High Power Density Silicon Carbide Power Electronic Converters

DOE Energy Storage & Power Electronics Research Programs

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Sandia National Laboratories

Energy Storage Systems Program

Overview

- Broader Impact of SiC-based Power Converter
- Development of 10-kVA SiC Inverter
  - APEI's Goals
  - SiC Power Devices Selection and Characterization
  - Testing of 10-kVA All SiC Inverter Prototype
- Summary

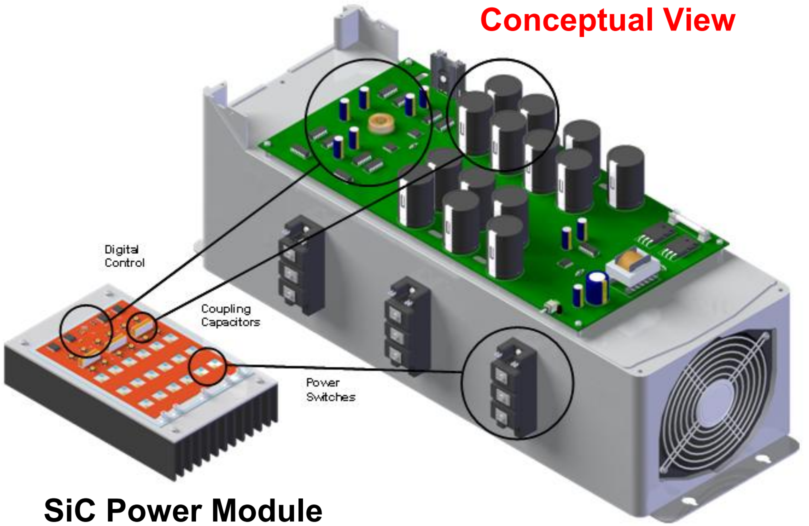
Advantages of Silicon Carbide (SiC)

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

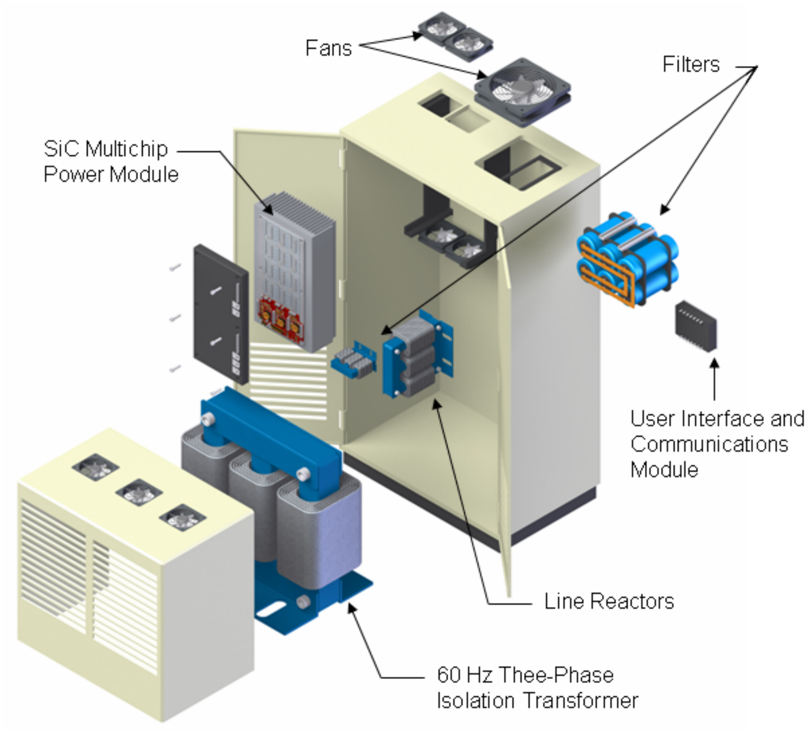
- SiC device theoretical limit exceeds 600 °C
  Very high power densities can be achieved with these junction temperatures
- SiC has a very high thermal conductivity—excellent for power devices and thermal transfer, increases power density



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

DOE ESS Phase II SBIR (FY06)

- Phase II started on August 2006
- 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
- Ratings of Phase II Prototype
  - Power: 10 kVA
  - VDC from 350V to 700 V
  - Efficiency > 96%
  - Ambient Temperature > 75 °C
  - Weight << 100 lbs
  - Volume << 2.5 cubic foot
  - Other Important parameters:
    - Maximum AC current ~ 31 Arms
    - AC output current THD < 5 %
    - Maximum DC current ~32 A



SiC Devices Presently "Available"

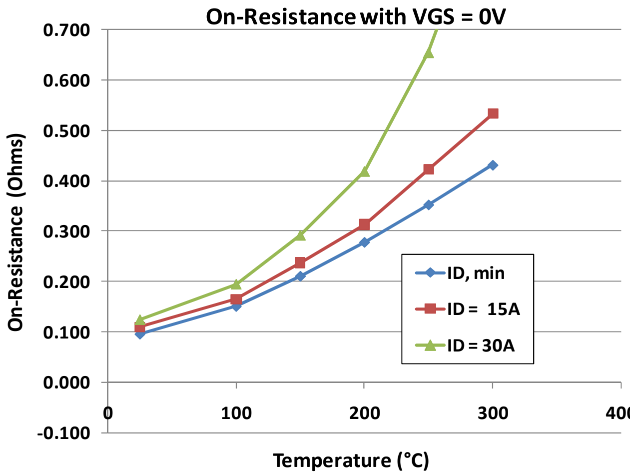
SiC Diodes

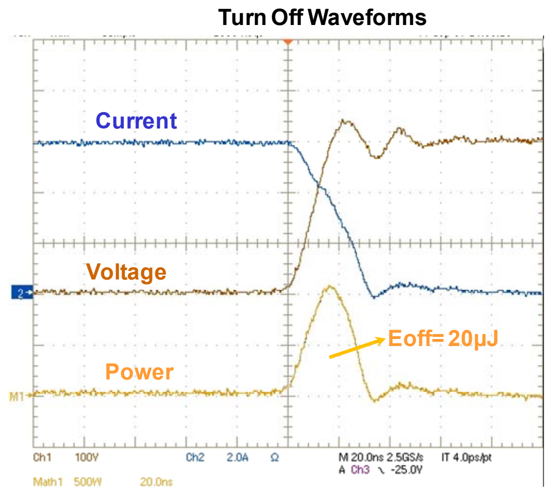
- Several commercial products available
- Schottky diodes from Cree, Inc. and Infineon (SiCED)
  - 300V, 600V and 1200V
  - 20+A and recently 50+A single die

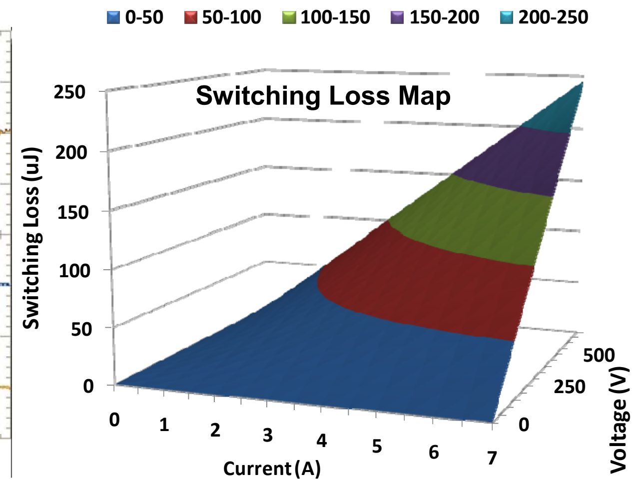
SiC Controllable Switches

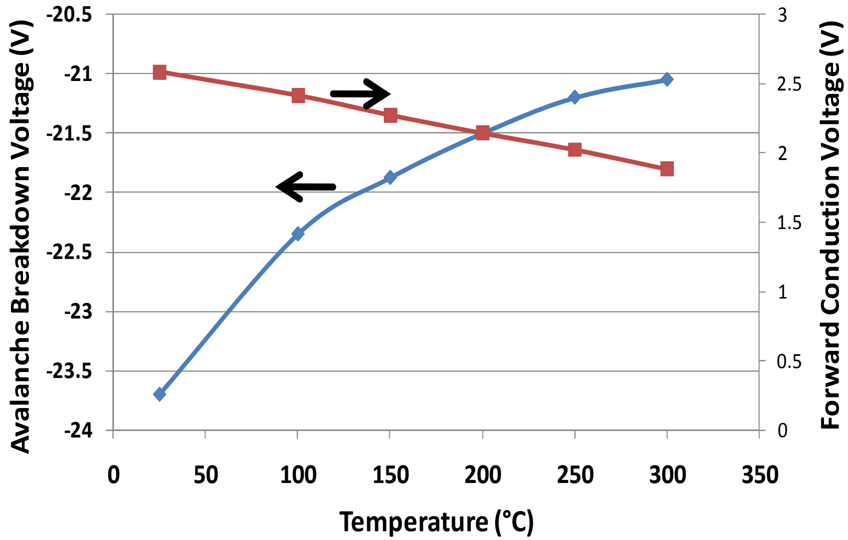
- Normally-off: VJFETs (Lower Voltage), BJTs, MOSFETs and Thyristors
- Normally-on: VJFETs (also MESFETs and SIT)
- SiC normally-on VJFETs is one of the most mature
  - 1200V and 1600V 50+A per die (SiCED)
  - 600V and 1200V up to 20A per die (Microsemi)
  - SiC SuperJFET, 1200V/50 die (GeneSiC)
- SiC BJTs 1200V up to 20A per die (TranSiC, also Cree)
- SiC MOSFETs 600V,900V and 1200V up to 30A
  (Cree, Northrop Grumman, Rohm)

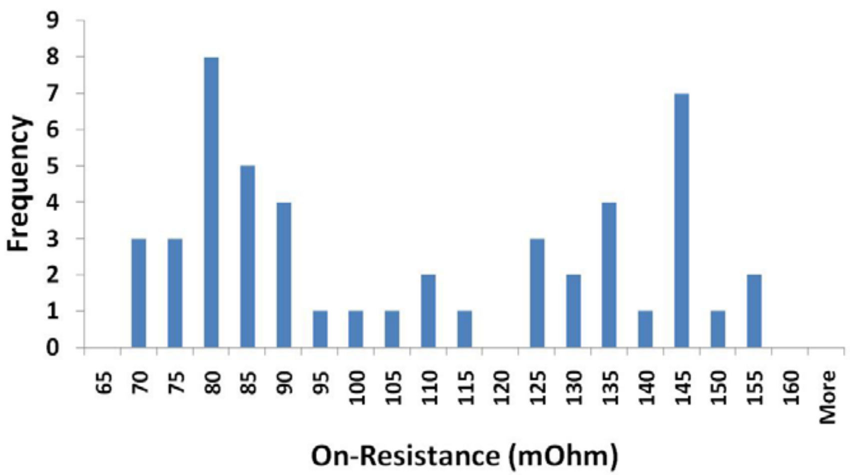
Characterization of SiC Devices











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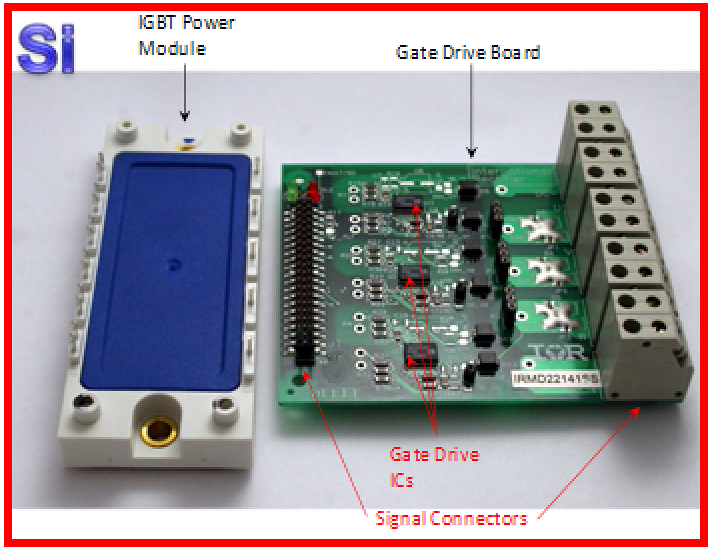
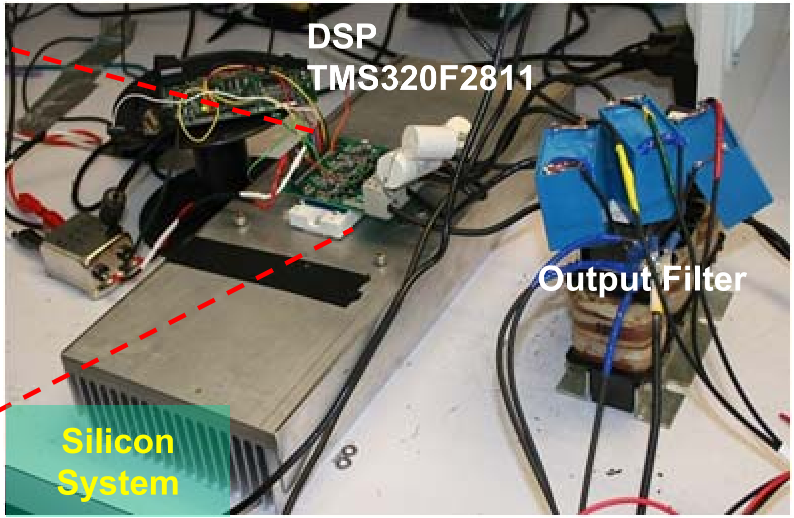
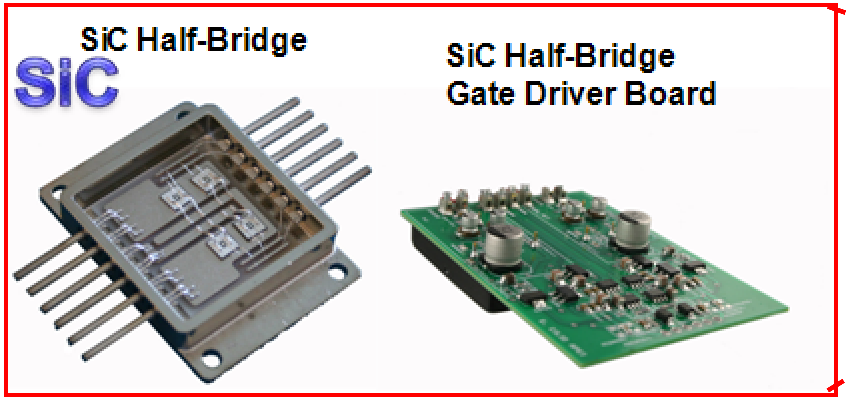
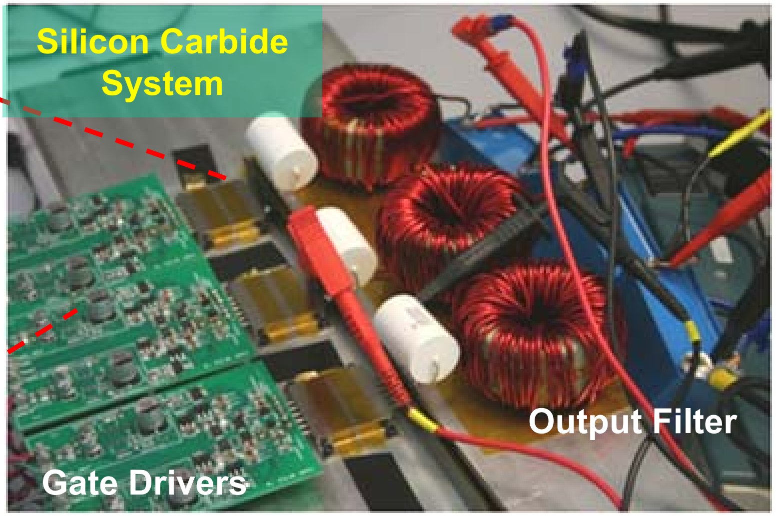
10-kVA Three-Phase Inverter Prototypes





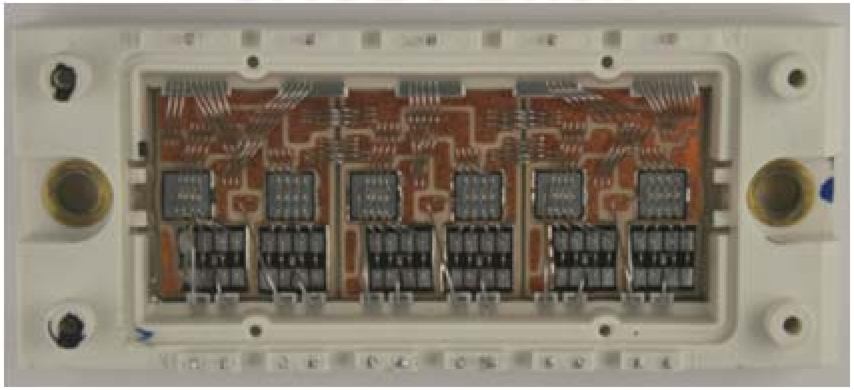


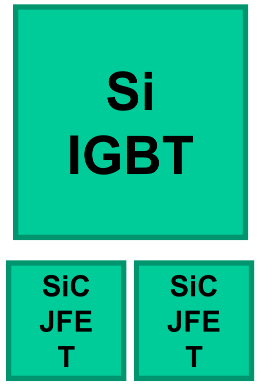
* Three modules were used



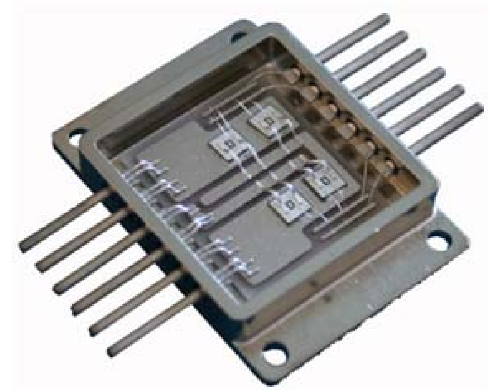
Comparison of Used Si and SiC Devices

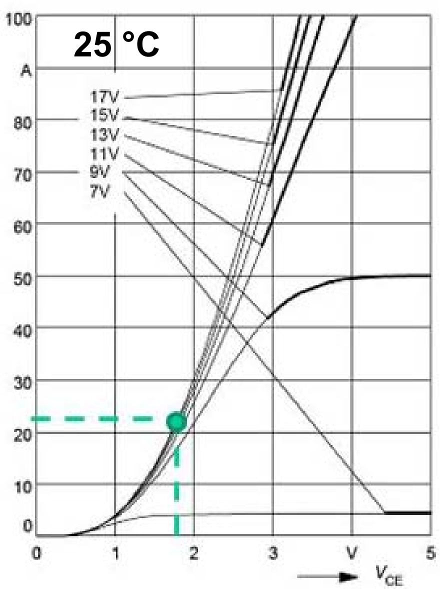
Si IGBT Brick

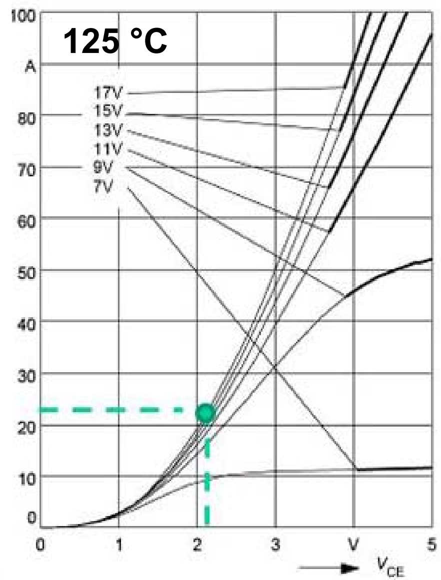


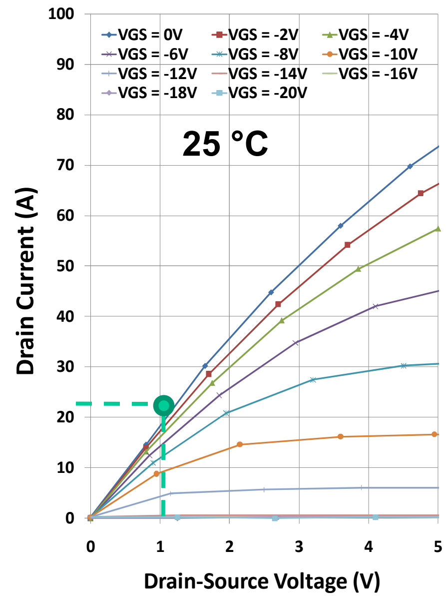


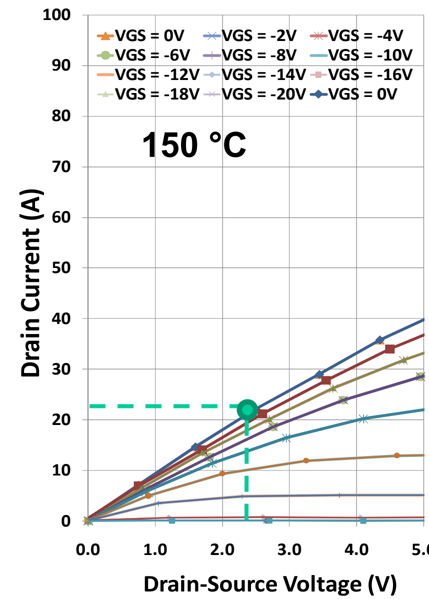
SiC VJFET Brick







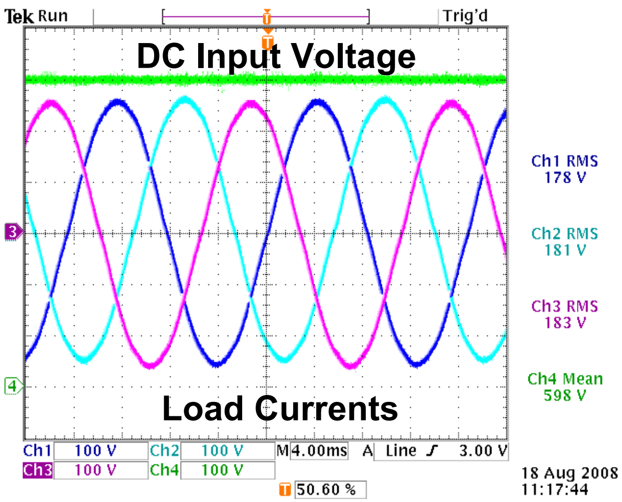


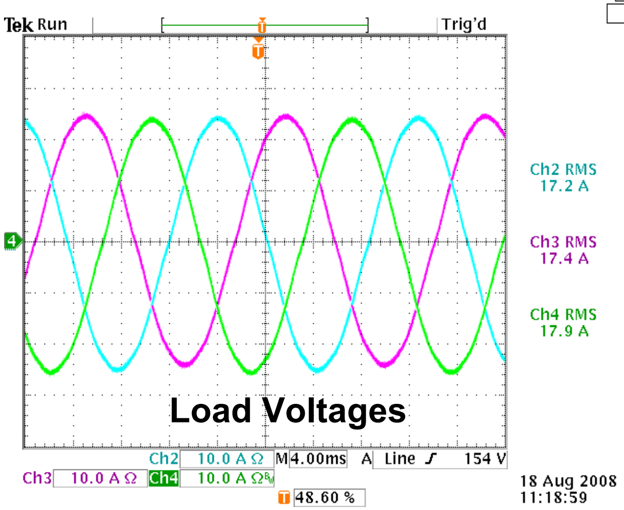


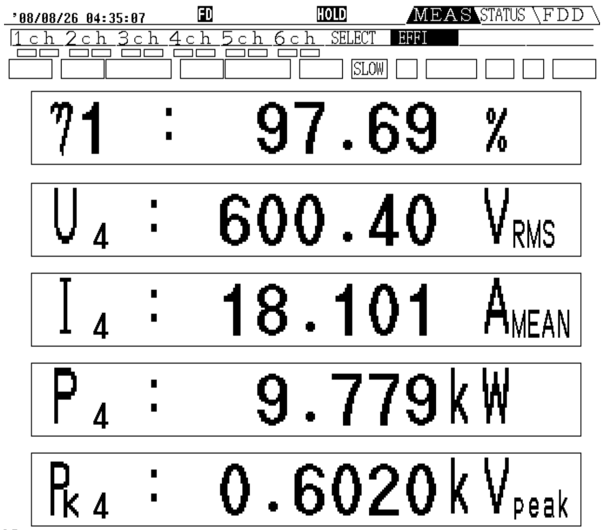
Characterization of SiC Inverter

Efficiency Measurements on SiC Inverter

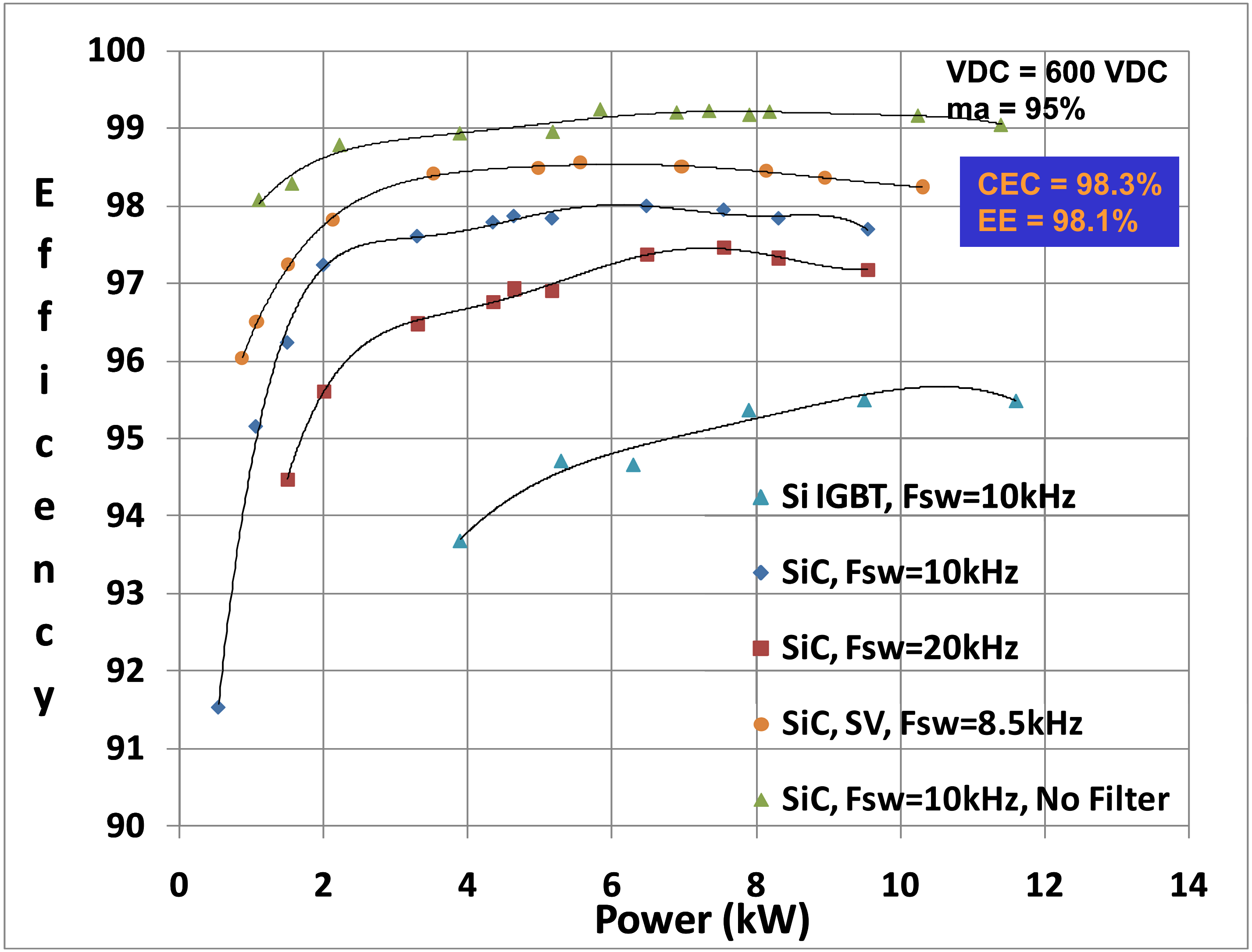
- Variable Resistive Load
- Various LC Output Filters were used
- Several Switching Frequencies: 8 kHz, 10 kHz and 20 k Hz
- PWM Generation: Sine Triangular and Space Vector
- Multiple DC Bus Voltages From 450 VDC to 600 VDC
- Measurements were taken under constant ma.



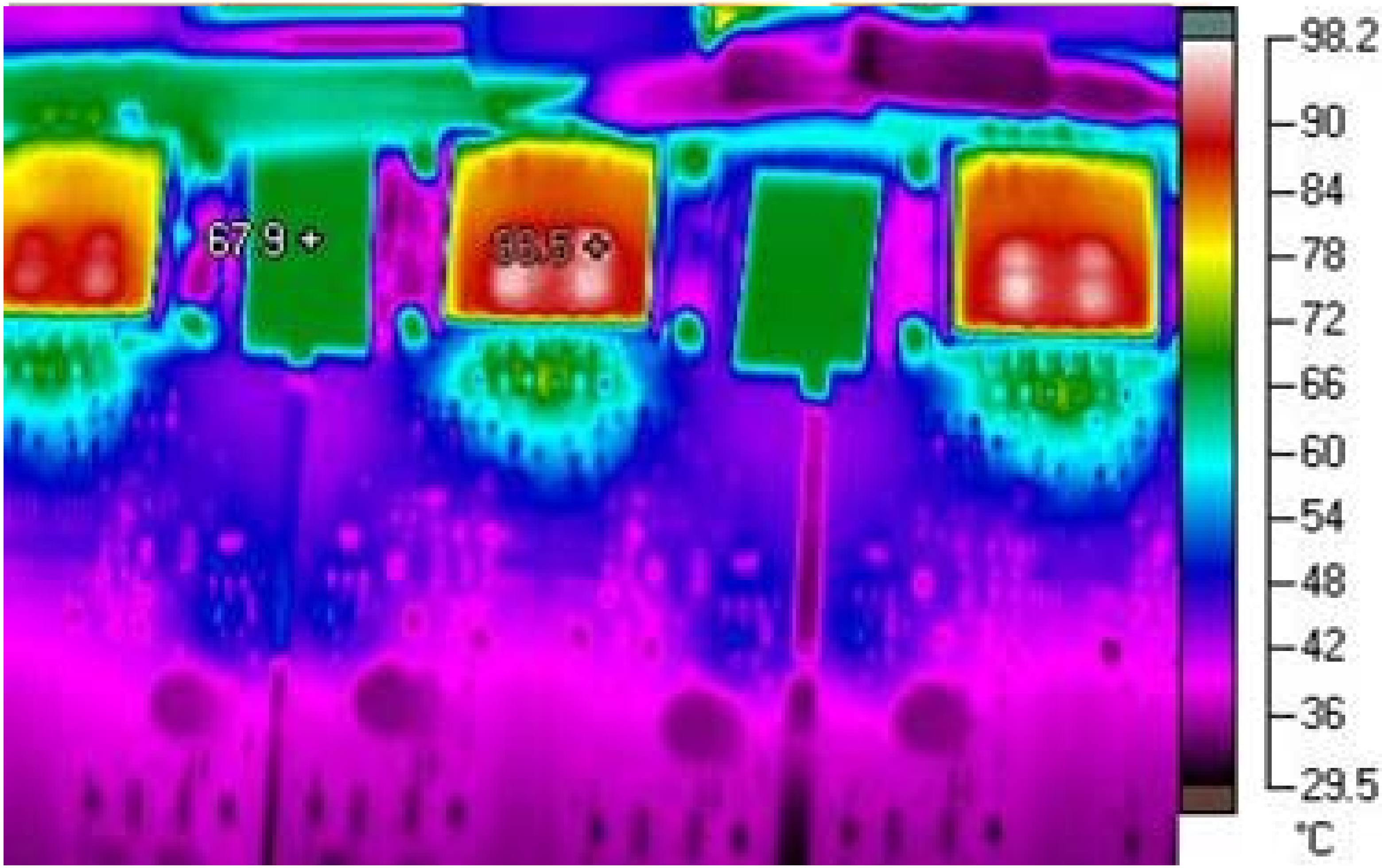




Efficiency Characterization

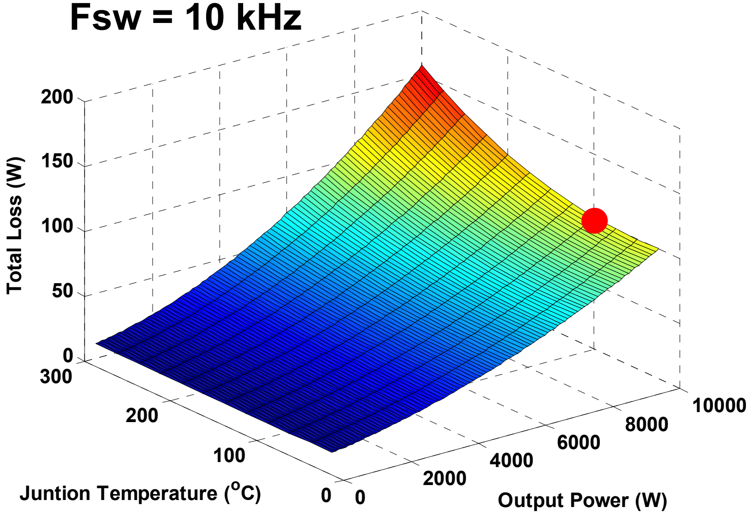


Potential For Size Optimization

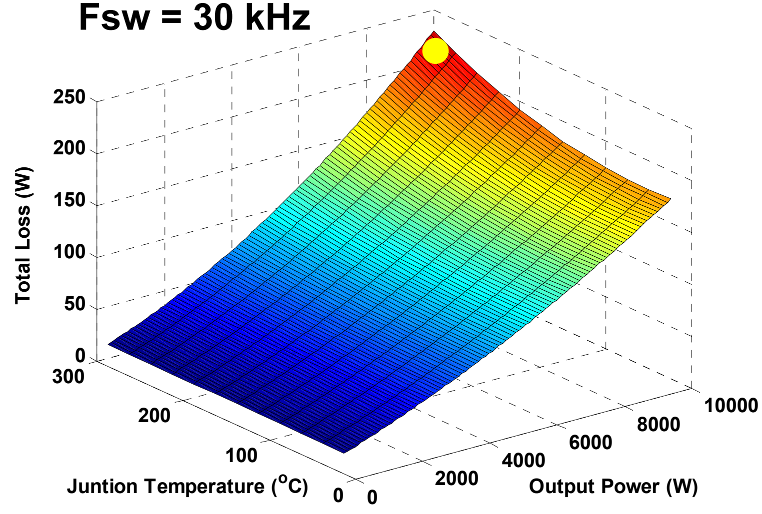


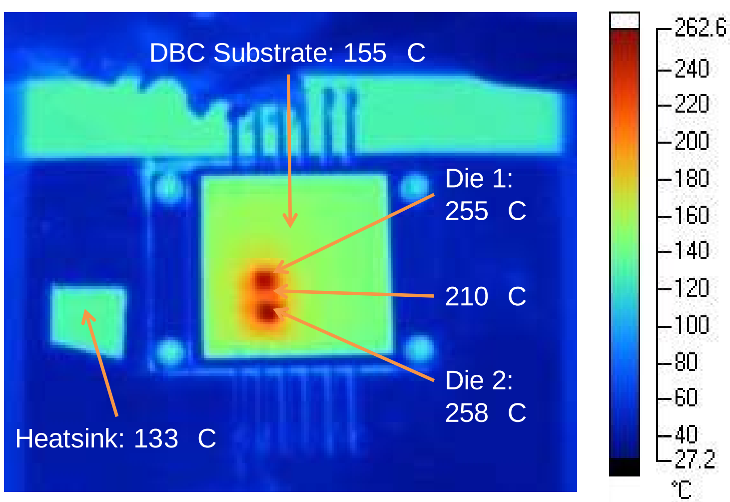
Potential For Size Optimization

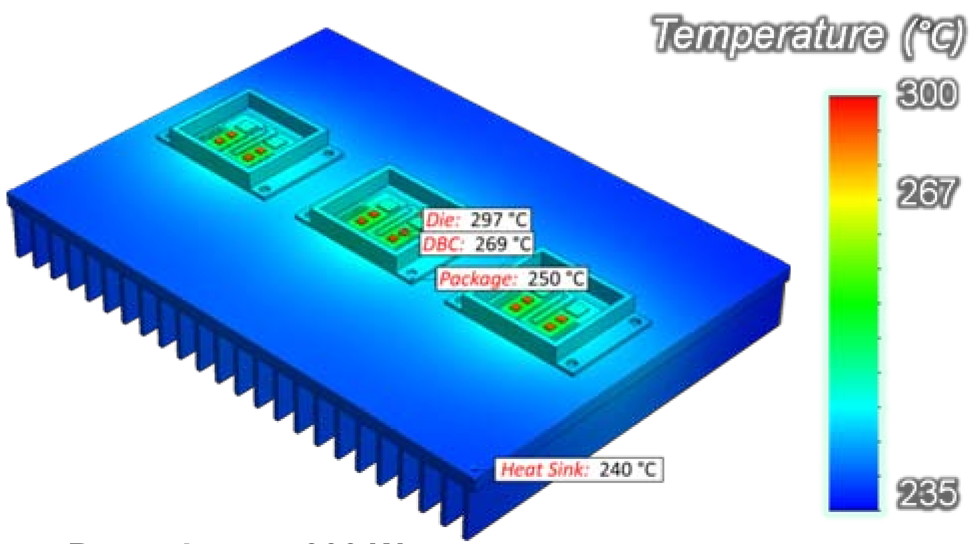
Fsw = 10 kHz



Fsw = 30 kHz







Power Loss = 300 Watts

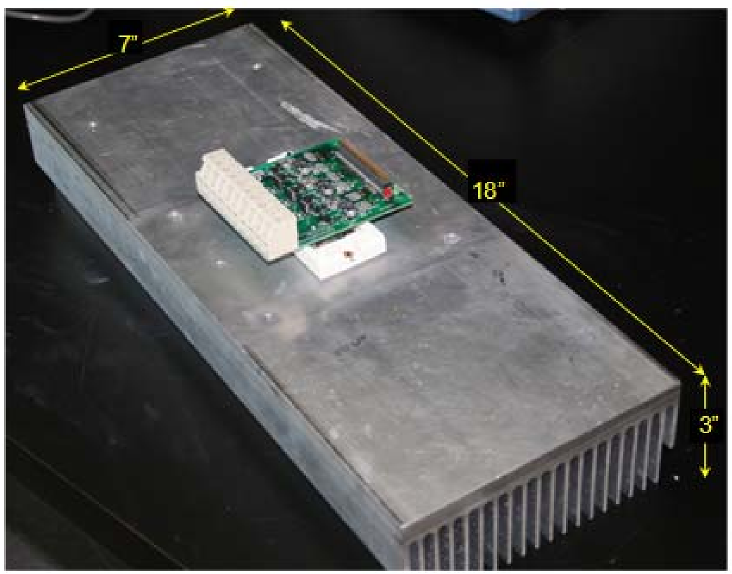
Potential Size Reduction

10-kVA Si IGBT Inverter

Estimated CEC Efficiency = 96%
Junction Temperature = 100 °C
Switching Frequency = 10 kHz
Estimated Power Loss = 230 W
Heatsink Dimension = 18"x7"x3"
Volume = 378 in^3

10 kHZ LC Filter

Dimensions: 5.75"x8"x5"
Volume: 230 in^3

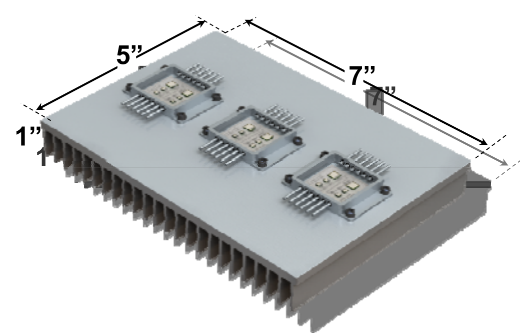


10-kVA SiC VJFET Inverter

Estimated CEC Efficiency = 96%
Junction Temperature = 300 °C
Switching Frequency = 30 kHz
Estimated Power Loss = 230 W
Heatsink Dimension = 7"x5"x1"
Volume = 35 in^3 (~ 10x reduction)

30 kHZ LC Filter

Dimensions: 5"x5"x3"
Volume: ~ 75 in^3 (~ 3x reduction)



Summary

- **Goal of Phase II work**
  - Develop a 10-kVA all-SiC three-phase inverter
  - System efficiency (>96%)
  - Weight and volume minimization options
- **Contributions of Phase II work up to this point**
  - 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 up to this point (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 ECE = 98.3% and EE = 98.1%
  - Demonstration that important weight and volume minimization are possible (tradeoff studies)

- **Future work**
  - SiC system characterization while operating at high junction temperature (250+ °C)

Summary

- SiC device technology has the potential of greatly increase the performance of power converters
  - Higher efficiency
  - Smaller size
  - Higher reliability
  - And ultimate lower cost
- Where do we go from here?
  - Higher voltage and higher power applications
    - Power capability of single-chip devices
  - Advances in key components
  - Reliable packaging technologies
  - SiC Cost

Acknowledgments

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