Silicon Carbide MOSFETs for High Powered Modules

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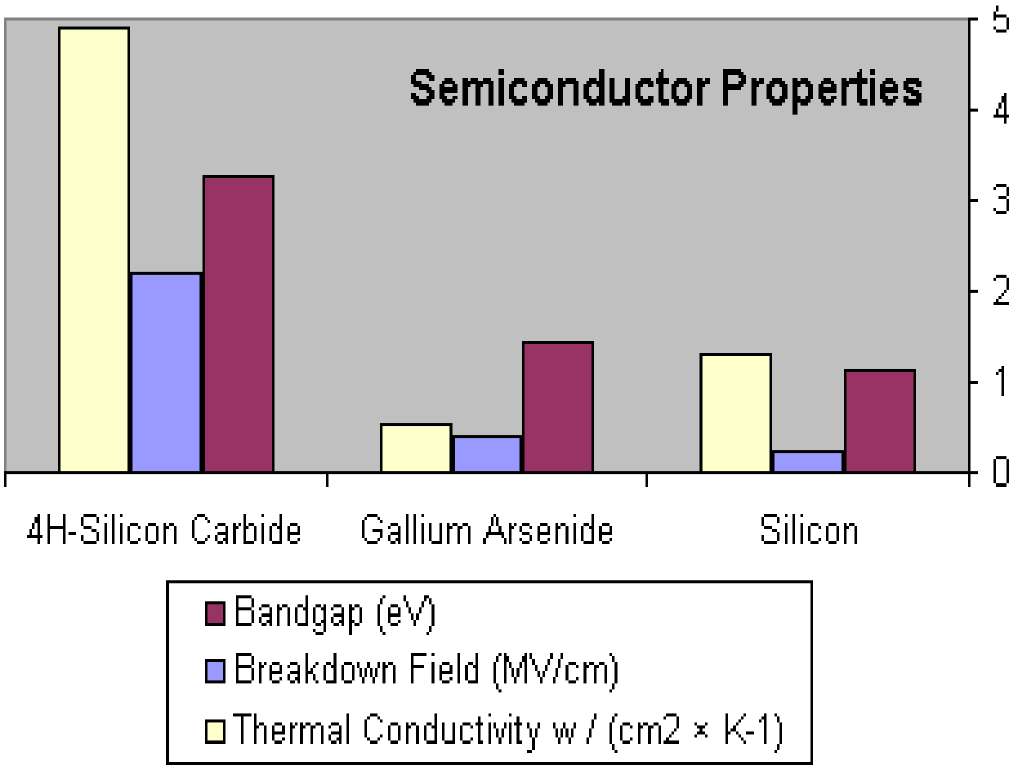
March 19, 2013

Outline

- Overview of SiC MOSFETs
  - Reliability
- Comparison of SiC MOSFETs to IGBTs
- Challenges for Module Technology
  - Higher current density
  - Higher power density
  - Higher switching speeds
- Performance of SiC MOSFETs in HEV Simulation Testing (ARL)
- Summary

SiC Power Enables Higher Efficiency and Lower Cost



Silicon carbide is superior to silicon as a semiconductor in 3 critical properties

- **Wider bandgap:** SiC supports 10 times higher electric fields than Si
- **Higher thermal conductivity:** SiC supports 3 times the power density of Si
- **Reliability:** 10X better of silicon

- **Above 600V, these properties enable SiC to provide lower loss and higher efficiency devices**
  - **Schottky diodes instead of p-i-n diodes**
  - **MOSFETS instead of IGBTs**
- **Higher frequency of operation → lower BOM cost**

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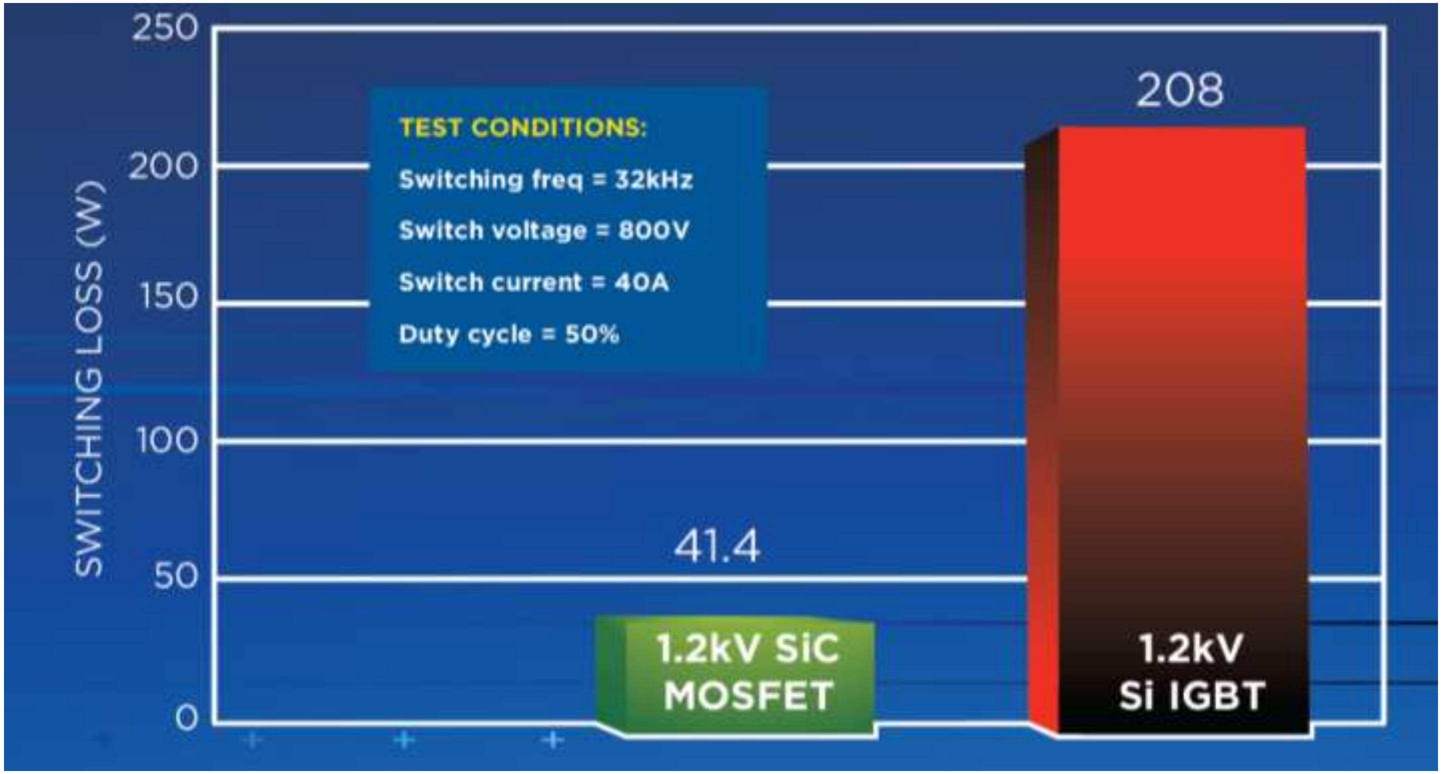
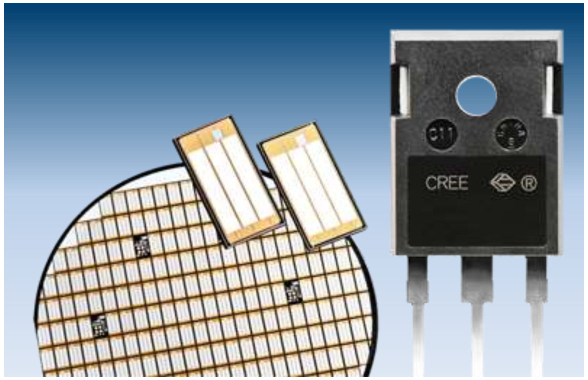
SiC MOSFETs More Efficient at Higher Frequencies



- **No tail current dramatically reduces switching losses**
- **Enables increased operating frequency, reducing size, weight and BOM cost – can be exploited in EVs for power conversion units**

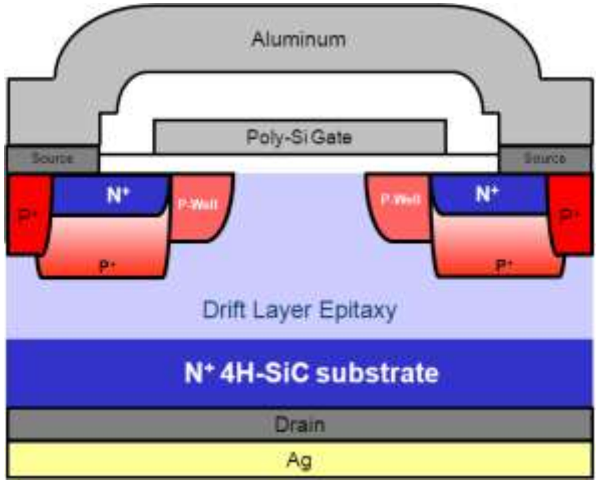
Cree's Second Generation MOSFETs

- **State-of the-art SiC Technology:**
  - Industry's First 50 Amp SiC MOSFET
  - Industry's lowest switching losses
- **More Capable than Silicon:**
  - High power density more than 3 times Si IGBT
  - Low switching losses: less than 20% of Si IGBT
- **Lower System Cost for OEM and End User:**
  - Higher efficiency reduces heat sink size
  - Higher frequency operation reduces magnetics
  - Lower Installation costs to end user



- 80 mOhm inTO-247
  - C2M0080120D
- 80 mOhm and 25 mOhm die
  - CPM2-1200-0080B
  - CPM2-1200-0025B

Planar SiC MOSFETs – Maximizing Reliability

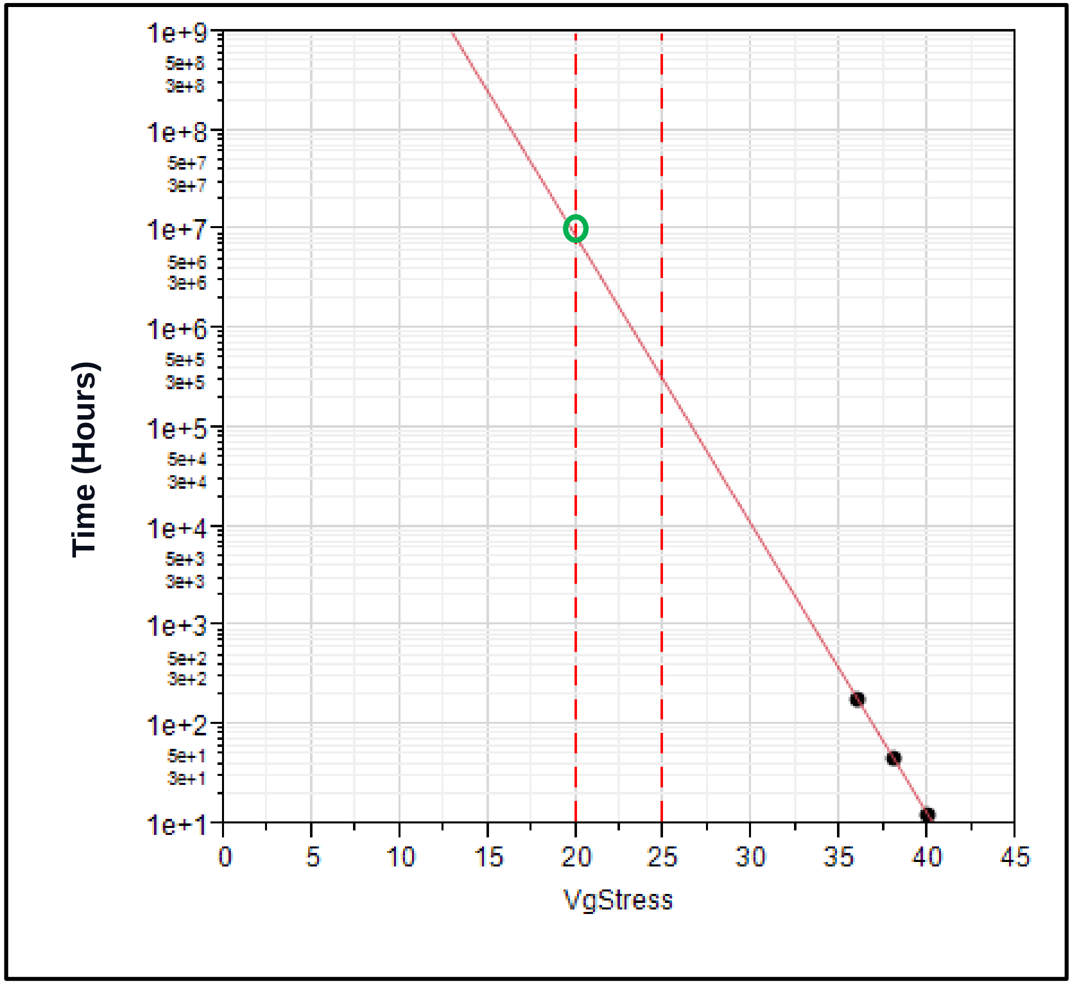


Schematic cross-Section of Unit Cell for Cree's Planar DMOSFET

- **Normally off – all reliability data taken at V_{GS} = 0V**
- **Planar structure to minimize all critical electric fields**
- **Gate oxide represents state-of-the-art for reliability and electron mobility**
- **Fully passivated and passes stringent THB requirements**

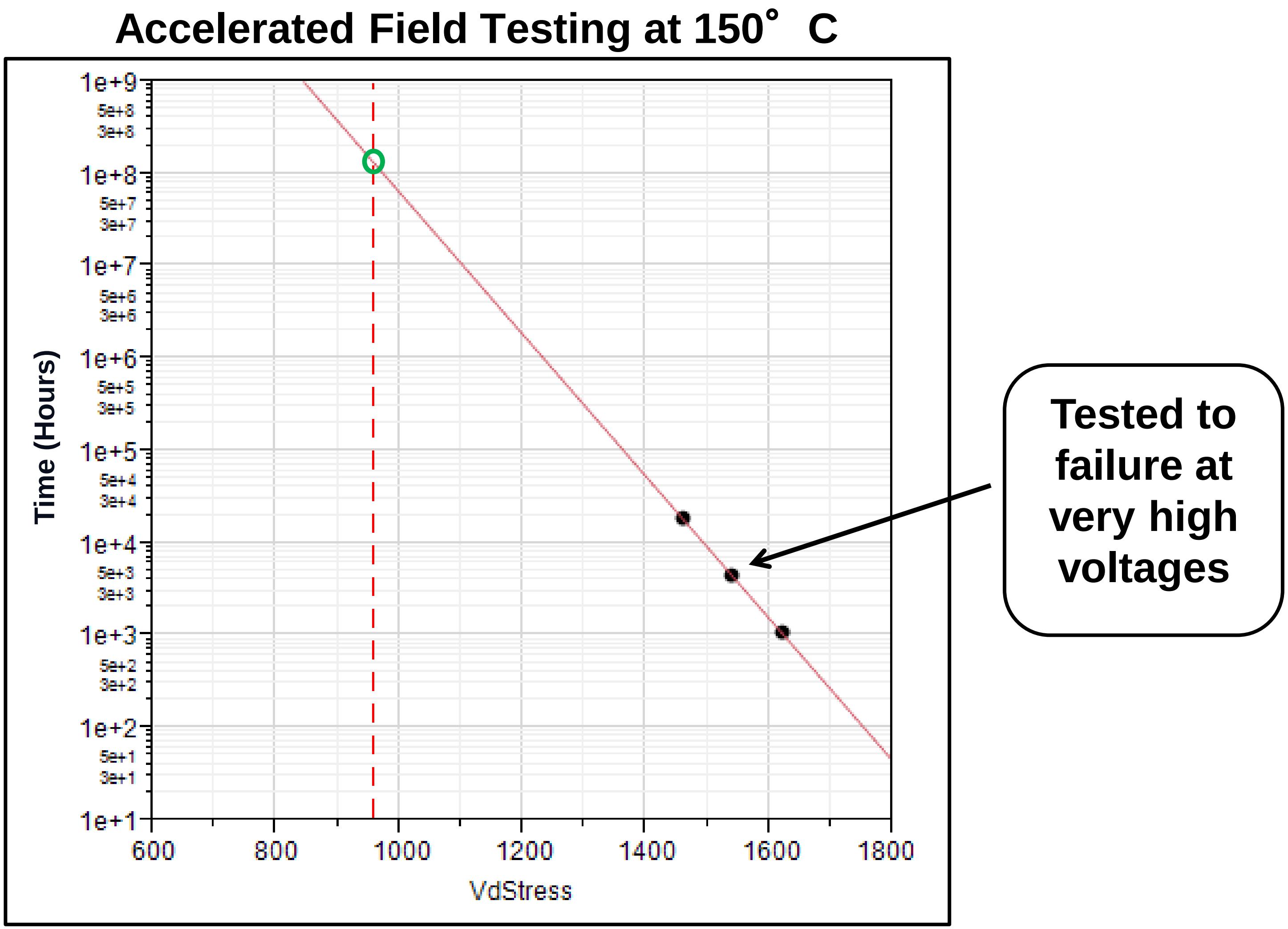
10 Million Hour Reliability of Cree's Gen 2 Gate Oxide

TDDB of Gate Oxide on 20 Amp Gen 2 MOSFETs



Extrapolated MTTF of 1E7 hours at V_{GS} = 20V

Gen 2 Reliability: 1E8 Hours MTTF at 960V



Extrapolated MTTF of 1E8 hours at V_{DS} = 960 V

Field Reliability Data for Cree SiC: Zero MOSFET Fails

Diode Field Failure Rate Data since Jan. 2004

Product	Device Hours	FIT (fails/billion hrs)
CSDxxx60	301,100,000,000	0.11
C2Dxx120	90,100,000,000	0.82
C3Dxxx60	179,000,000,000	0.06
C4Dxxx60	2,840,000,000	0.35
Total	573 Billion	0.21

FIT rate of 0.21 is 10 times lower than the typical silicon

- **MOSFETs in production since January, 2011**
- **Estimated 138 million field hours to date**
- **Zero reported failures**
- **Assuming 1 failure to do the math, FIT rate = 7 per billion hours**

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  - Beneficial Properties of SiC MOSFETs
- **Comparison of SiC MOSFETs to IGBTs**
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  - Higher current density
  - Higher power density
  - Higher switching speeds
- Summary

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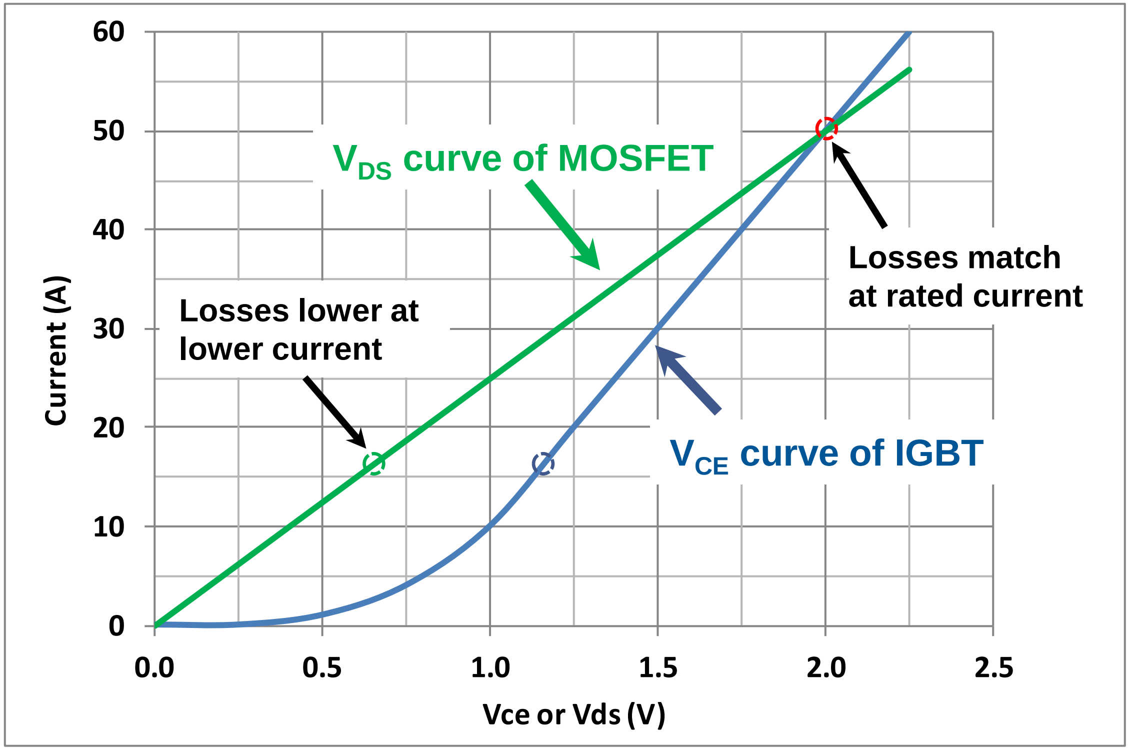
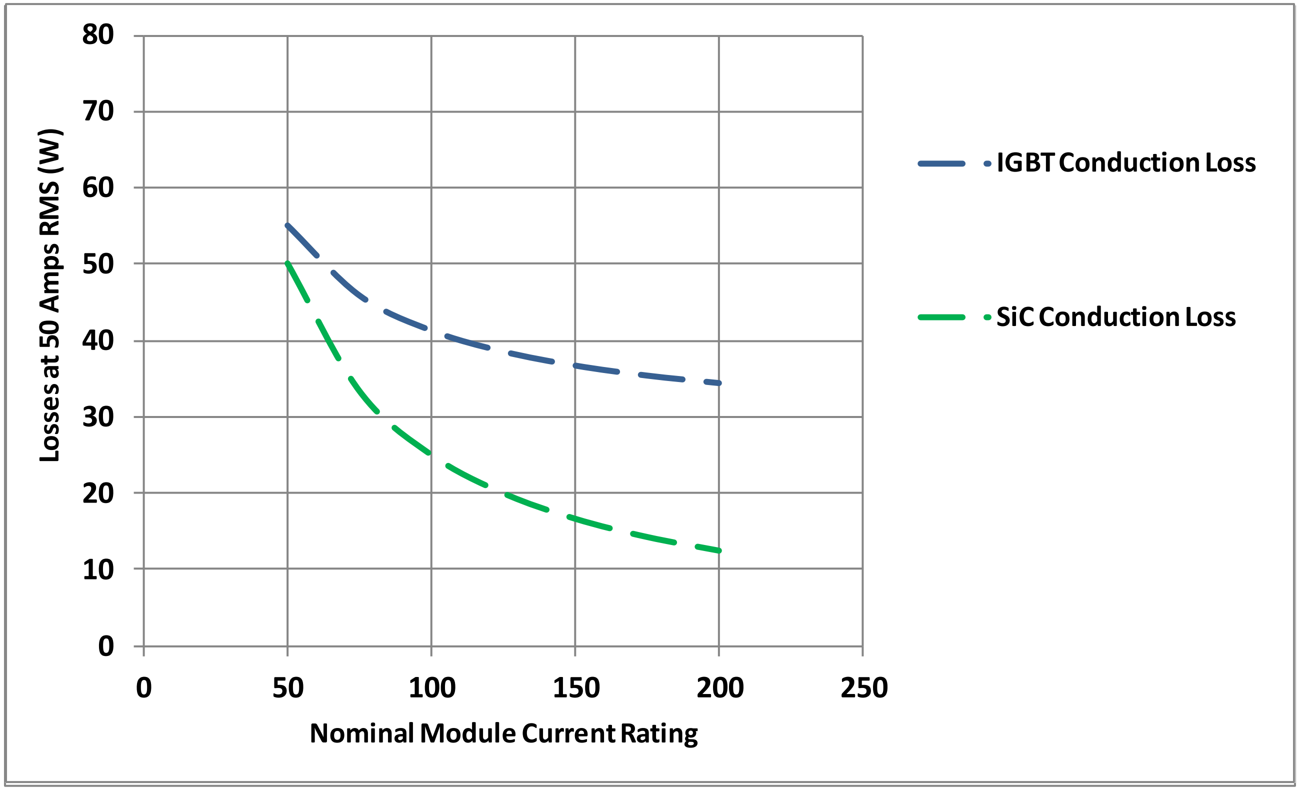
Conduction Losses of SiC MOSFETs Lower than in IGBTs



Comparison of 50 Amp IGBT4 to 50 Amp SiC MOSFET in module at T_J = 150° C

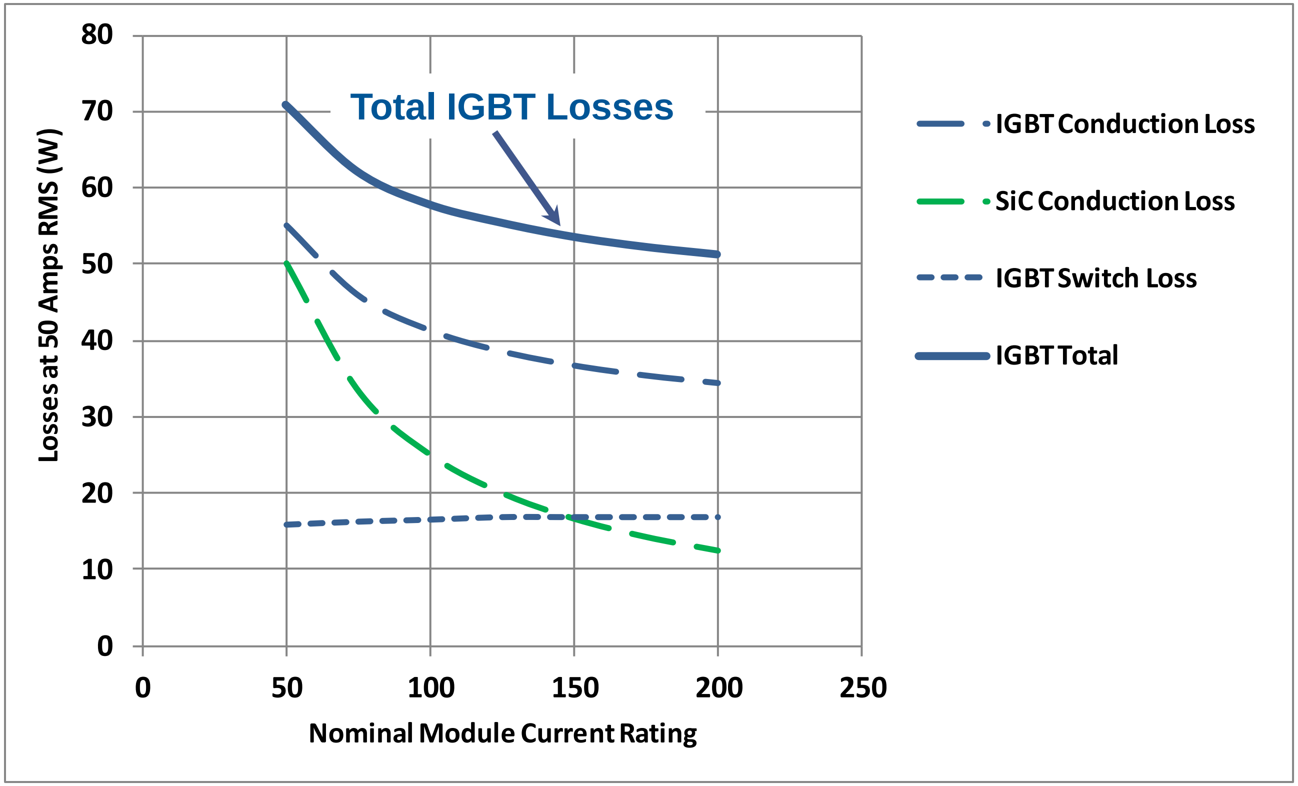
- **MOSFET conduction losses are half of the IGBT when backed off to 1/3 of rated current**

Efficiency Benefits of Larger SiC MOSFET Modules



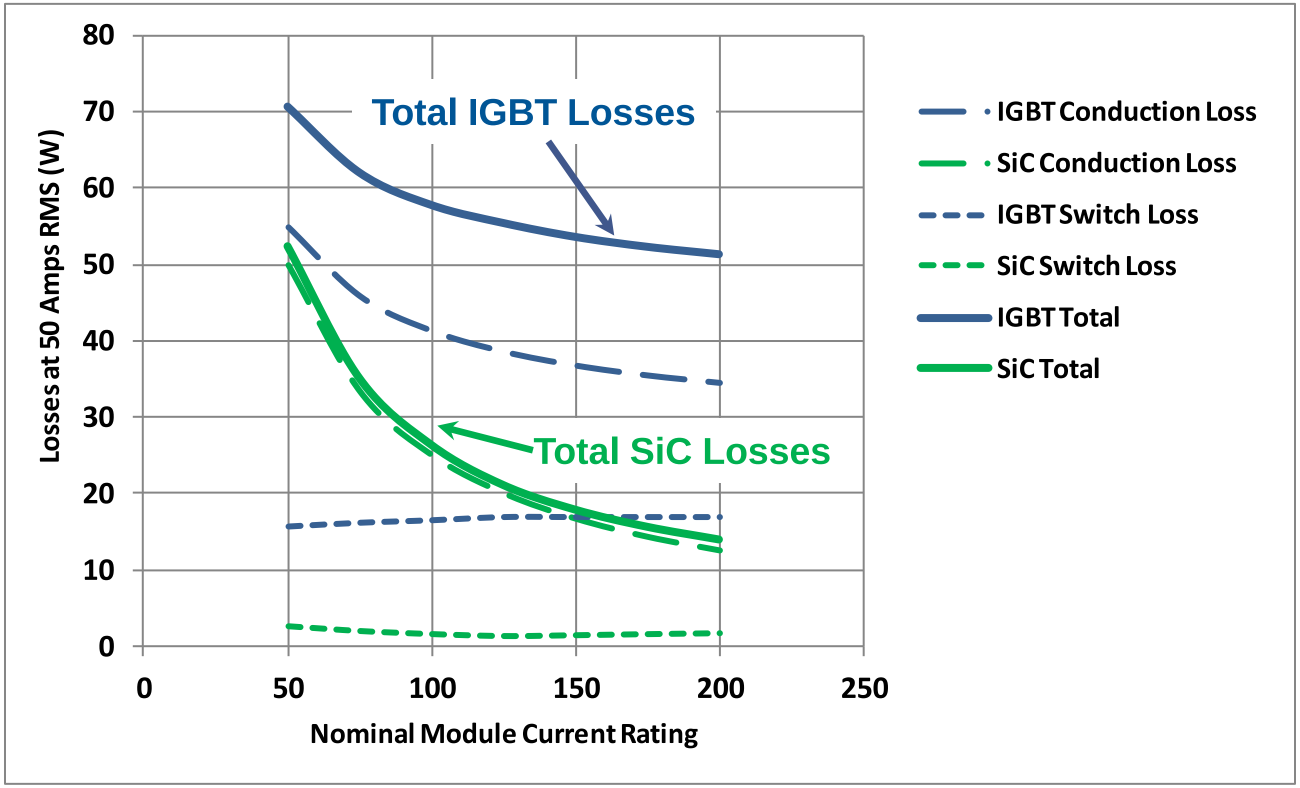
- SiC losses decrease faster than IGBTs with increasing die count

Switching Losses in IGBTs are High



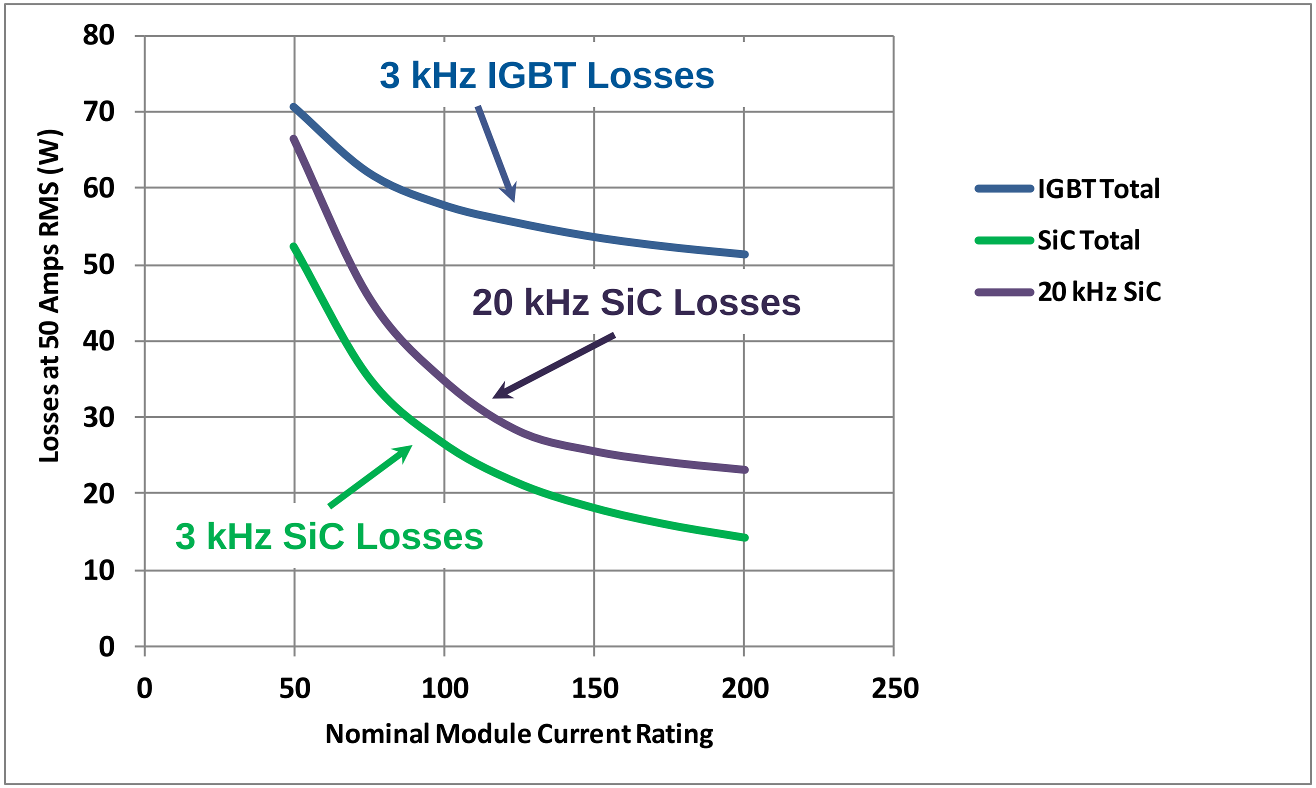
- Switching losses in IGBTs are significant even at 3 kHz
- 30% of the total loss with a 200A IGBT module would be from switching

Low Losses in SiC MOSFETs Provide System Advantages



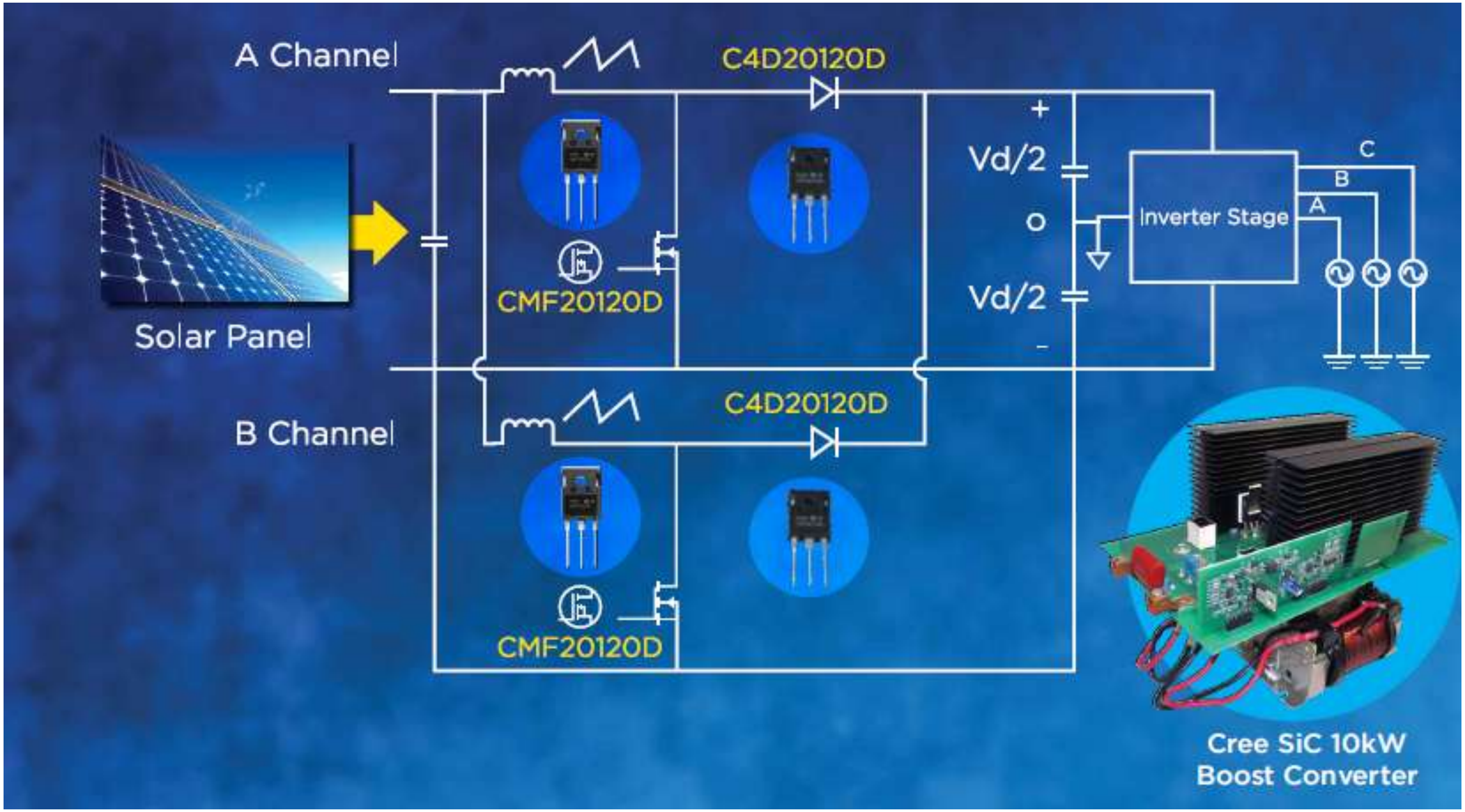
- **50 Amp SiC module is more efficient than 150 Amp IGBT module**

Higher Frequency Enabled with SiC MOSFETs



- 50 Amp SiC module is more efficient than 150 Amp IGBT module
- SiC module at 20 kHz is more efficient than an IGBT module at 3 kHz

High Frequency 10 kW Boost Inverter with SiC MOSFETs



Architecture of all-SiC Boost Inverter

Summary of SiC Boost Converter Advantages

Increase in system frequency dramatically reduces size and weight

Cost Comparison	Silicon Solution	SiC Solution
Frequency	**20 kHz**	**100 kHz**
Inductors	$75	$20
Capacitors	$65	$65
Heat sink	$45	$38
Si IGBT or SiC MOSFET	$4	$25
Si or SiC Diode	$2	$6
Total Cost	**$191**	**$154**

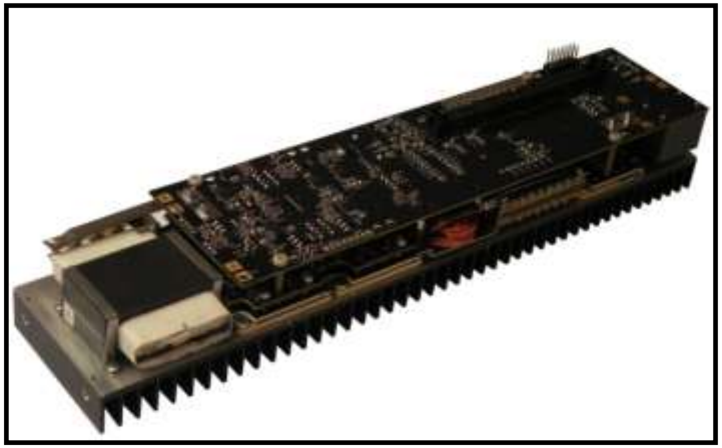
Transformer at 20 kHz

Transformer at 100 kHz

- **SiC solution is 60% smaller and 20% lower cost**
- **Directly applicable to power converters in EVs**

On Board Charger with SiC for High Power Density (APEI)

Prototype 6 kW SiC Charger



Measured Performance

Parameter	Value
Peak Output Power	6.06 kW
System Volume	1.077 L
System Mass	1.448 kg
Volumetric Power Density	5627 W/L
Gravimetric Power Density	4186 W/kg
Peak Efficiency	95.0%
THD at full power	4.2%
True power factor at full pwr.	0.996

- **Two-stage charger with SiC MOSFETs and diodes**
- **Both stages operating at 200 kHz to give power density of 5.6 kW/liter**
- **6 kW output power at 95% efficiency**

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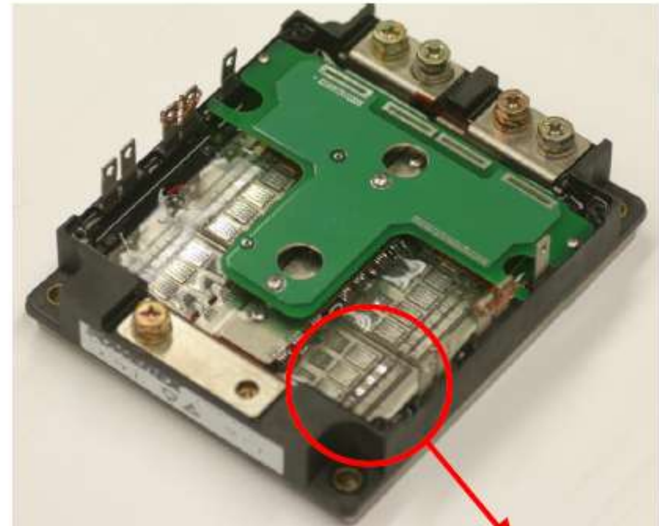
- Comparison of SiC MOSFETs to IGBTs
- **Challenges for Module Technology**
  - **Higher current density: need better interconnects**
  - **Higher power density: need improved heat transfer**
  - **Higher switching speeds: need lower inductance**
- Summary

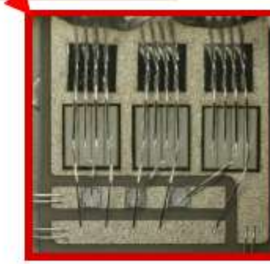
Extremely High Current Density in SiC MOSFETs Modules

- Cree's Gen 2 MOSFET is half the size of a comparable IGBT
  - $200\ A/cm^2$ nominal current rating
  - Another 50% die shrink planned over next 2 generations
- Higher over-current capability
  - SiC has more capability for surge/ start-up currents
  - Power density can temporarily increase by another factor of 2-3
- SiC modules operating at half the nominal rating of IGBT modules
  - Result : 4 - 8x increase in current density
  - Offset by lower dissipated power
  - Future generations could operate at 2 - 4x the thermal load
- Goal is to keep the MOSFETs cool, not exploit high temperature capability
  - Performance, efficiency, mechanical reliability of module

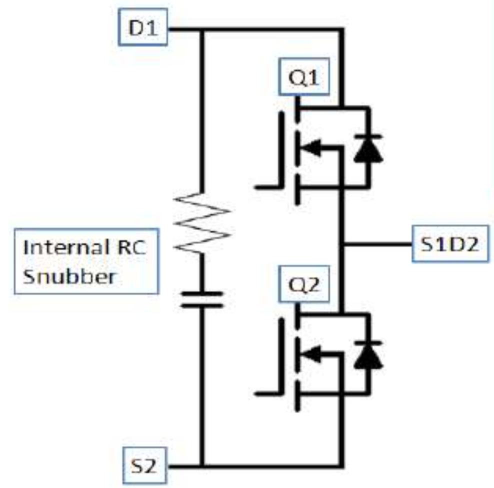
1200-V, 880-A All-SiC Dual Module

Module fabricated by Powerex SiC die supplied by CREE





- **1200-V, 880-A all-SiC dual module**
  - **Designed and fabricated modules to demonstrate feasibility to massively parallel SiC devices**
  - **Features:**
    - **Eleven 80-A DMOSFET per switch**
    - **Eleven 50-A JBS diodes per switch**
    - **Liquid-cooled heat sink**
    - **Integrated RC snubber**
    - **Two RTDs to measure MOSFET temperature**
- **Module details have been reported**
  - **Experimental evaluation of: V_{DS}, V_{SD}, V_{REV}, E_{ON}, E_{OFF}, and E_{RR}**
  - IEEE Transactions on Power Electronics, vol.26, no.9, pp.2504-2511, Sept. 2011
  - Proceedings of PCIM, May 2010, pp. 293–298.

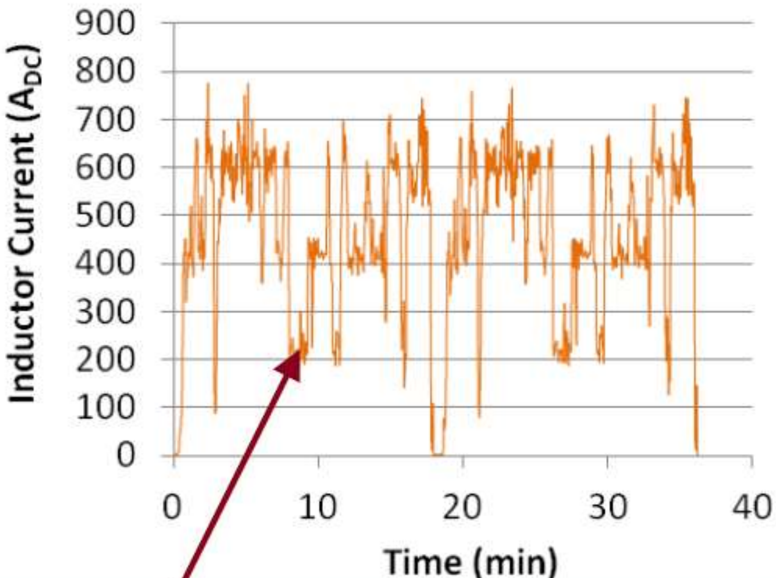


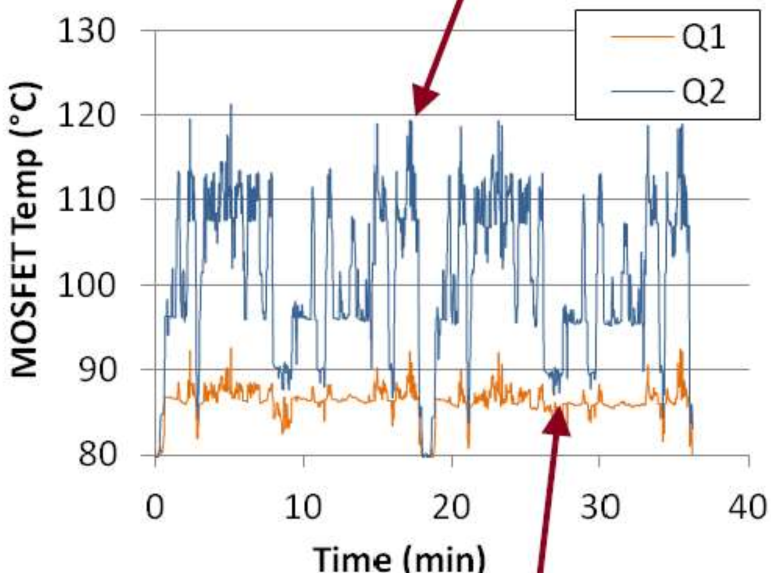
Profile Used to Stress Module

Alternated between right and left inverter sets for a 35 minute profile
~ 2 Profiles in 1 Hour
~17 Profiles in 10 Hours
~171 Profiles in 100 Hours

One profile represents 7.5 Miles on the Churchville B Course

Average Q_2 Temp = 100.8 °C
Peak Q_2 Temp = 121.2 °C





Average Inductor Current = 456 A_{DC}
Peak Inductor Current = 773 A_{DC}

Average Q_1 Temp = 86.2 °C
Peak Q_1 Temp = 92.6 °C

Summary of EV Results

- Completed 3142 profiles 1,000 hours of testing in simulator
- Equivalent to 12,000 road miles
- Zero failures and no measurable degradation
- Excellent demonstration of the readiness of SiC technology

Approved for Public Release

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Summary

- SiC MOSFETs now available for high power applications
  - 50 Amp chips at 1200V and 1700V
  - Modules from 100A – 300A
  - All reliability requirements for automotive have been met
- SiC modules optimum at half the amperage of IGBTs
- Challenges for Module Technology
  - Higher current density: 4-8 x
  - Higher power density: 2-4x
  - Higher switching speeds: ringing generated at up to 20 MHz
- SiC solutions can now be lower cost than Si IGBTs at the system level when optimizing design for frequency and power density