Very High Temperature (400+ °C) High-Power Silicon Carbide (SiC) Power Electronics Converter

DOE Energy Storage & Power Electronics Research Programs
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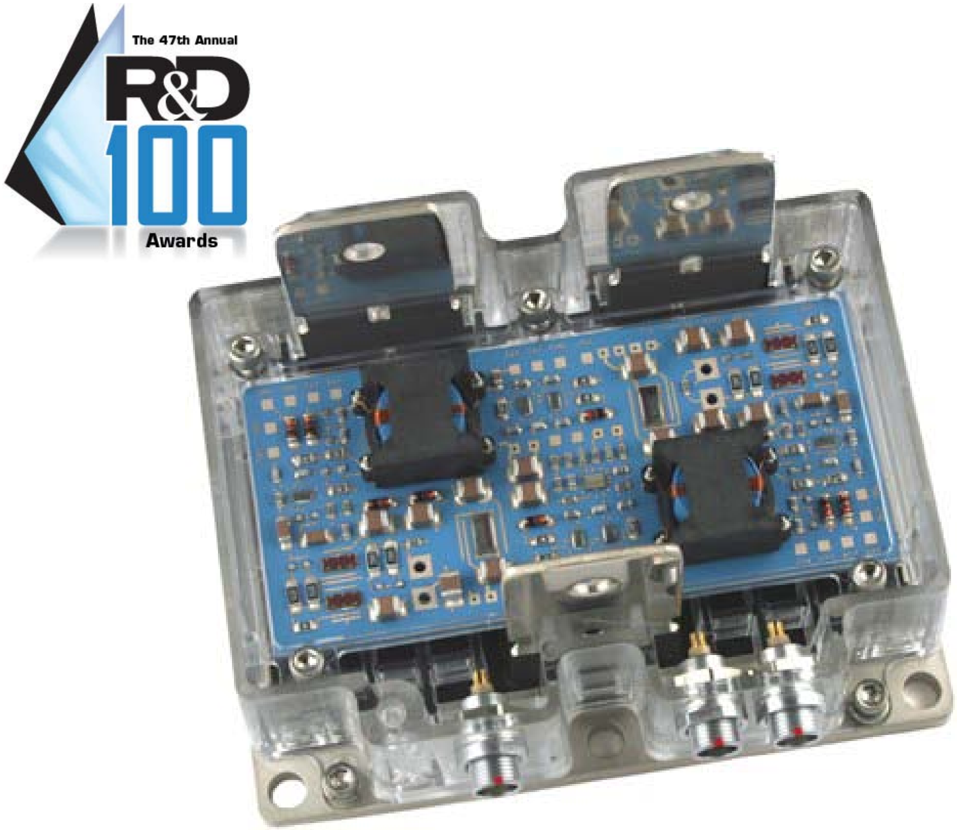
Overview

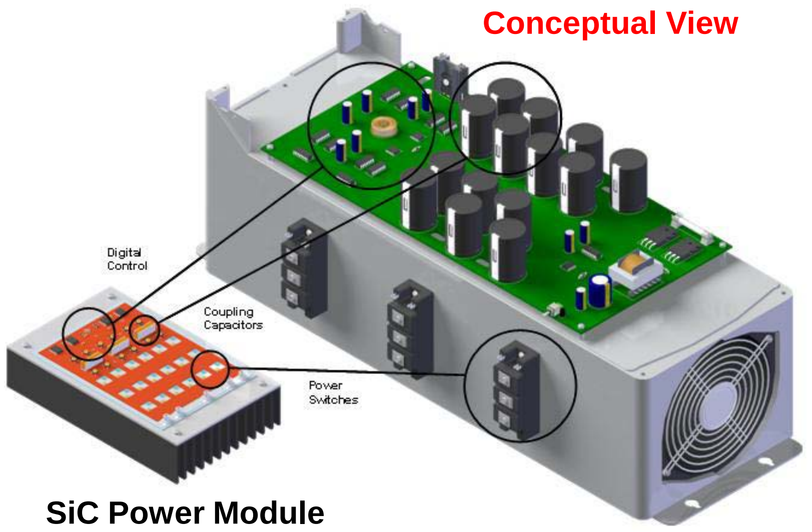
- Broader Impact of SiC-based Power Converter
- Phase I Review
- Phase II Review
- Related Activities
- Summary



Advantages of Silicon Carbide (SiC)

Theoretical Electrical Advantages

- Very high voltage blocking
- Very low switching losses (up to 1/10th of Silicon)
- Low on-resistance
- Up to 10s of GHz switching range



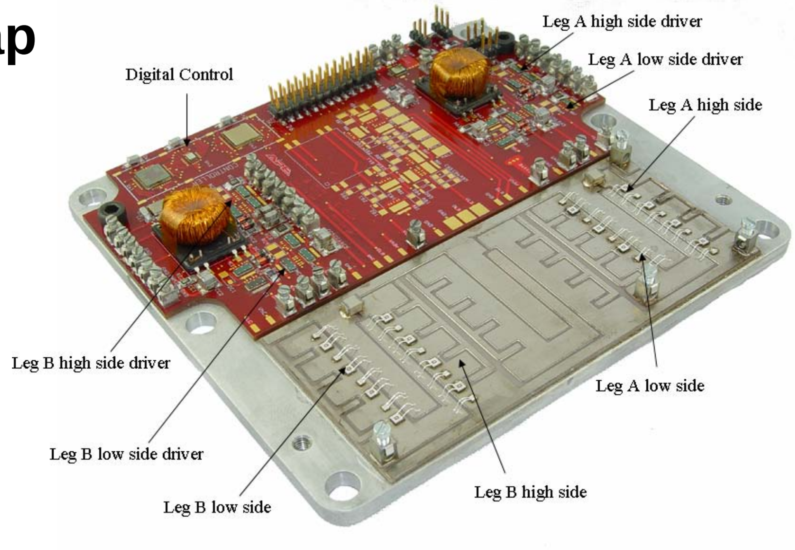
Theoretical Thermal Advantages

- SiC device theoretical limit exceeds 600 C
  Very high power densities can be achieved with these junction temperatures
- SiC has a very high thermal conductivity—excellent for power devices and thermal transfer, increases power density

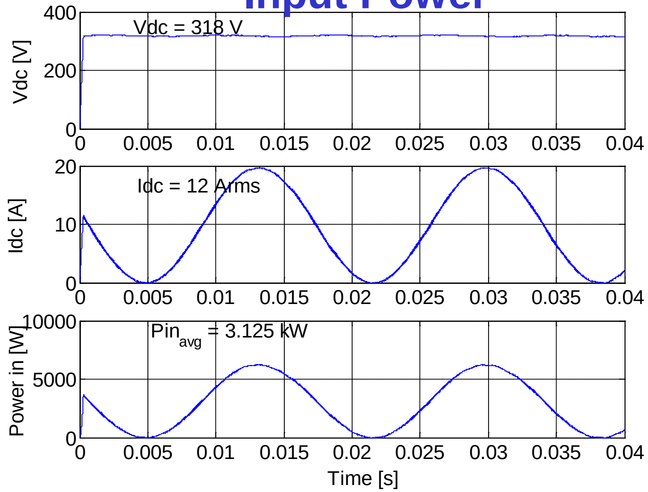
- **Disadvantage:** No device packaging technology exists to take full advantage of thermal capabilities
  Requires packaging advances in die attach, interconnects, and reliability

Phase I: Very High Temperature (400+ °C) High-Power Silicon Carbide (SiC) Power Electronics Converter

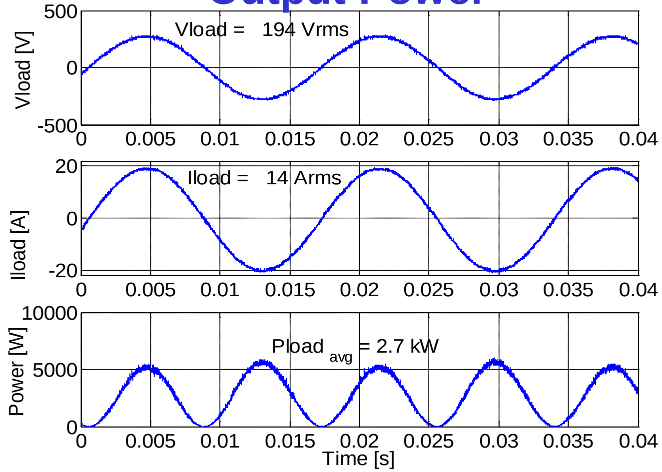
- **DOE SBIR, Topic: 1.a Wide Band Gap Power Converter Application (FY05)**
- **Goals**
  - **Multi-chip power module**
  - **High temperature operation**
  - **Size reduction**
  - **3-kW 120V single-phase inverter (250 ºC+)**



Input Power



Output Power



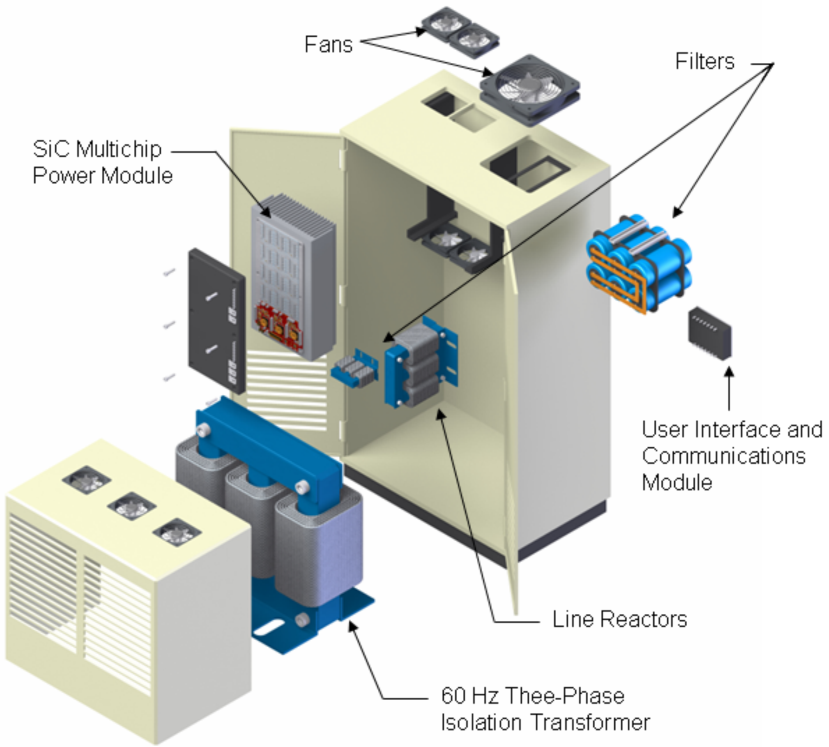
> 90% efficiency (estimated)

DOE ESS Phase I SBIR Review

APEI, Inc.'s SiC-based MCPM power inverter module has an estimated power density of 11 W/in^3 (using only passive cooling)

DOE ESS Phase II SBIR

- **Title: High Power Density (100 kW) Silicon Carbide (SiC) Three-Phase Inverter (FY06)**
- **Goals of Phase II:**
  1. **Develop a higher power SiC-based fully-functional multi-purpose inverter**
  2. **Improved efficiency (> 96%)**
  3. **Large weight and volume reduction**
  4. **Similar functionality**
- **Due to limited power of single SiC dies (switches), power target was reduced to ~ 10 kVA**
- **Solar inverter range**
- **Ratings of Phase II Prototype**
  - **Power: 10 kVA**
  - **VDC from 350 V to 700 V**
  - **Efficiency > 96%**
  - **Ambient Temperature > 75 °C**
  - **Weight << 100 lbs**
  - **Volume << 2.5 cubic foot**



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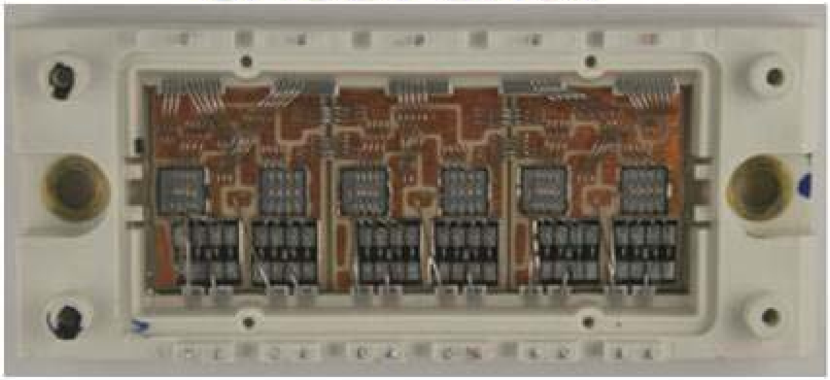
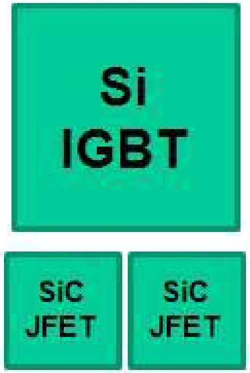
Comparison of Used Si and SiC Devices

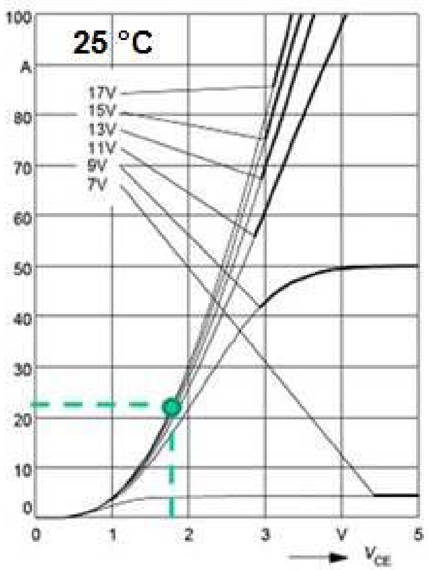
Si IGBT Brick

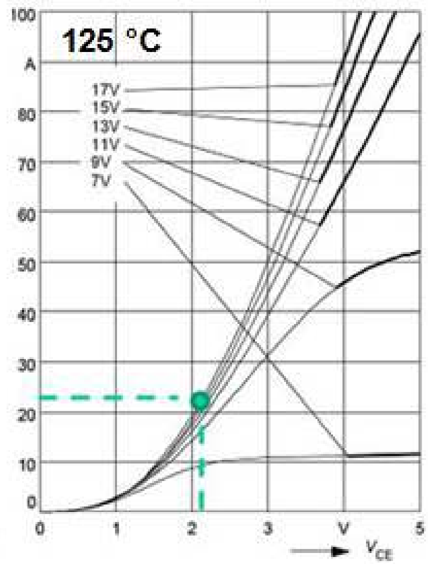


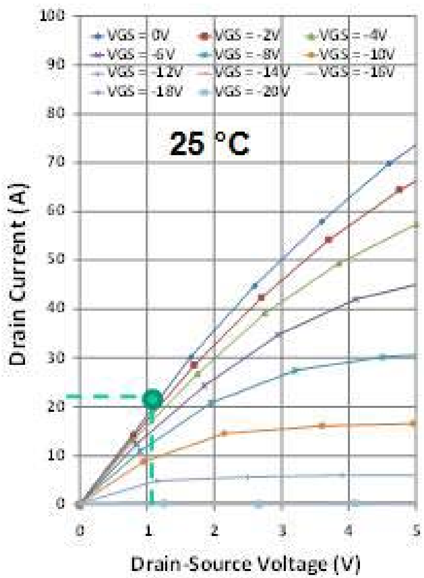
Device Area

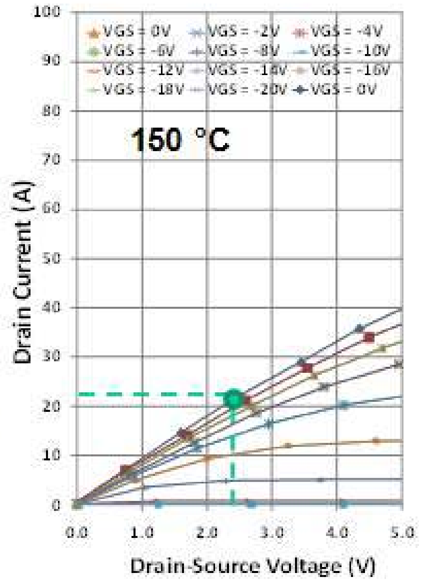


SiC VJFET Brick









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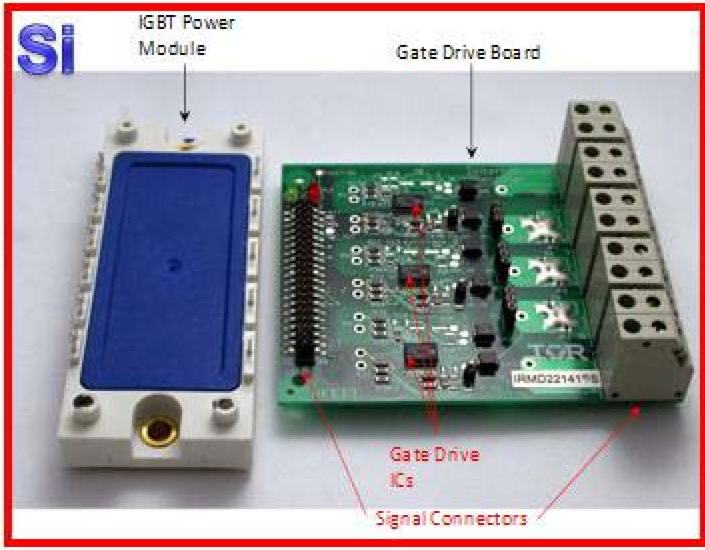
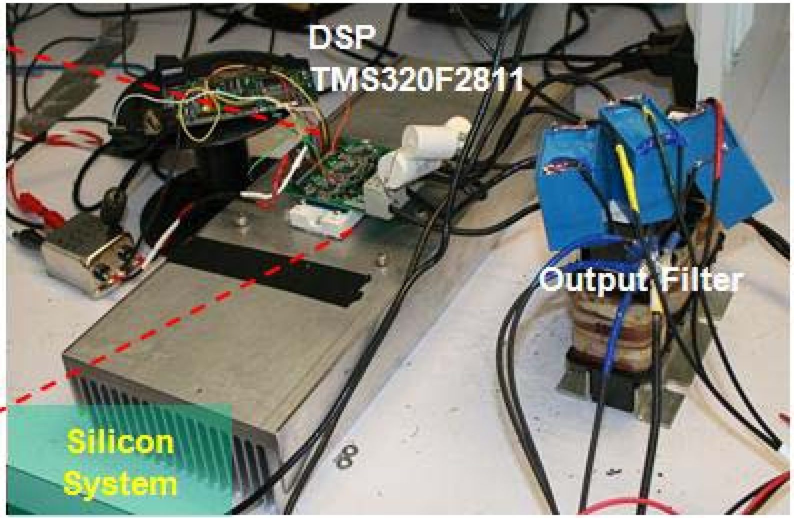
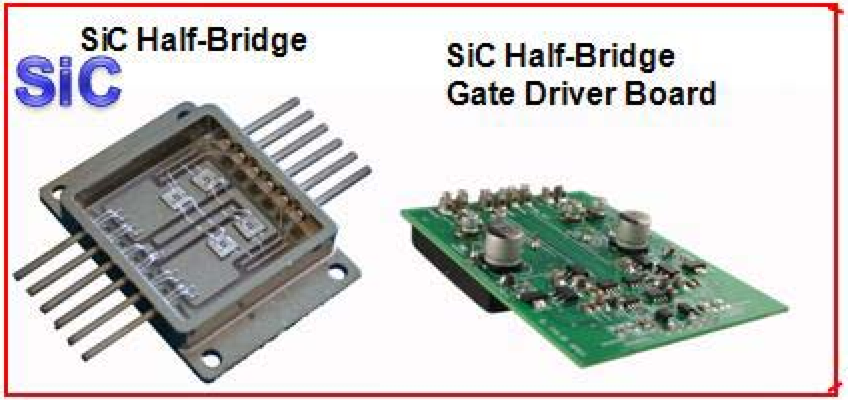
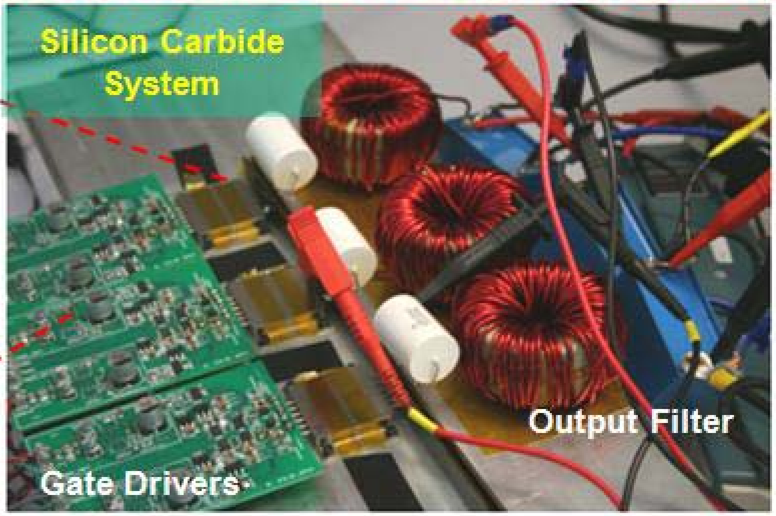
10-kVA Three-Phase Inverter Prototypes







* Three modules were used



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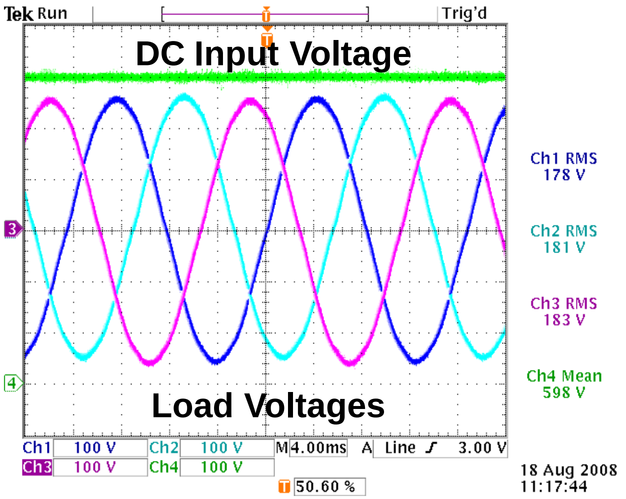
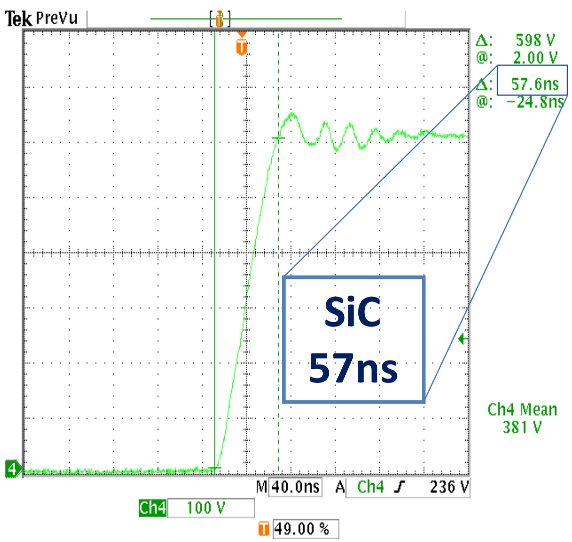
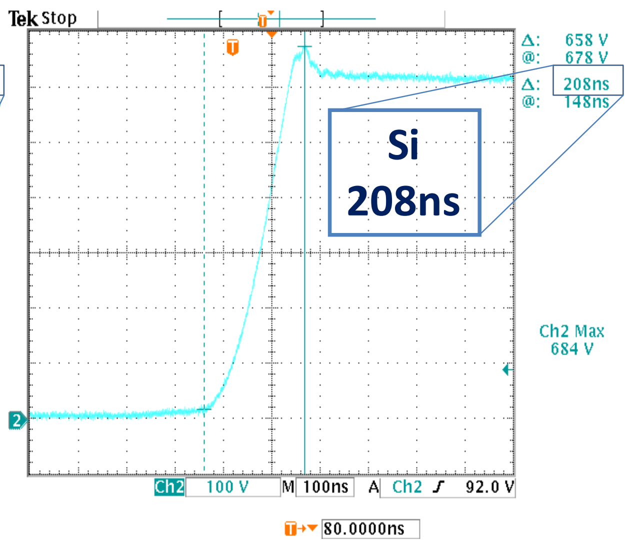
Characterization of SiC Inverter

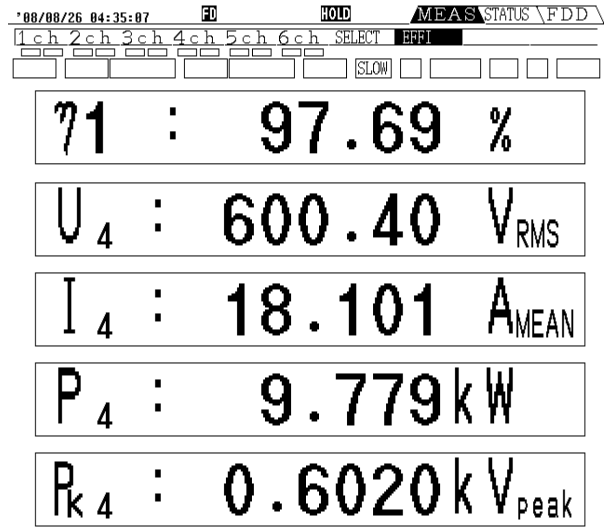
Efficiency Measurements on SiC Inverter

- Variable resistive load
- Various LC output filters were used
- Several switching frequencies: 8 kHz, 10 kHz and 20 k Hz
- PWM generation: sine triangular and space vector
- Multiple DC bus voltages from 450 VDC to 600 VDC
- Measurements were taken under constant ma







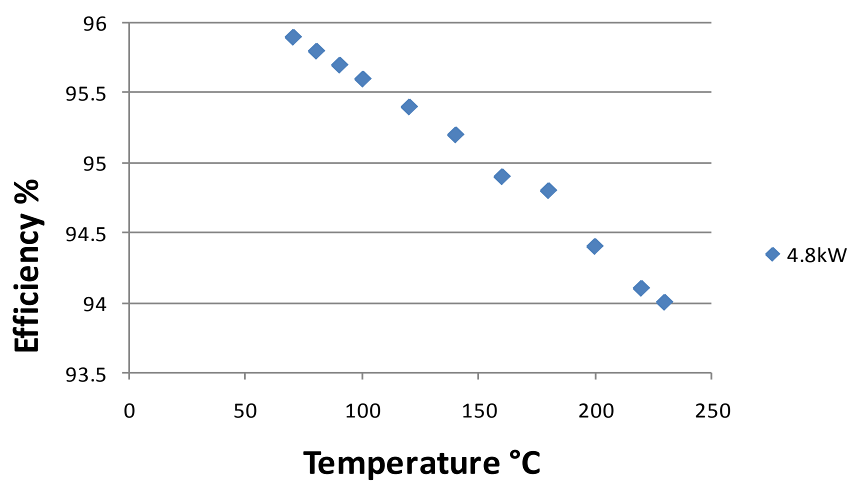


Inverter Efficiency Comparison

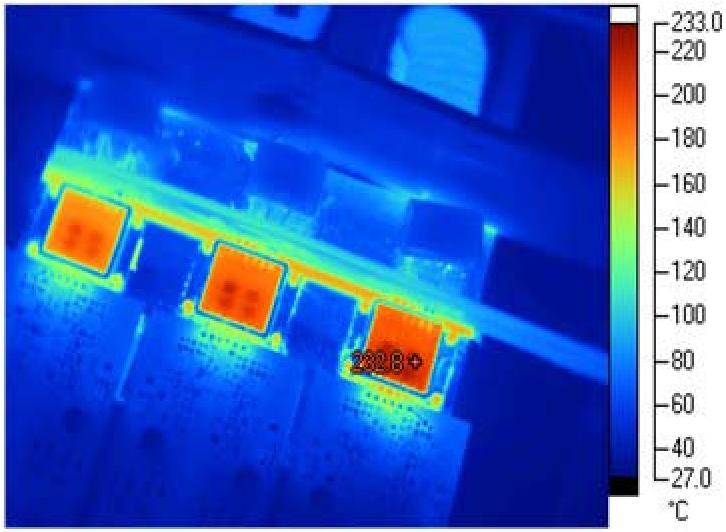
- 8.6 W/cm^2
- 7.3 kW/kg
- Power density increases 4.5× from 95°C to 150°C

	Efficiency			Passive Cooling System	
	California Energy Commission	European	Peak	Heat Sink Size Volume (cm^3) / Weight (kg)	Volumetric Power Density (W / cm^3)
Si IGBT Inverter	95.0 %	94.8 %	95.5 %	7 / 6.12	1.75
SiC JFET Inverter	98.3 %	98.1 %	98.6 %	7 / 6.12	1.75
SiC JFET Inverter @ 150 °C	97.5 %	97.3 %	97.8 %	2.3 / 1.4	8.6

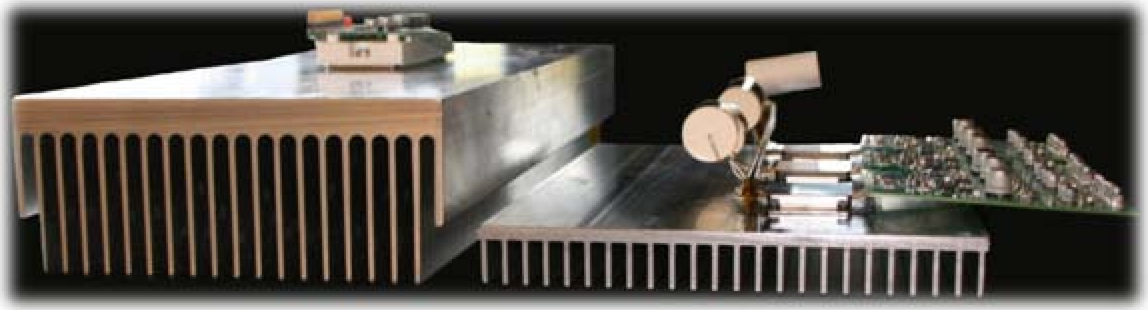
High Power Density Characterization



Three phase SiC inverter efficiency vs. temperature



Three phase inverter operating at ~233 °C



- ❑ Heatsink Dimension = 7” × 5” × 1”
- ❑ Volume = 35 in^3 (~ 10× reduction)

- 1200V/150A SiC Half Bridge Intelligent Power Modules -

ROHM

- SiC Module
  - 8 parallel SiC DMOSFETs per “switch position”
  - Includes miniaturized integrated high temperature gate driver
  - Module demo operation at 250 °C junction
  - Packaging operational to 300 °C junction

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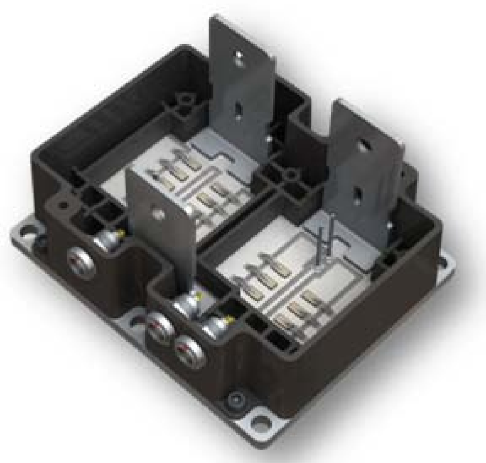
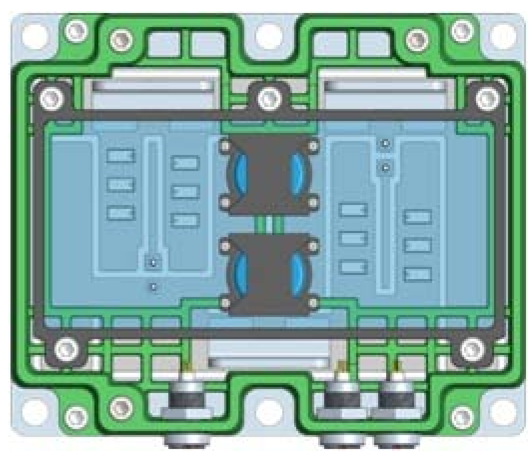
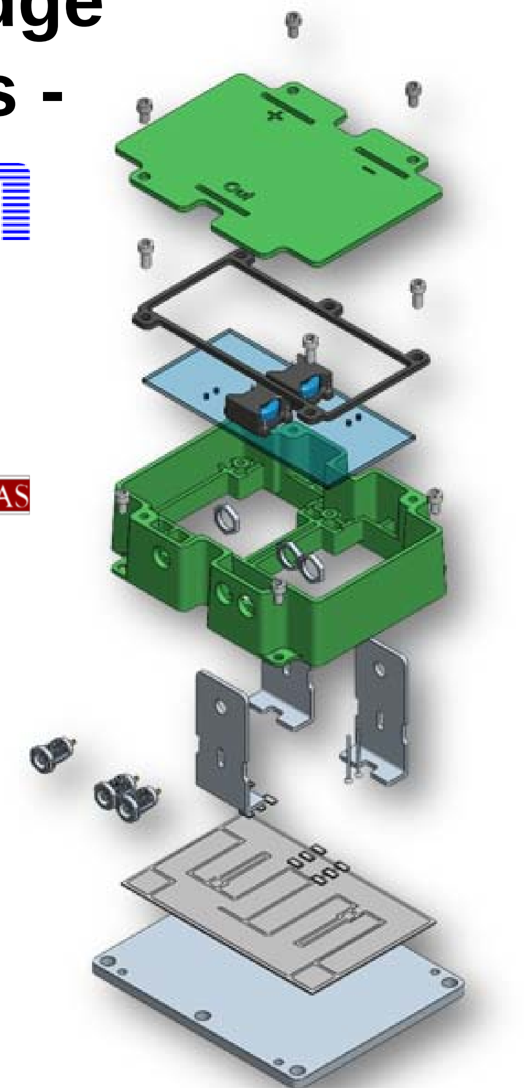
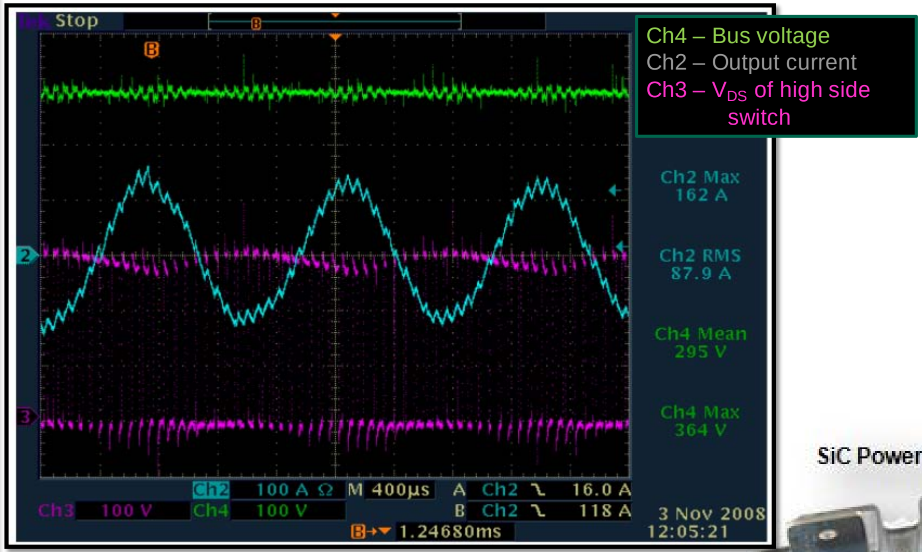
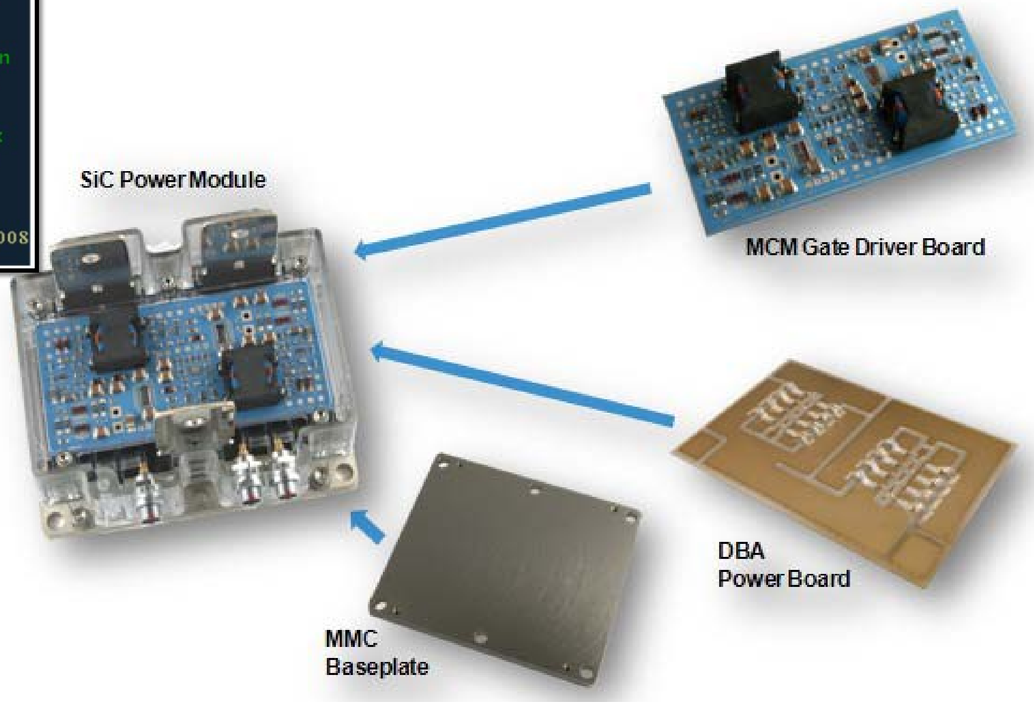






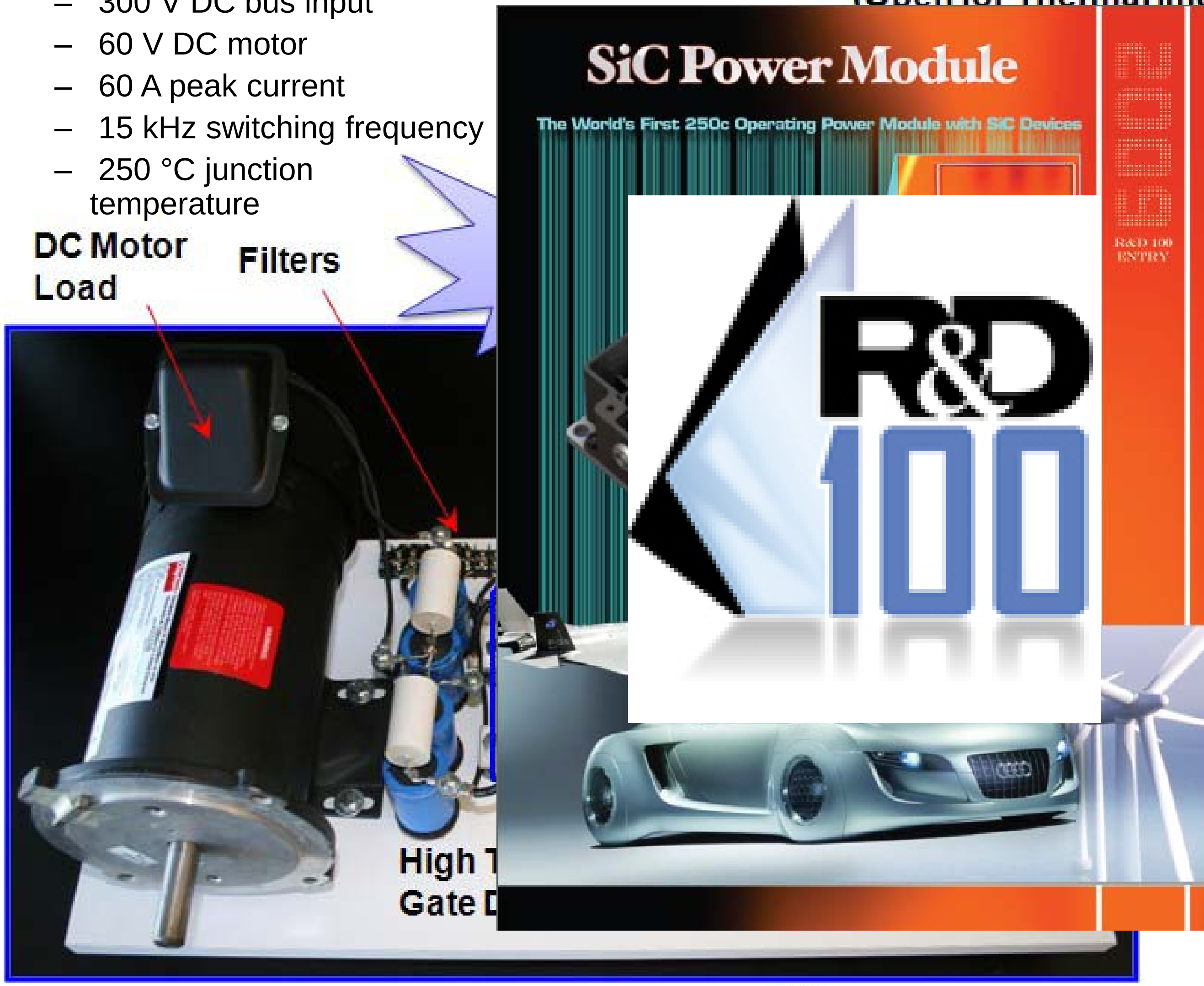
1200V/150A SiC Half Bridge Intelligent Power Modules



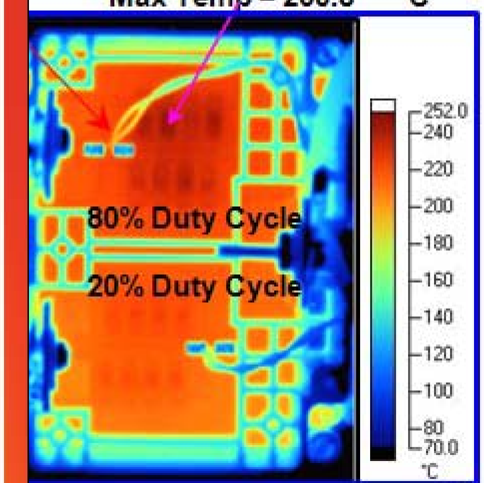


- SiC Power Module Demonstration -

- Demonstration System
  - 300 V DC bus input
  - 60 V DC motor
  - 60 A peak current
  - 15 kHz switching frequency
  - 250 °C junction temperature



SiC Power Module processing 4 kW (Open for Thermal Imaging)



Voltage Regulator for PWM Control

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wer Supply

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Summary

➢ Goal of Phase II Work

- Develop a higher power (10-kVA) all-SiC three-phase inverter
- System efficiency (>96%)
- Weight and volume minimization options

➢ Contributions of Phase II Work

- Design, fabrication, testing and characterization of 10-kVA all SiC Inverter
  - Selection and full characterization of used SiC devices (i.e., static and dynamic characterization vs. temperature, statistical dispersion)
  - Paralleling of multiple SiC devices
  - Developed high temperature (300+ °C) SiC device packaging technology (i.e., wire bonds, die attach, substrate and encapsulation)
  - Developed of gate driver circuitry

Summary

- **Contributions of Phase II Work (Cont.)**
  - Demonstration of high efficiency operation:
    - Multiple output filters and PWM modulation schemes were compared
    - Performance comparison to "equivalent" Si system
    - Measured SiC system showed an CEC = 98.3% and EE = 98.1%
  - Demonstration that important weight and volume minimization are possible (tradeoff studies)
- **SiC device technology has the potential of greatly increase the performance of power converters**
  - Higher efficiency
  - Smaller size
  - Higher reliability
  - And ultimate lower cost
- **Developed technology received a 2009 R&D 100 award**

Acknowledgments

- **APEI's Partners**
  - **GeneSiC**
  - **State of Arkansas**
  - **Rohm Corp.**
  - **University of Arkansas**
- **Energy Storage System Program, Dr. Imre Gyuk**
- **Sandia National Laboratories, Dr. Stan Atcitty**