch lines
- clearances
- tolerances

**Tradeoffs**
- thermal performance
- stress & displacement
- weight vs. performance
- volume vs. performance
- plastic reinforcements
Example Base Plate Analysis

Simulation data is extracted and organized into design surfaces. Tradeoffs are identified and visualized.

Copper Moly

![Graph 1: Die Temperature vs. Side Length and Thickness](image1)

![Graph 2: Peak Displacement vs. Side Length and Thickness](image2)
Example Die Attach Analysis

The thermal conductivity of the die attach exhibits diminishing returns.
Example Housing Analysis

Plastic reinforcing features are carefully designed for minimal stress & displacement.

Displacement @ 200°C

0 mil
(0 mm)

0.9 mil
(0.023 mm)

Von Mises Stress @ 200°C

0 MPa

2 MPa
Hermetic Modules

design and features
Hermetic Sealed Modules

Extreme environment, high frequency all SiC half-bridge power stage.

**Ratings**
- 1200V
- ≤100A

**Temperature**
- 300°C peak (packaging)

**Devices**
- up to 10 die in parallel per switch position

* pictured: SemiSouth 50mΩ JFET (SJECl20R050)
Packaging

- Kovar Lid (Hermetic Seam Weld)
- Titanium Alloy Body
- Copper Tungsten MMC Base Plate
- 400°C Qualified Hermetic Isolation
- Copper Core Pins

APEC International
A high performance 3-phase inverter was designed and fabricated with hermetic modules.

<table>
<thead>
<tr>
<th>Maximum Power</th>
<th>Switching Freq.</th>
<th>Peak Junction Temp.</th>
</tr>
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<tbody>
<tr>
<td>5 kW</td>
<td>50 kHz</td>
<td>200°C</td>
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- **Passive Heat Sink**
- **High Freq. Gate Drives**
  (XT-1000 modules underneath)
- **Input Filter**
- **Output Filter**
- **Power Bussing**

**Inverter System**
System Comparison

**Volume**
- IGBT: 0.042 m³
- SiC: 0.006 m³

7x smaller

**Weight**
- IGBT: 26.3 kg
- SiC: 3.2 kg

8x lighter

**Temperature**
- IGBT: 125 °C
- SiC: 250 °C

2x higher

**Efficiency**
- IGBT: 95.5%
- MOSFET: 96.8%
- JFET: 97.0%

1.25% higher
High Performance Modules
design and features
High Performance Modules

High temperature, high frequency, high power density all SiC half or full-bridge power stage.

**Ratings**
- 1200V
- >150A

**Temperature**
- 250°C peak (packaging)

**Devices**
- up to 16 die in parallel per switch position

* pictured: SemiSouth 50mΩ JFET (SJEC120R050)
Packaging

Multiple Material Choices Based on Application

- High Temp. Plastic Housing
- Very Low Profile 0.43 in (10.9 mm)
- Entire Package Width Used for Conduction
- Completely Flux Free Assembly
- MMC Base Plate
Full Systems

Modules have custom bussing and gate drives to achieve high performance switching

High Frequency Gate Drive With Bussing
Characterization

The paralleled switch positions exhibit very low on state resistances, even at high temperature.

MOSFET Configuration
6 MOSFETs per switch position

- 200 A
- 20 A

JFET Configuration
8 JFETs per switch position

- 160 A
- 80 A
Extremely low switching losses may be achieved with simultaneous switching events and high freq. gate drives.

**Turn Off Loss**

- $T_j = 25^\circ C, R_g = 0\Omega$

**Turn On Loss**

- $T_j = 25^\circ C, R_g = 0\Omega$

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**Graphs**

- **Turn Off Loss**
  - Drain Current (A) vs. $E_{OFF}$ (µJ)
  - Levels: 300 V, 600 V

- **Turn On Loss**
  - Drain Current (A) vs. $E_{ON}$ (µJ)
  - Levels: 300 V, 600 V
Switching Loss (vs. IGBT)

Turn Off Loss Comparison

- IGBT Modules (1200V, 200A)
- HT-2000

5.5x lower
High Performance Module (Cree MOSFET)
High Performance Module (Cree MOSFET)

**DEVICE INFO:**
- Chip Dimensions: 7.0 mm x 8.0 mm
- $R_{DS-ON}$ per chip = 24 mOhms @ 25 °C
- 1200 V

**MODULE INFO:**
- 16 Cree DMOSFETs
- 8 DMOSFETs per switch position
- $R_{DS-ON}$ Module ~3 mOhms @ 25 °C
- 1200 V, ~500 A
- Wire Bondless Packaging Technology

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**$I_{DS}$ vs $V_{DS}$ @ 25 °C**

![Graph showing $I_{DS}$ vs $V_{DS}$ at 25 °C with different $V_{gs}$ values](image)

**$R_{DS-ON}$ @ (25 °C, $V_{GS} = 20V$)**

![Graph showing $R_{DS-ON}$ vs $I_{DS}$ at 25 °C](image)
High Performance Module (Rohm TMOS)

DEVICE INFO:
- Chip Dimensions: 4.8 mm x 4.8 mm
- $R_{DS-ON}$ per chip =12 mOhms @ 25 °C
- 600 V

MODULE INFO:
- 16 Rohm TMOSFETs
- 8 Trench MOSFETs per switch position
- $R_{DS-ON}$ Module =1.5 mOhms @ 25 °C
- 600 V, 1000 A

$I_{DS}$ vs $V_{DS}$ @ 25 °C

$R_{DS-ON}$ @ (25 °C, $V_{GS} = 20$V)
High Performance Module (Rohm TMOS)

3 devices in parallel

$I_{DS}$ vs $V_{DS}$ @ 25 °C

$I_{DS}$ vs $V_{DS}$ @ 25, 150, & 200 °C
These newly developed high performance SiC power modules can provide substantial system benefits, including:

**Increased**
- efficiency
- power density

**Reduced**
- volume
- weight

**Higher**
- junction temperatures
- ambient temperatures
Thank You!

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