Future High Voltage Silicon Carbide Power Devices

Workshop on Future Large CO_2 Compression Systems

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"All I'm saying is now is the time to develop technology to deflect the asteroid."

Benefits of SiC Power Technology

10X Breakdown Field of Si

- Tradeoff higher breakdown voltage
- Lower specific on-resistance
- Faster switching

3X Thermal Conductivity of Si

- Higher current densities

3X Bandgap of Si

- Low $n_i \Rightarrow$ Low leakage current
- Higher temperature operation

- Higher Breakdown Field and Current Densities in SiC Devices
- Replace Si Bipolar With SiC Unipolar Devices

↓

> 2x Reduction in Total Losses

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Plus Operation at 200ºC SiC Junction Temperature

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- 85% Reduction in Cooling
- 3-5% Higher Efficiency

↓

Plus Higher SiC Device Switching Frequency

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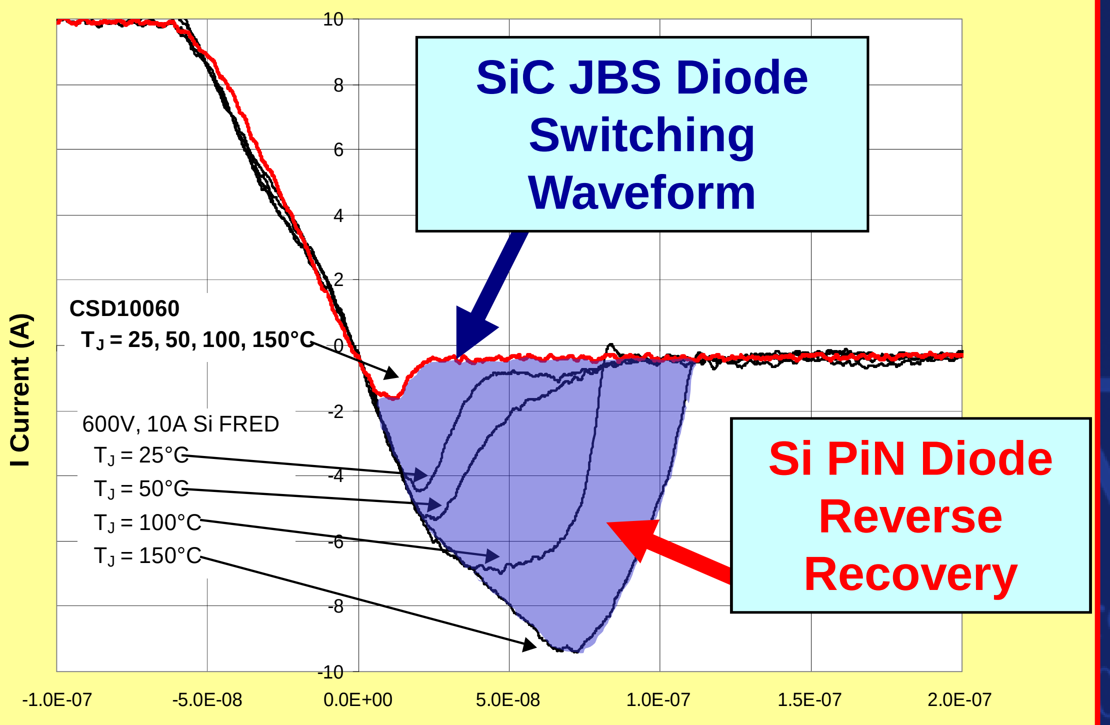
Dramatic Reduction in Size & Weight of Power Modules & Converters

SiC MOSFETs and Schottky Diodes show Zero Q_{rr}

Reduced Losses Using SiC JBS Diode



SiC JBS Diode Switching Waveform

Si PiN Diode Reverse Recovery

Commercially Available SiC JBS Rectifiers

- Cree ***ZERO RECOVERY***^{TM} Rectifier Product Family
  - 600V 2A, 4A, 6A, 8A, 10A & 20A
  - 1200V 5A, 10A, 20A, 50A

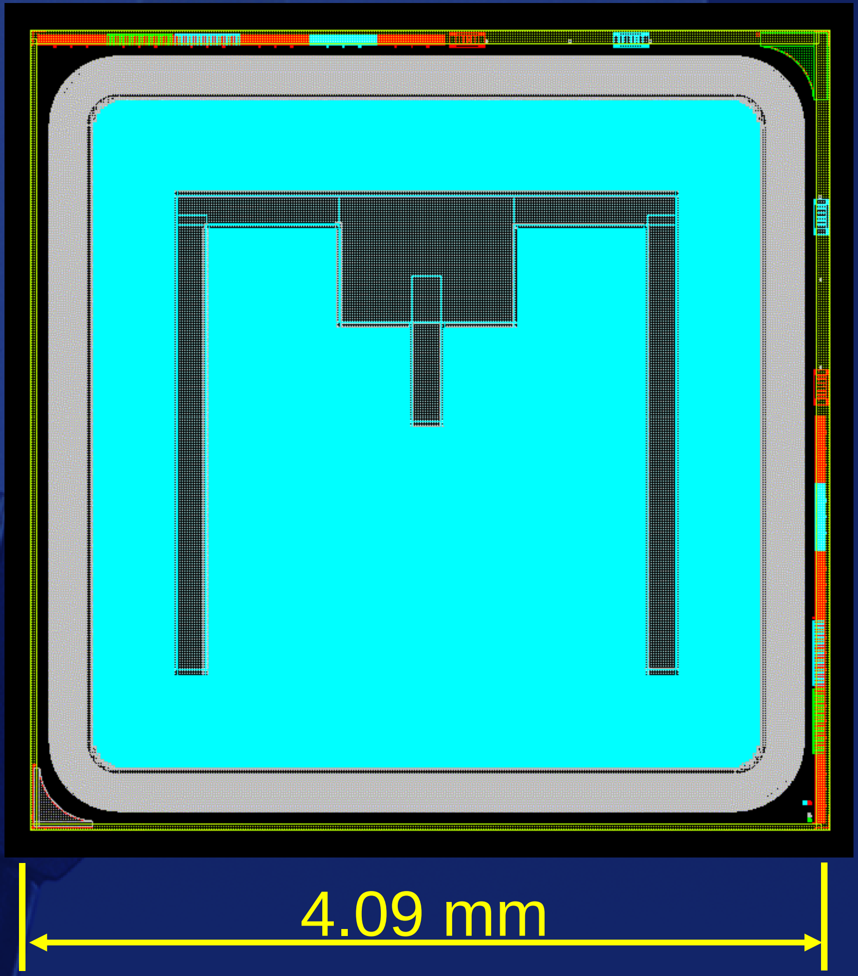
- Major Applications
  - Power Factor Correction (PFC) in Switch Mode Power Supplies (SMPS)
  - Anti-Parallel rectifier in Motor Control
  - Boost Converter and Inverter Section for solar conversion

Extremely Low Field Failure Rate Of Cree SiC JBS Diodes

Cree Field Failure Rate Data since Jan. 2004		
Product	**Device Hours**	**FIT** (fails/billion hrs)
CSDxxx60	75,200,000,000	0.6
CSDxxx60	42,700,000,000	0.1
CSDxxx60	7,060,000,000	0.1
CSDxxx60	2,440,000,000	0.4
Total	127,400,000,000	0.4

- 1200 V Schottkys have zero field failures since introduced in Sept. 2006
- 2 largest Cree Customers: "Your SiC parts are much more reliable than the Silicon parts we were using."

4H-SiC 1200V 20A DMOSFET Chip Layout

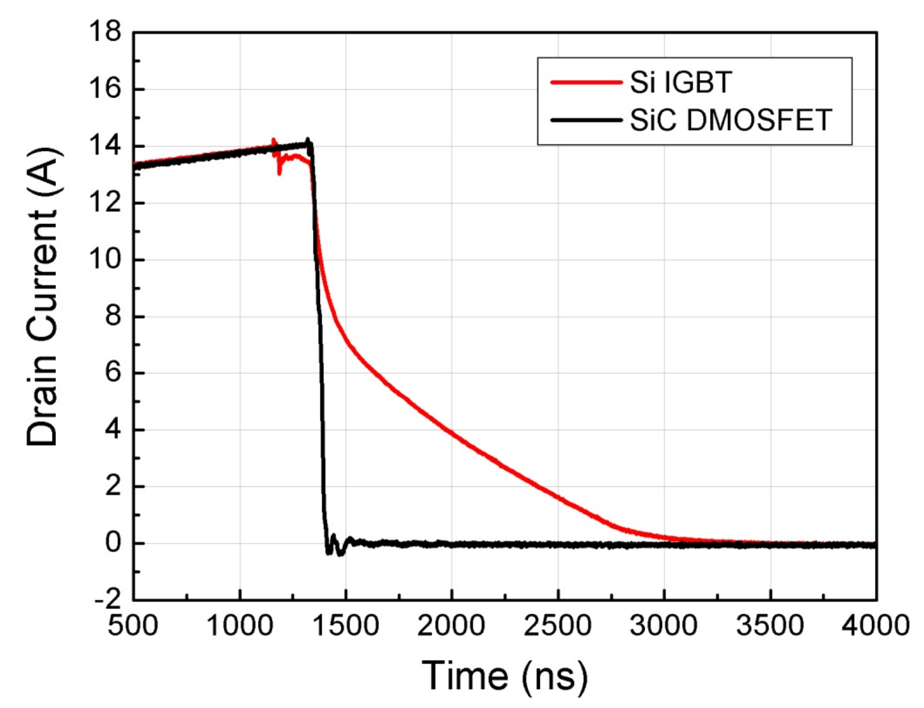


>50,000 cells per chip

4.09 mm x 4.09 mm chip size
0.101 cm^2 active device area

$R_{on,sp} \approx 10\ m\Omega\cdot cm^2$
$R_{on} \approx 100\ m\Omega$
At $V_{gs} = 15\ V$

Switching Loss Comparison of 1200 V / 10 A SiC DMOSFET vs Si IGBT (IRG4PH40KD)



Switching at 150°C

Switching Energies

SiC DMOSFET: 457 μJ

Si IGBT: 4490 μJ

Switching Losses (μJ)

Temp. (°C)	Turn On		Turn Off	
	SiC DMOS	Si IGBT	SiC DMOS	Si IGBT
25	423	303	84	973
50	381	335	82	1310
75	369	373	87	1710
100	362	413	96	2240
125	352	455	104	2980
150	348	500	109	3990

Total Power Loss Comparison of 1.2kV / 10A SiC DMOSFET vs. Si IGBT (IRG4PH40KD)

P_{Total} = On-State Power + Turn-off Power + Turn-on Power

$P_{Total} = I \cdot V \cdot \text{Duty Cycle} + (W_{off} + W_{on}) \cdot \text{frequency}$

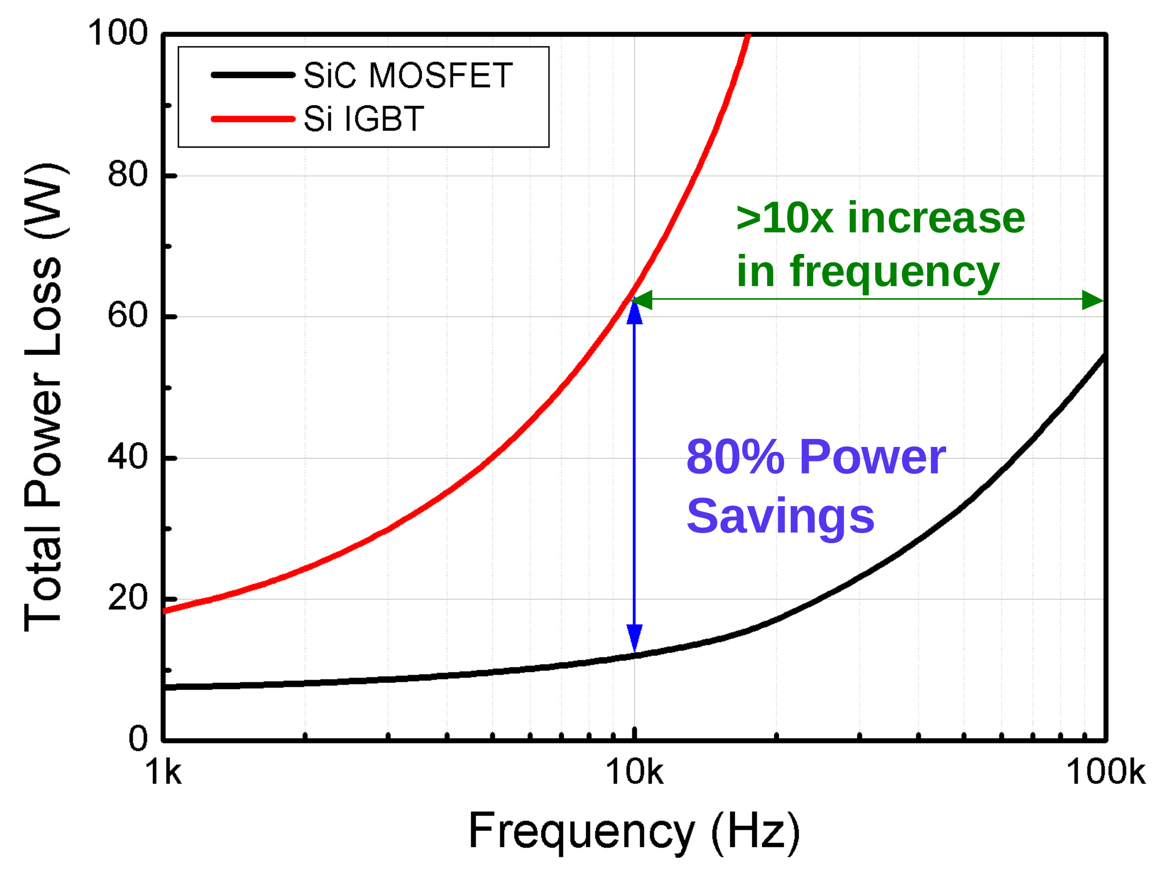
Calculation Parameters

T = 150°C

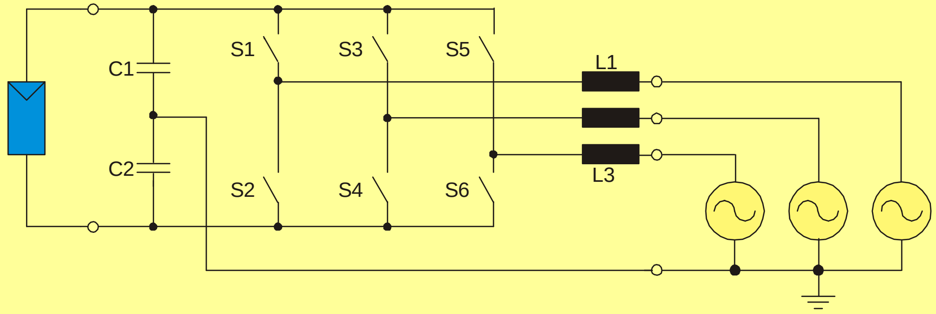
I = 10 Amps

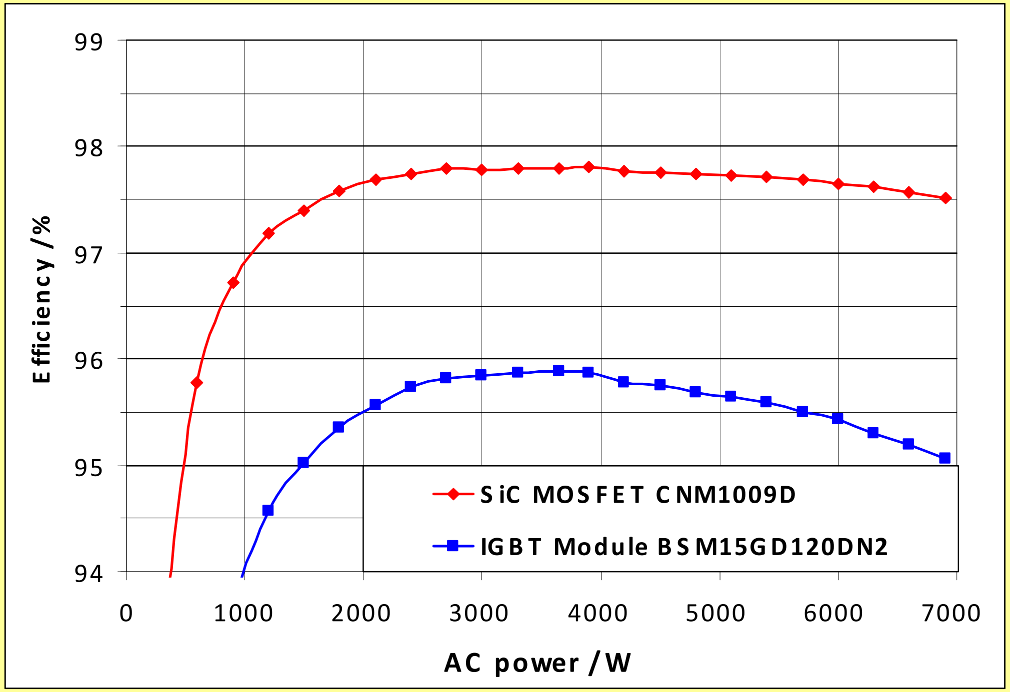
Duty Cycle = 50%

Si IGBT Is Impractical at High Frequencies



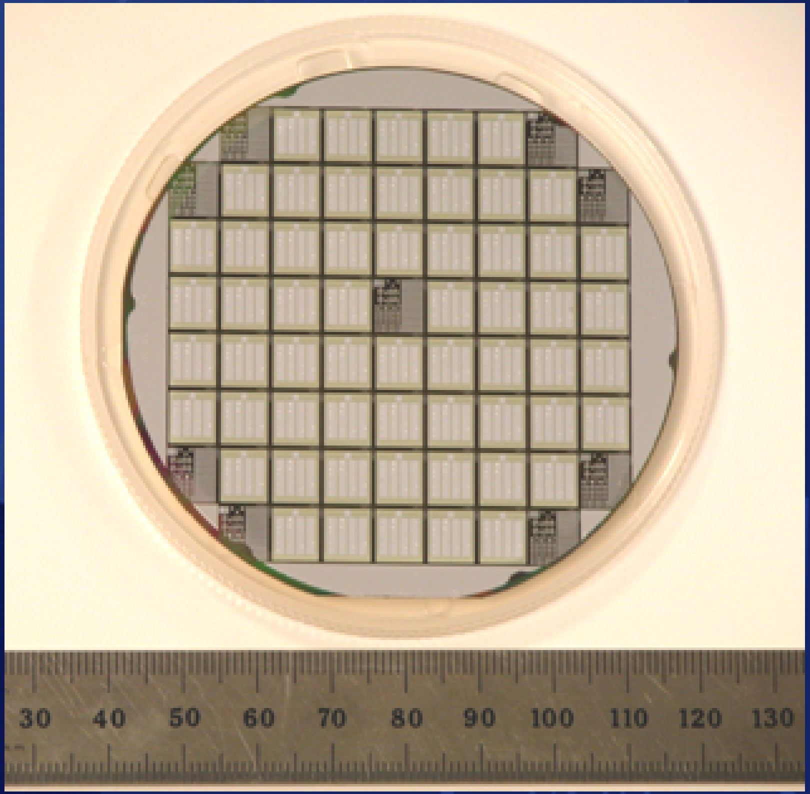
Dramatic Increase in Efficiency of 3-Phase Solar Inverter Using 1200V SiC DMOSFET





- 2.4% Increase in Efficiency of 3-Phase Solar Inverter Achieved Using Cree 1200V SiC DMOSFET
- Replaced 1200V Si IGBTs in Solar Inverter With 1200V SiC DMOSFETs w/o Optimization
- Significant Cost Savings
  - 81 Euro/yr in Northern Europe
  - 164 Euro/yr in Southern Europe

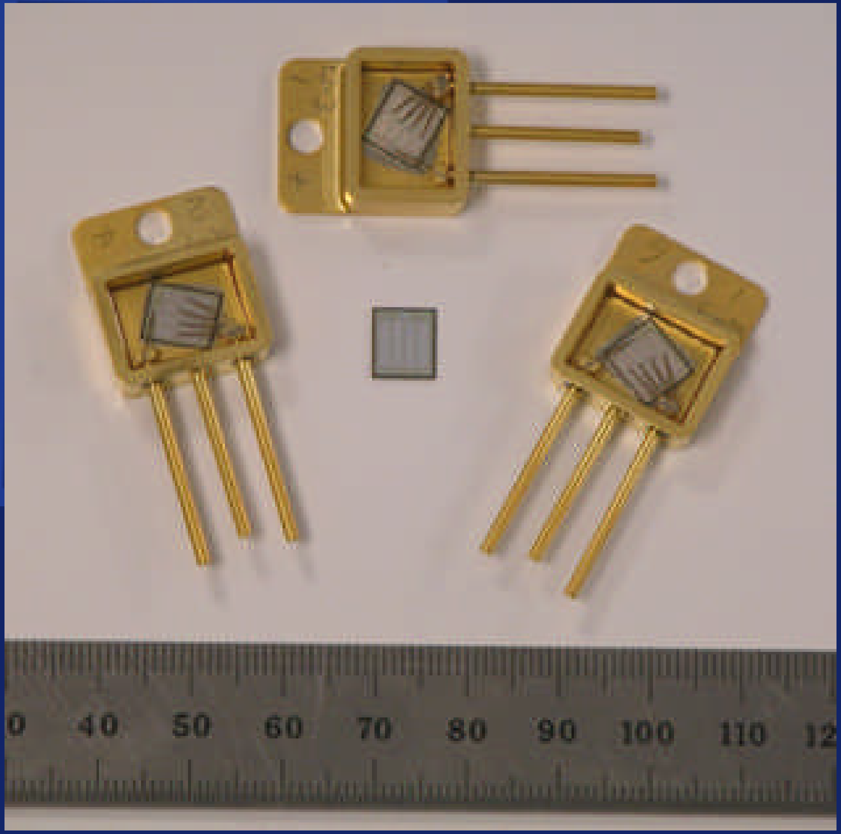
Scaling up to 1200 V, 60 A DMOSFET



60 Die Per 3 inch Wafer

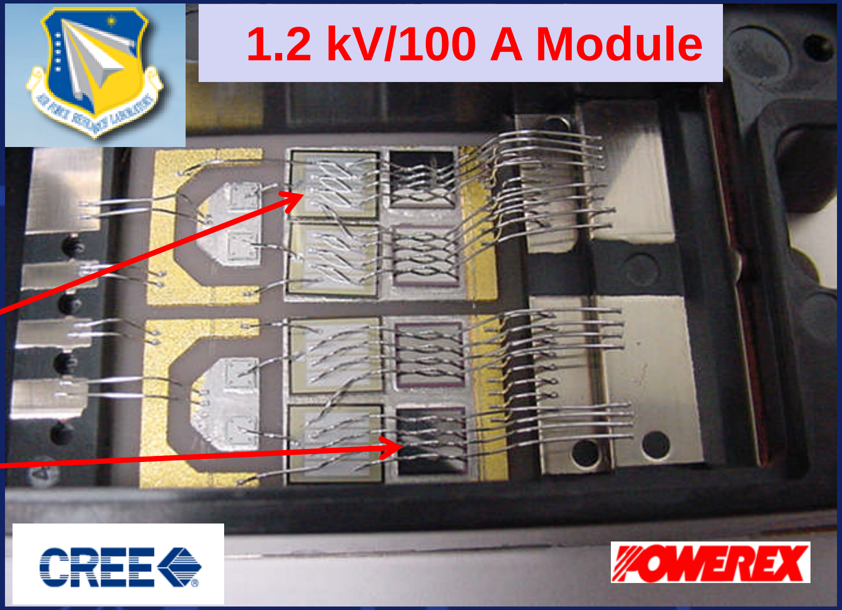
111 Die Per 100 mm Wafer
(in progress)

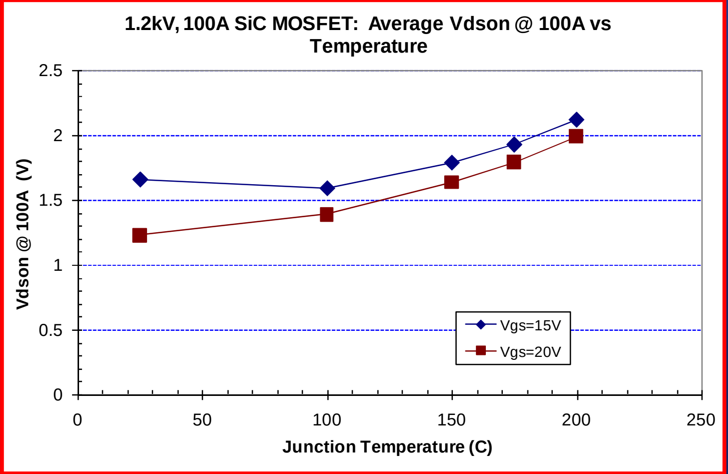
TO-258 Metal Packages
Four 10 mil Al wires to Source
Silicone Encapsulant

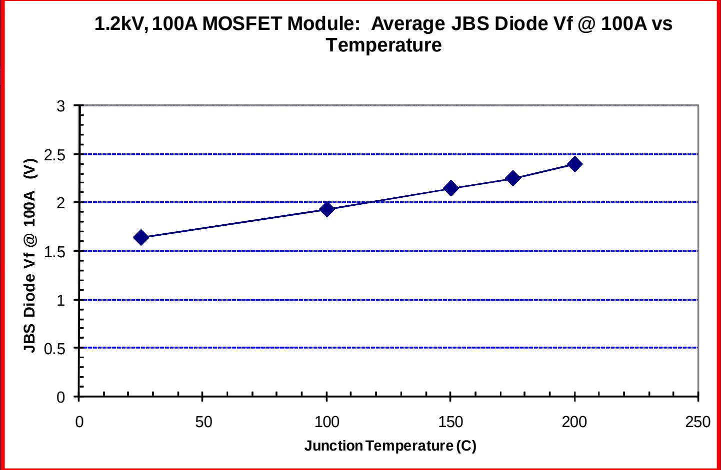


1.2kV/100A SiC DMOSFET/JBS Diode 200°C Half H-Bridge Module

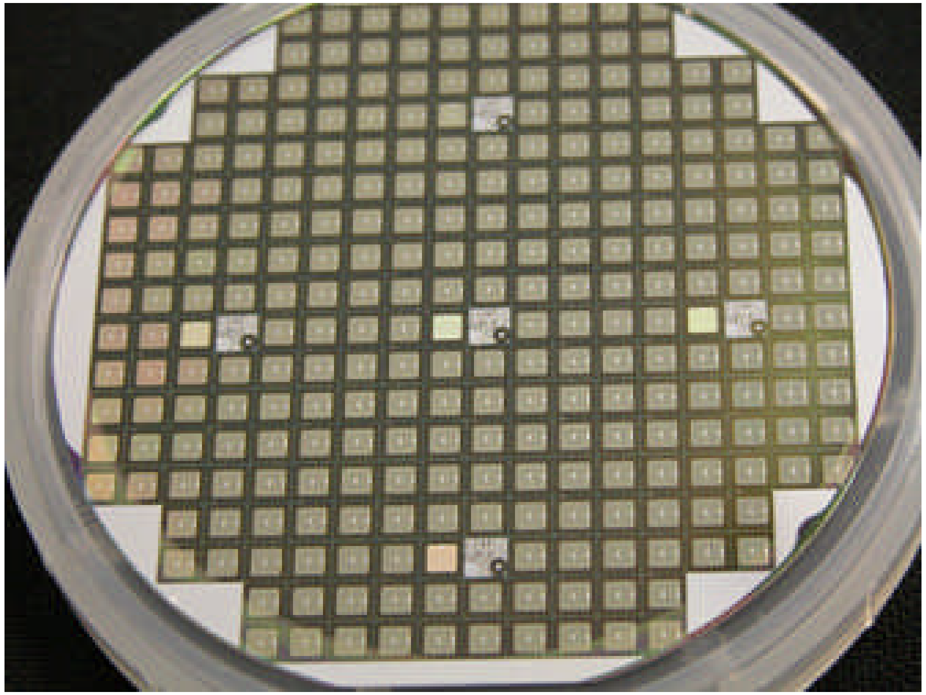
- **1.2kV/100A SiC DMOSFET Half H-Bridge Module**
- **Capable of T_j = 200 °C Operation**
- **4x 1.2kV/50A SiC DMOSFETs**
- **4x 1.2kV/50A SiC JBS Diodes**



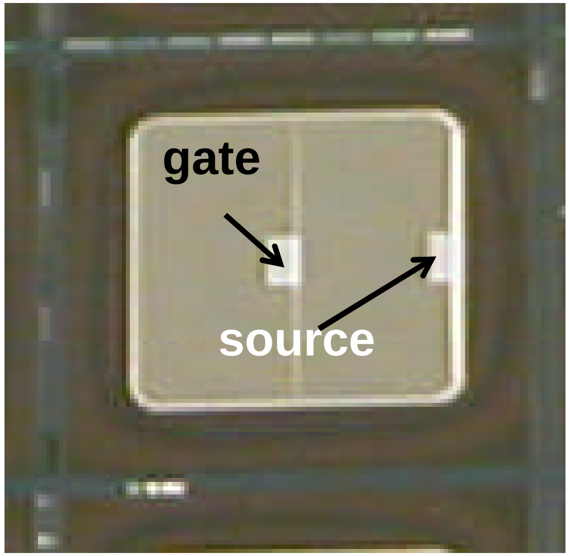




Wafer and die photographs of 3200 V 2 A DMOSFETs

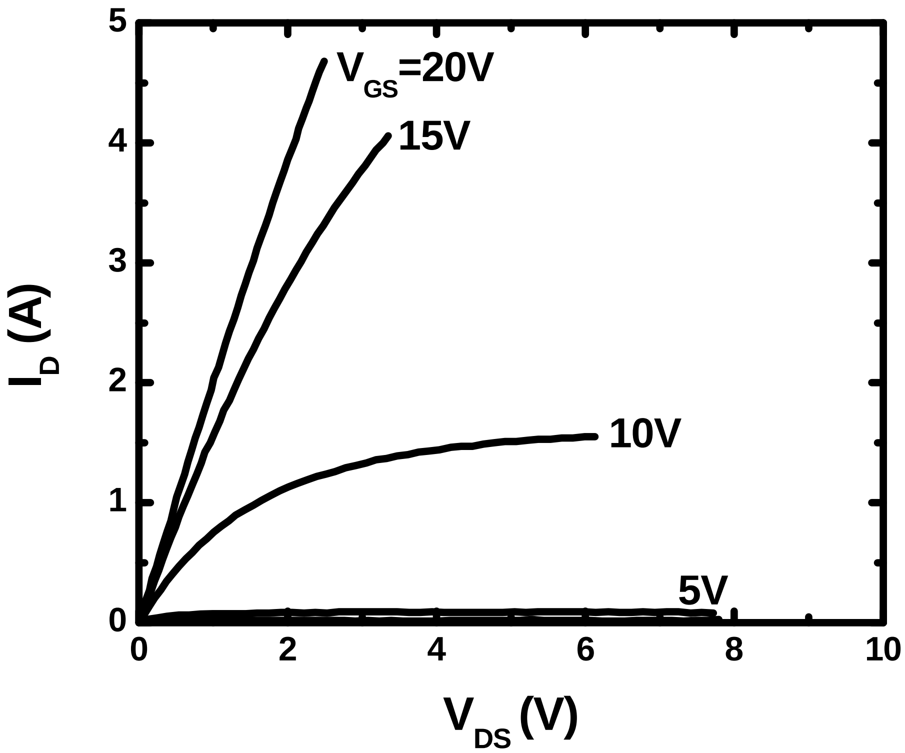


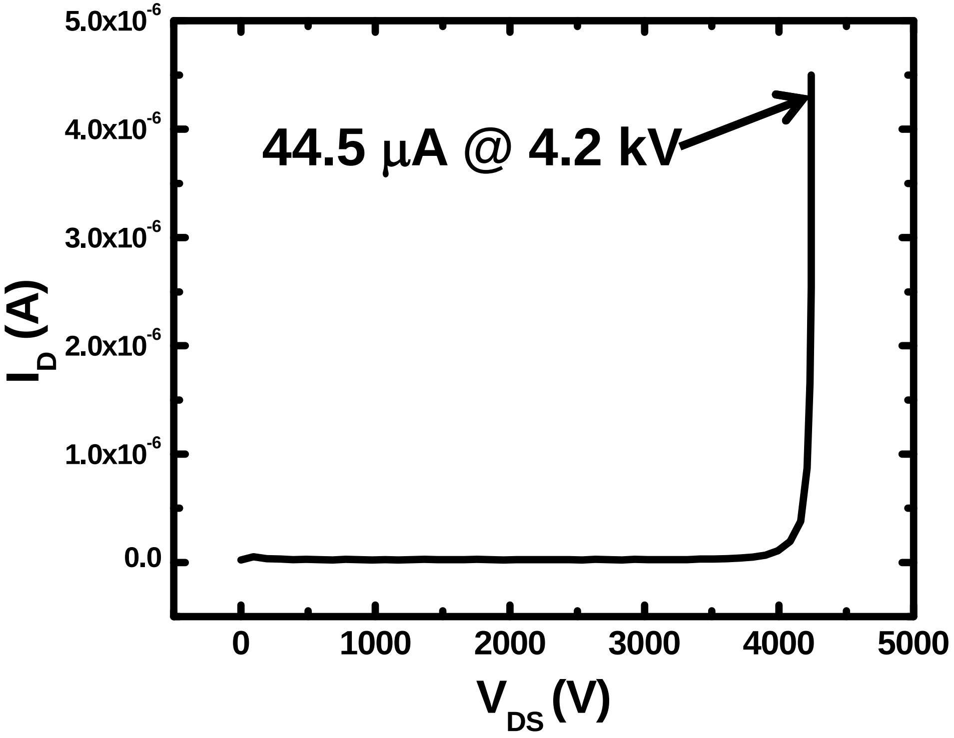
3.2 kV, 2A DMOSFETs on a 3 inch wafer



Chip size: 4 mm x 4 mm
Active area: 5.76 x 10^{-2} cm^2 including pad areas

Room temperature static IV characteristics



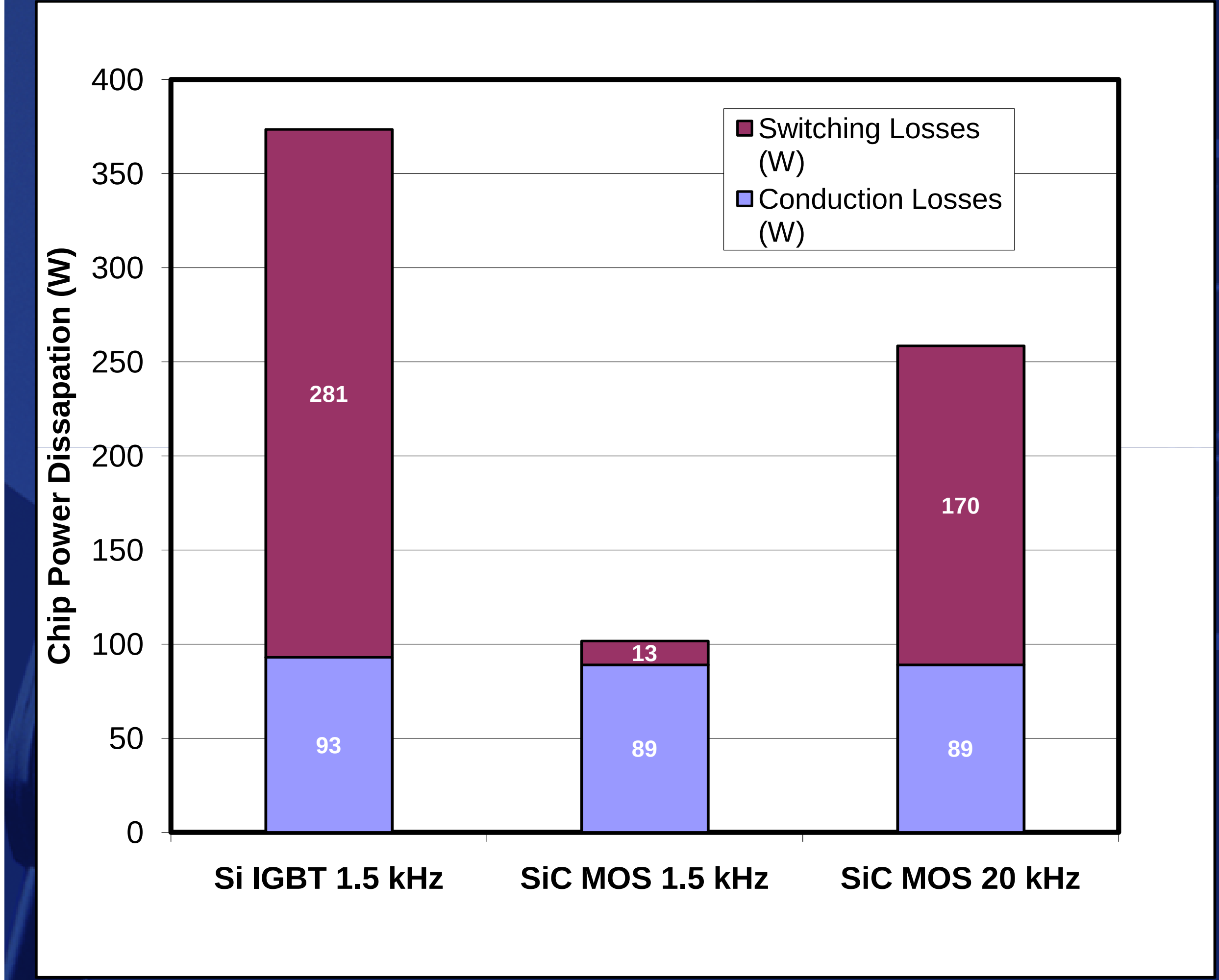


$R_{on,\,sp}$ = 35 mΩ-cm² @V_{GS}=15V
= 28 mΩ-cm² @ V_{GS}=20V

BV = 4.2 kV with V_{GS} =0 V

Creating Technology That Creates Solutions

3.3kV SiC DMOSFET & 3.3kV Si IGBT Loss Comparison at 125 °C

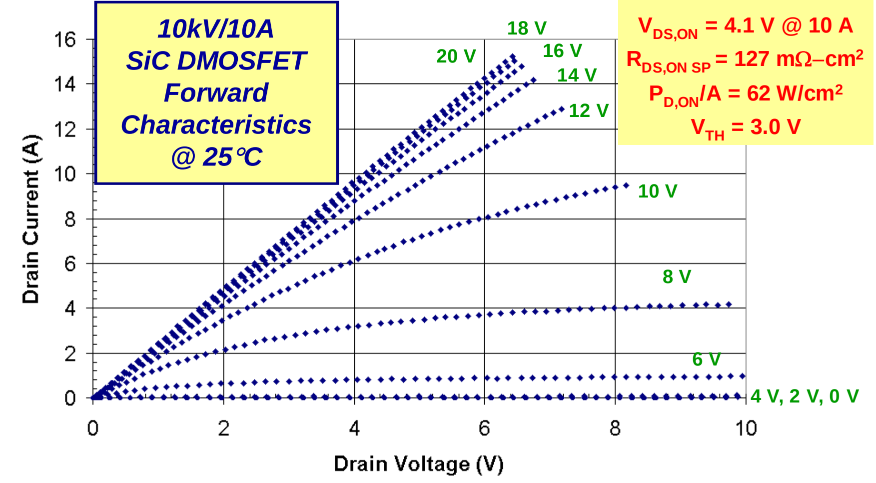


- **3.3kV SiC DMOSFET Switching Losses > 10X Lower Than 3.3kV Si IGBT @ 125C**
- **3.3kV SiC DMOSFET Conduction Losses Slightly Lower Than 3.3kV Si IGBT @ 125C**
- **3.3kV SiC DMOSFET Capable of 20kHz Switching Operation**

Conditions:

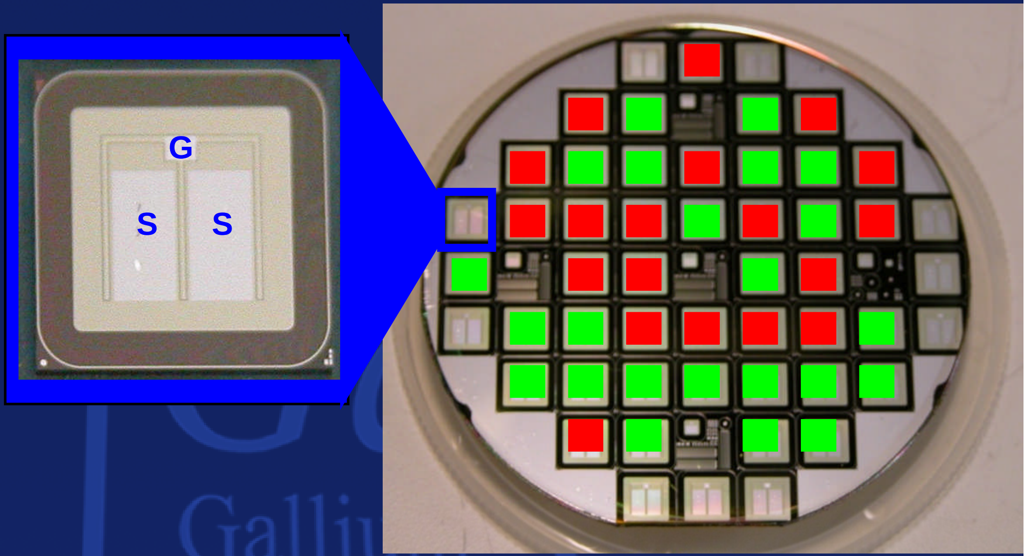
- I_C, I_D = 62 A
- V_{CE}, V_{DS} = 1.8 kV
- Duty = 50 %

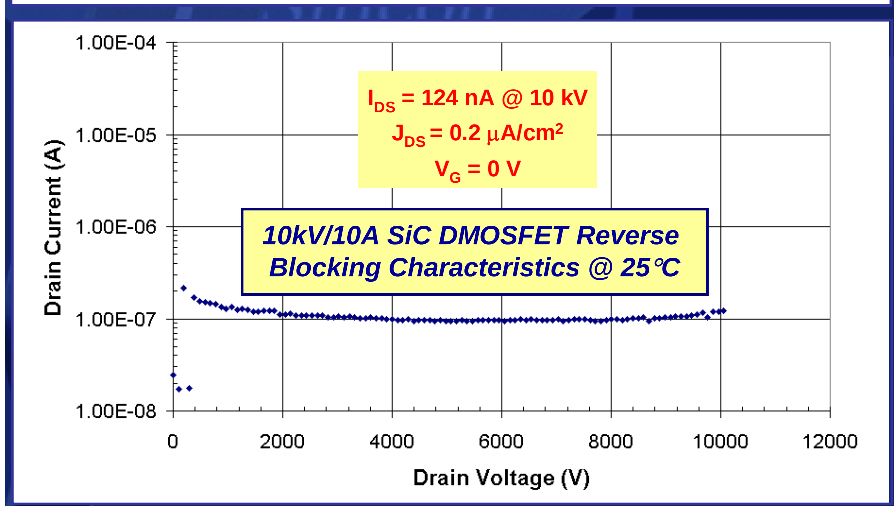
High Yield Fabrication of 10kV/10A SiC DMOSFETs



10kV/10A SiC DMOSFET Forward Characteristics @ 25°C

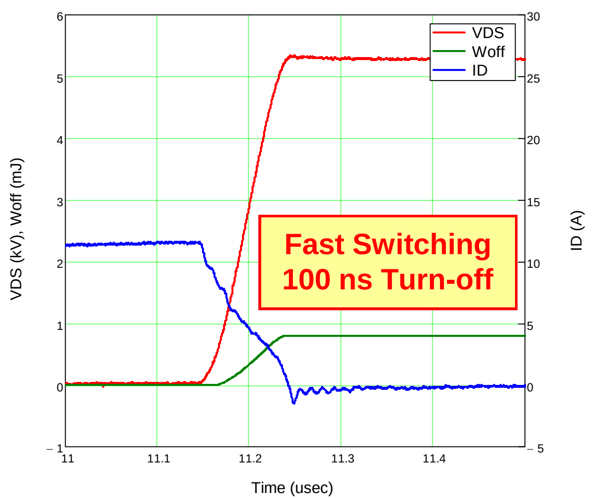
$V_{DS,ON}$ = 4.1 V @ 10 A
$R_{DS,ON\ SP}$ = 127 mΩ–cm²
$P_{D,ON}/A$ = 62 W/cm²
V_{TH} = 3.0 V





I_{DS} = 124 nA @ 10 kV
J_{DS} = 0.2 μA/cm²
V_G = 0 V

10kV/10A SiC DMOSFET Reverse Blocking Characteristics @ 25°C

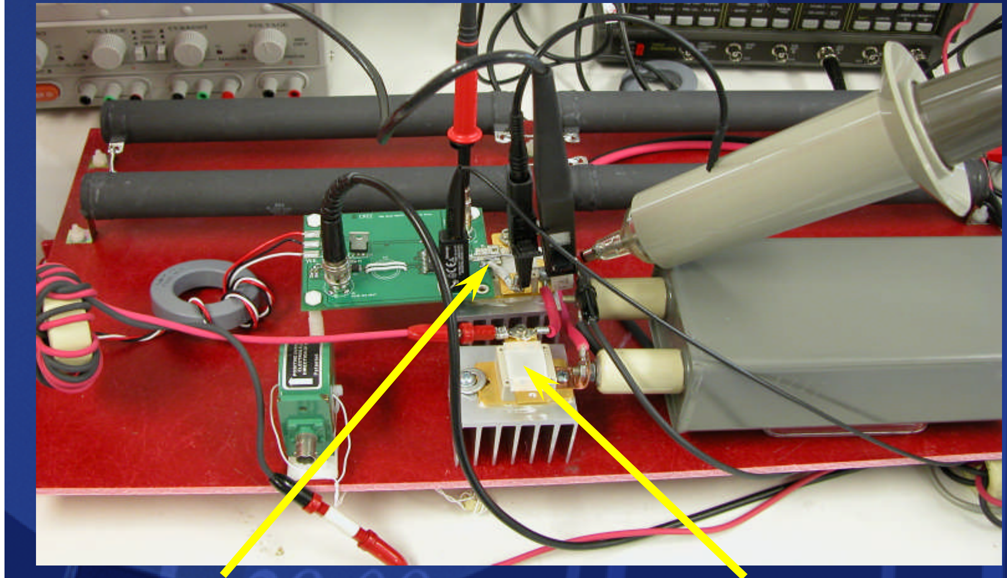


Fast Switching
100 ns Turn-off

- **High Yield Fabrication of 10kV/10A SiC DMOSFETs on 3-inch Wafers**
  - 8.1 x 8.1 mm Devices
  - Highest Yield = 55%
  - Green ⇒ Good Device on 3-inch Wafer

Courtesy: Dr. Mrinal Das, CREE

500V – 5kV / 20 KHz Boost Converter Using 10kV/10A SiC DMOSFETs and JBS Diodes

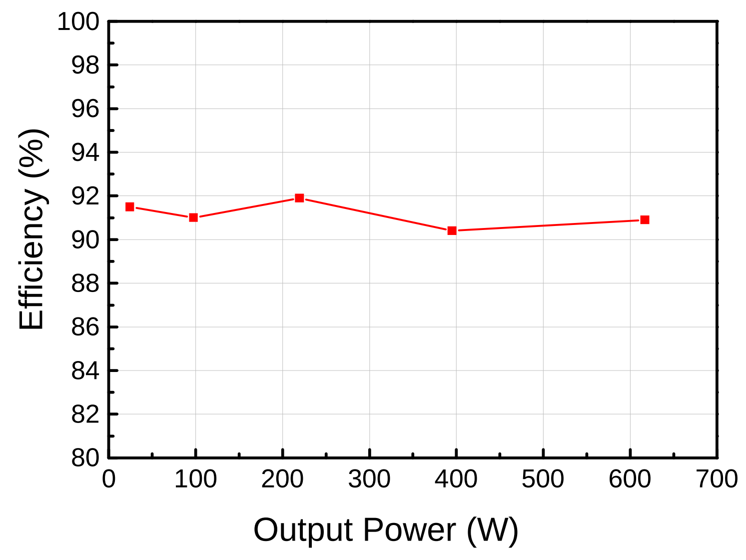


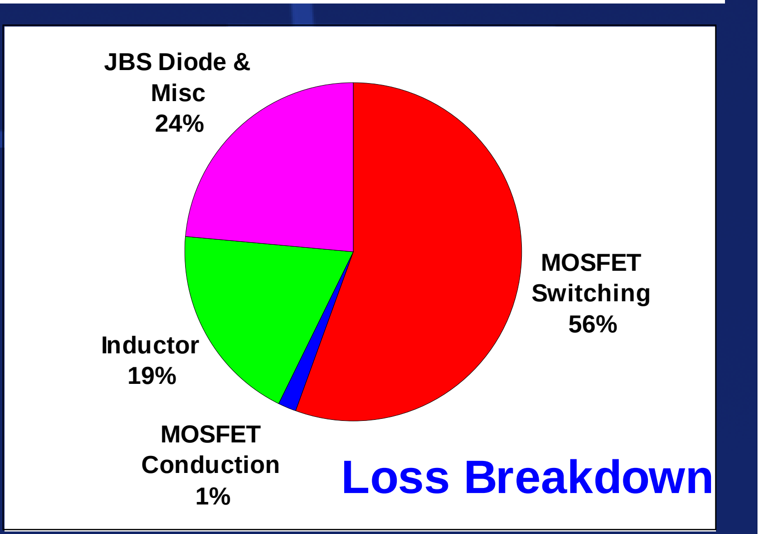
10kV/10A SiC DMOSFET

10kV/10A SiC JBS Diode

Input	Output	Duty Cycle
V_{IN} = 503 V	V_{OUT} = 5 kV	90%
I_{IN} = 1.35 A	I_{OUT} = 0.12 A	Operating
P_{IN} = 679 W	P_{OUT} = 617 W	at 20kHz

- **500V – 5kV Boost Converter Operating at 20kHz**
- **Maintained > 90% Efficiency Over Full Load Range**

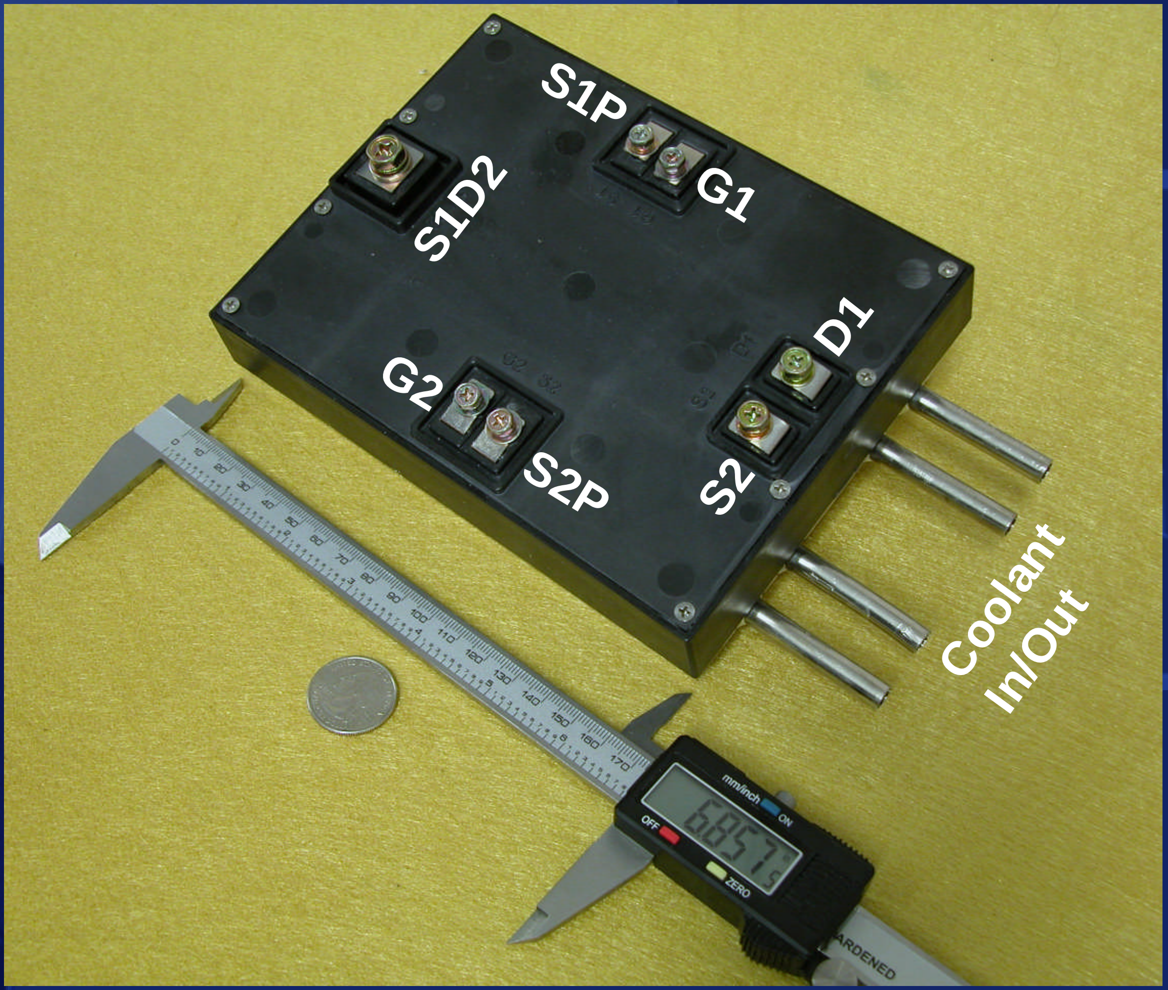


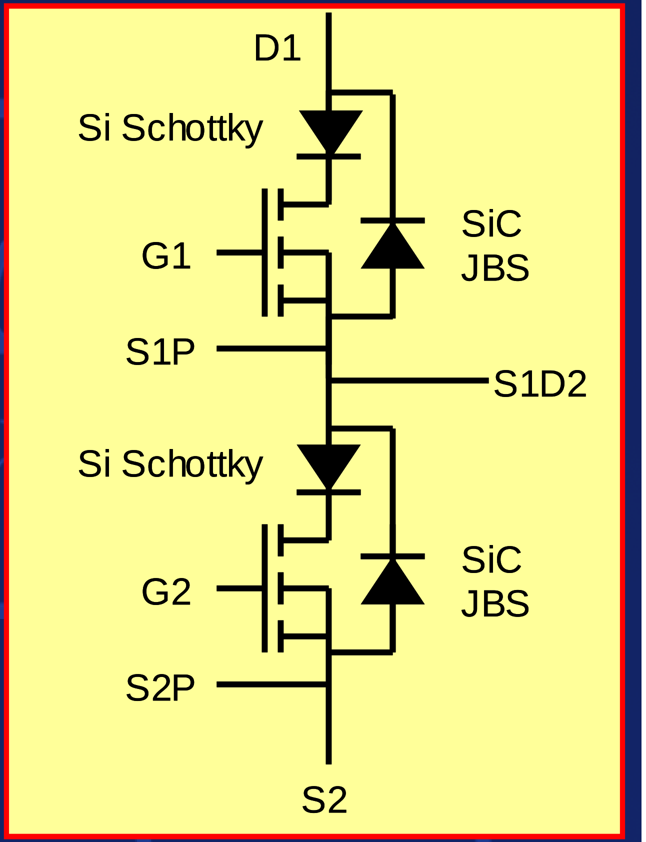


Loss Breakdown

Courtesy: Dr. Mrinal Das, CREE

DARPA HPE-II 10kV/50A SiC Half H-Bridge Module





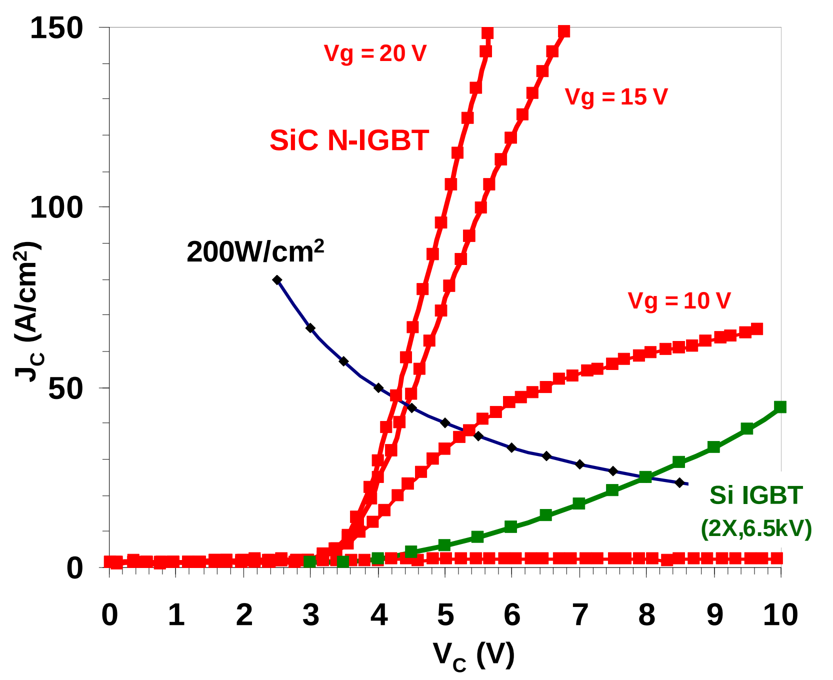
Module Dimensions ~ 7 x 5 inches

What Is Next for High Voltage SiC Power Devices?

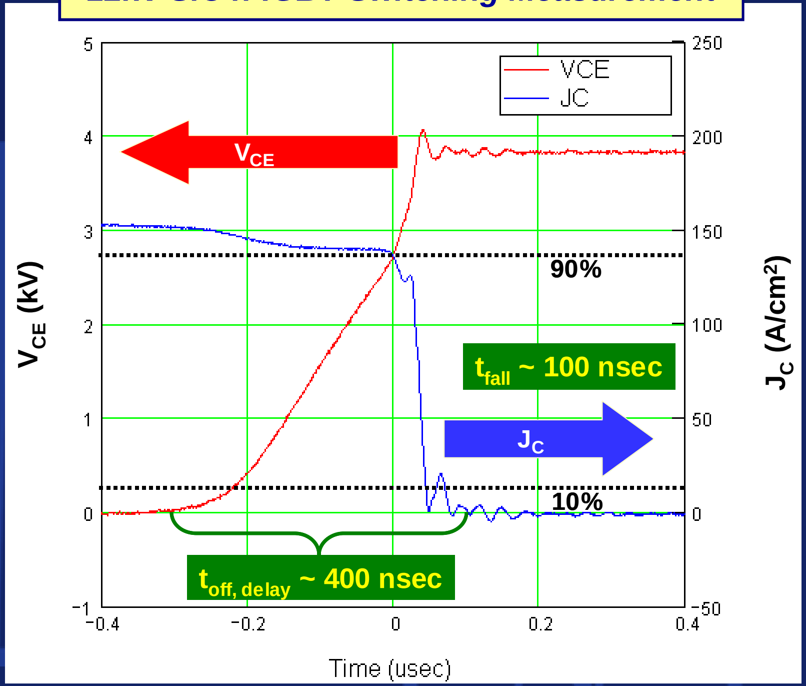
- 10 kV ~ Upper Limit of SiC Unipolar Devices
  - DMOSFETs and Schottky diodes
- Higher Voltage ⇒ Bipolar Devices
  - Si IGBT Replace Si DMOSFET at > 1kV
- For SiC Devices, This Holds True for >10 kV
  - SiC breakdown field 10x that of silicon

Over ~ 10kV - We Need SiC IGBTs, GTOs and PiN Diodes

Comparison of SiC n-IGBTs and Si IGBTs



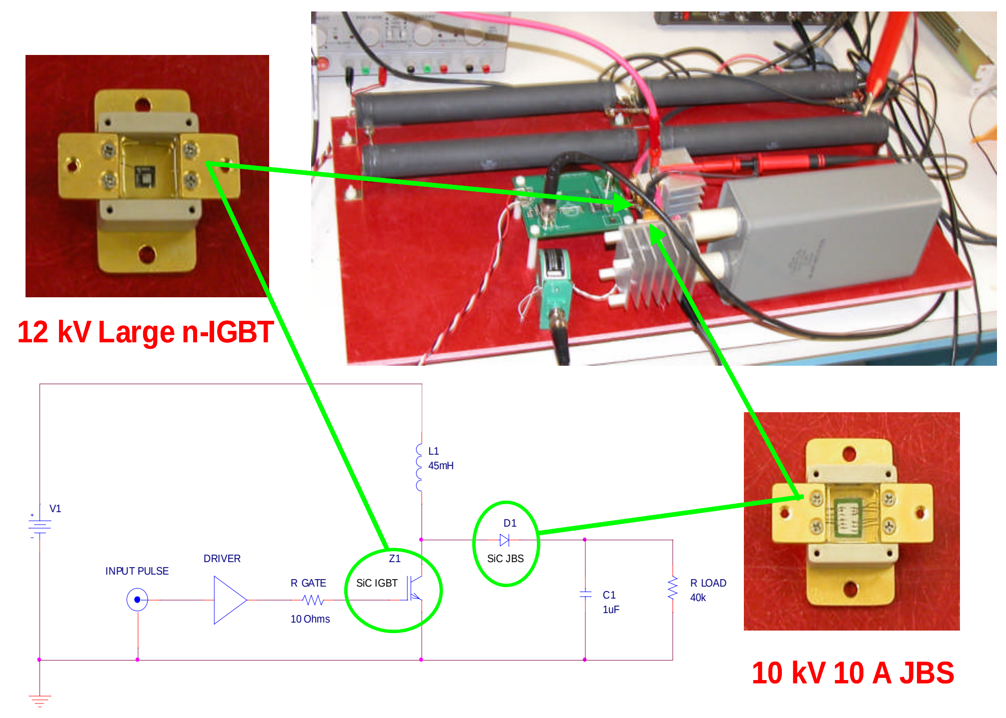
12kV SiC n-IGBT Switching Measurement



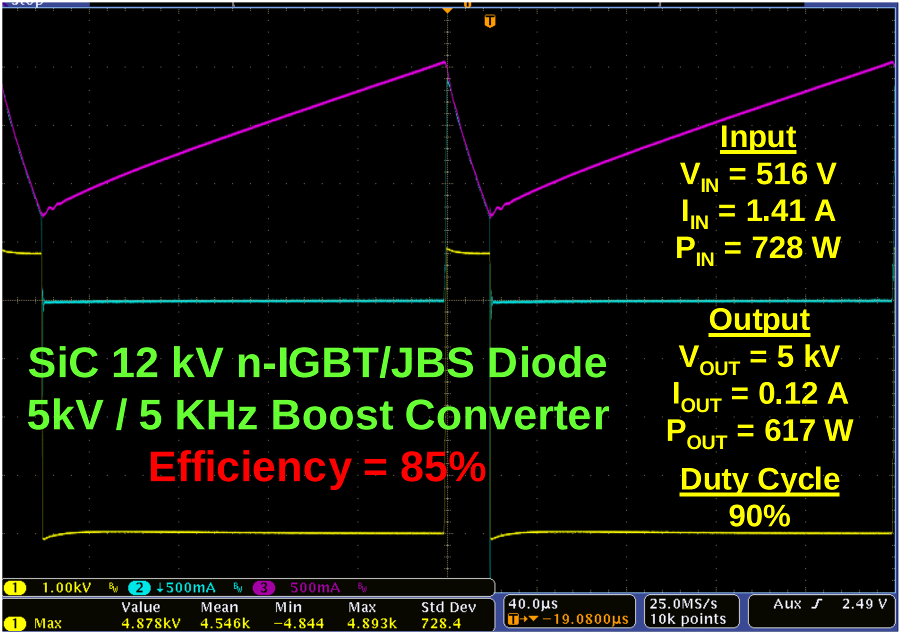
- **SiC IGBTs Are Superior to Si IGBTs at Higher Voltages**
  - **12kV SiC n-IGBTs Have >3x Lower $R_{on,sp}$ Than 6.5kV Si IGBTs**
  - **SiC n-IGBTs Have Much Lower Forward Voltage (V_F) & Higher Current Than Si IGBTs at Same BV**
  - **12kV SiC n-IGBTs Have 4x Faster Switching Speed and >4x Lower Switching Loss than 6.5kV Si IGBTs**

Courtesy: Dr. Mrinal Das, CREE

12kV SiC n-IGBT Boost Converter



12kV SiC n-IGBTs Used to Demonstrate 5 kV / 5 kHz Boost Converter With 85% Efficiency



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         Value    Mean     Min     Max     Std Dev
1 Max    4.878kV  4.546k   −4.844  4.893k  728.4
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SiC 12 kV n-IGBT/JBS Diode 5kV / 5 KHz Boost Converter

Efficiency = 85%

Input

V_{IN} = 516 V
I_{IN} = 1.41 A
P_{IN} = 728 W

Output

V_{OUT} = 5 kV
I_{OUT} = 0.12 A
P_{OUT} = 617 W

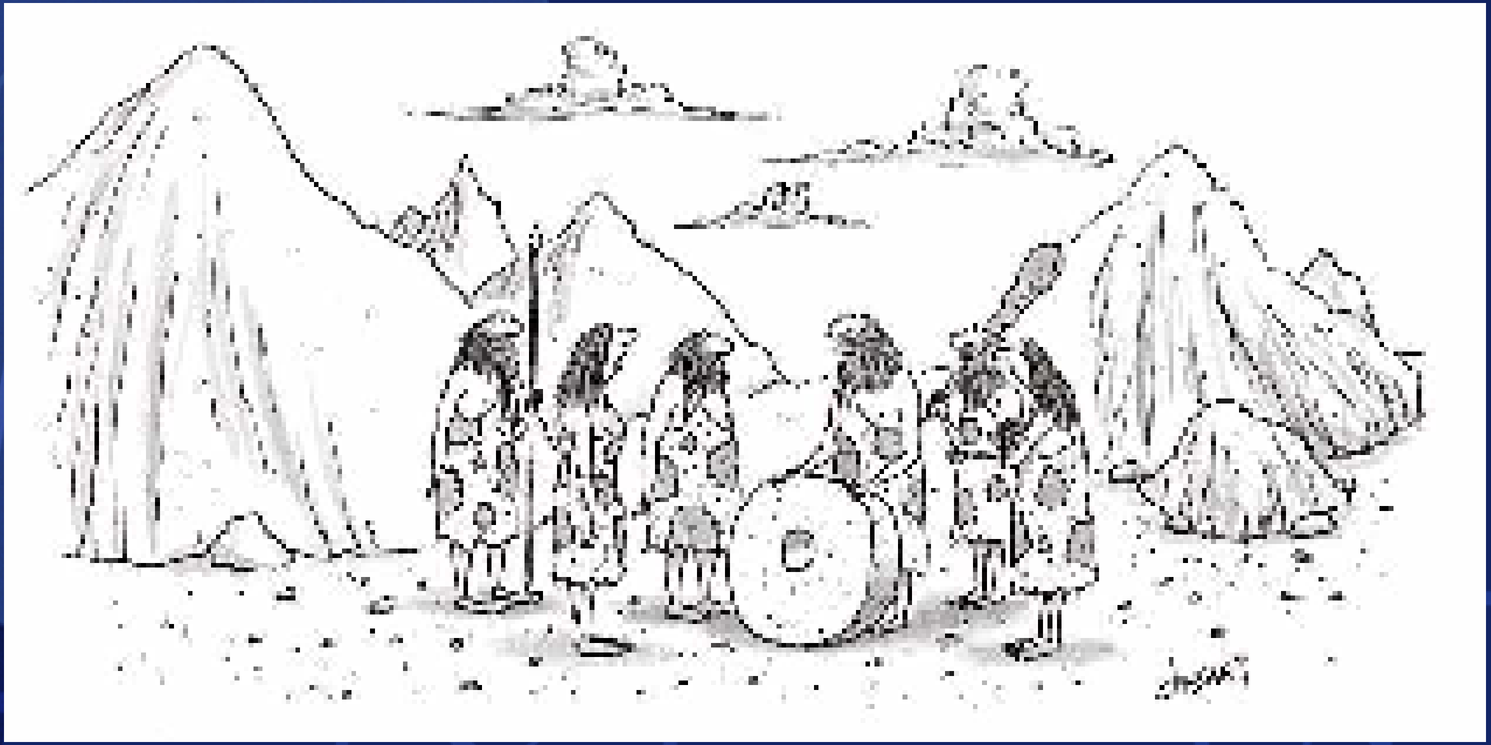
Duty Cycle

90%

SiC n-IGBT/JBS Diode 5kV/5KHz Boost Converter

SiC for High Voltage Devices

- SiC production and reliability proven at low voltages (600-1200V) and running in high volume
- SiC MOSFETs nearing production at 1.2 kV, and 3.2 kV – 10 kV devices are proven and circuit demos show incredible performance
- For higher voltage (>10 kV), GTOs and IGBTs have been demonstrated
- SiC will enable high voltage drive trains with efficiencies and frequencies far in excess of what can be achieved in Silicon



“That’s nice, BUT we’ll need an environmental-impact study,

a warranty, recall bulletins, recycling facilities,

and 24 hour customer service support!”