SiC Power Device and Material Technology For High Power Electronics

High Megawatt Power Technology R&D Roadmap Workshop

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AFRL – Jim Scofield

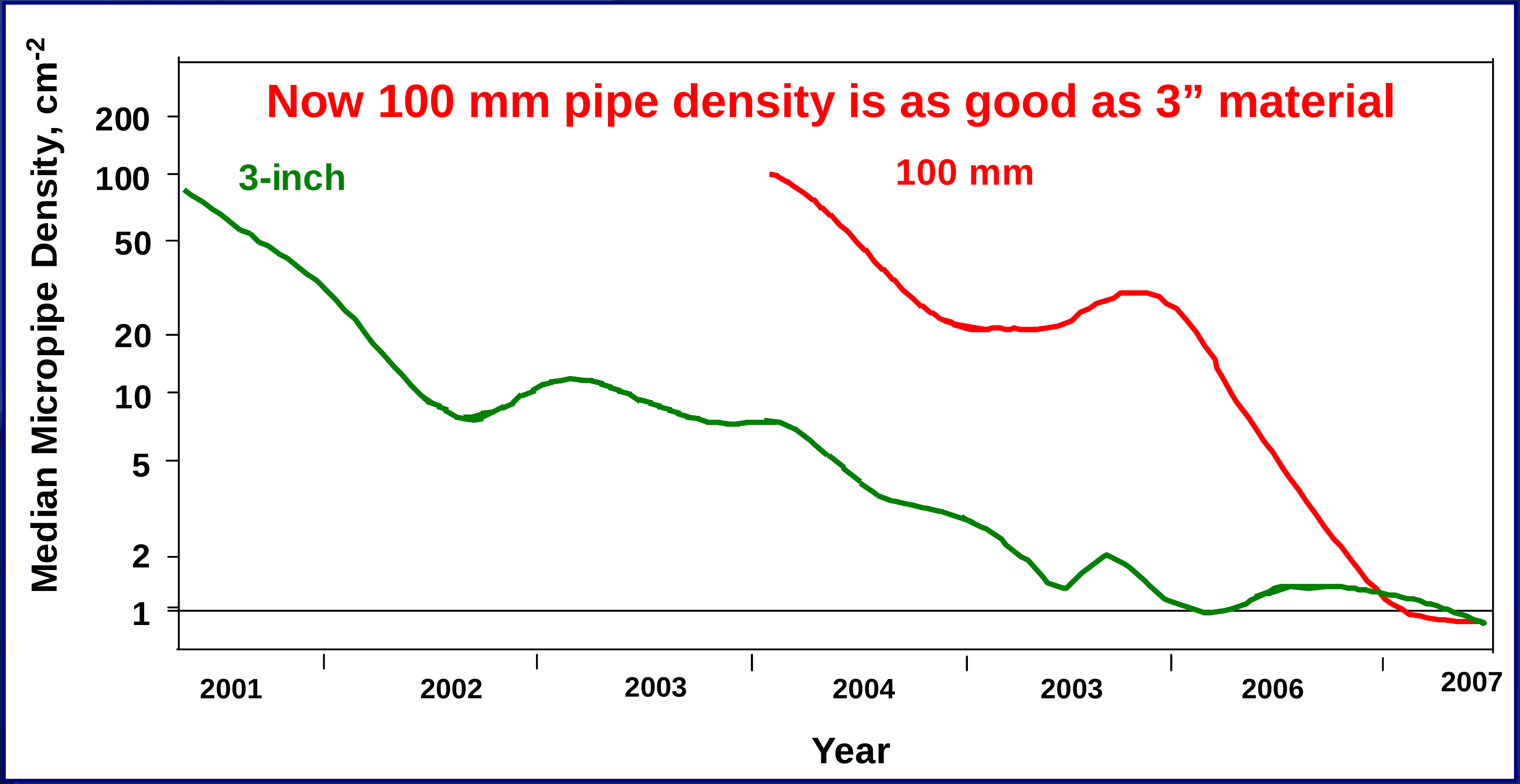
Cree Excellence in SiC Materials and WBG Device Manufacturing


Cree Corporate Headquarters
Durham, NC

- World’s Largest Fabricator of GaN-on-SiC
  - Ship > 15 million devices per day
- World’s Largest Supplier of SiC substrates
  - Supply 95% of the world’s supply of single crystal SiC
- Vertical Integration
  - Crystal Growth => Device Fabrication => Package/Test

Dramatic Reduction in 4HN SiC Substrate Micropipe Densities

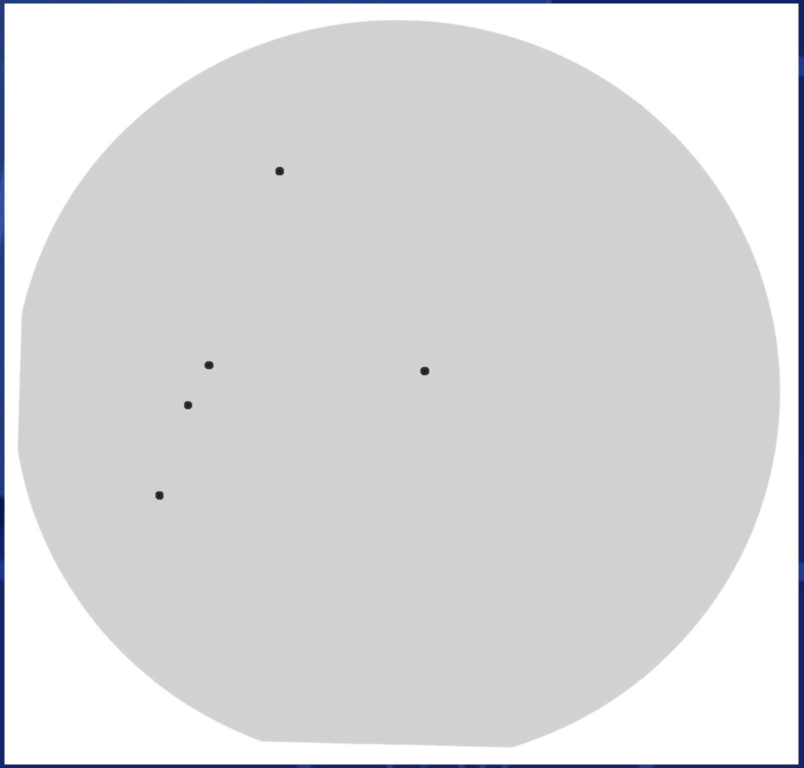
Monthly <u>median</u> micropipe density of 4H n-type wafers is < 0.8 cm^{-2}



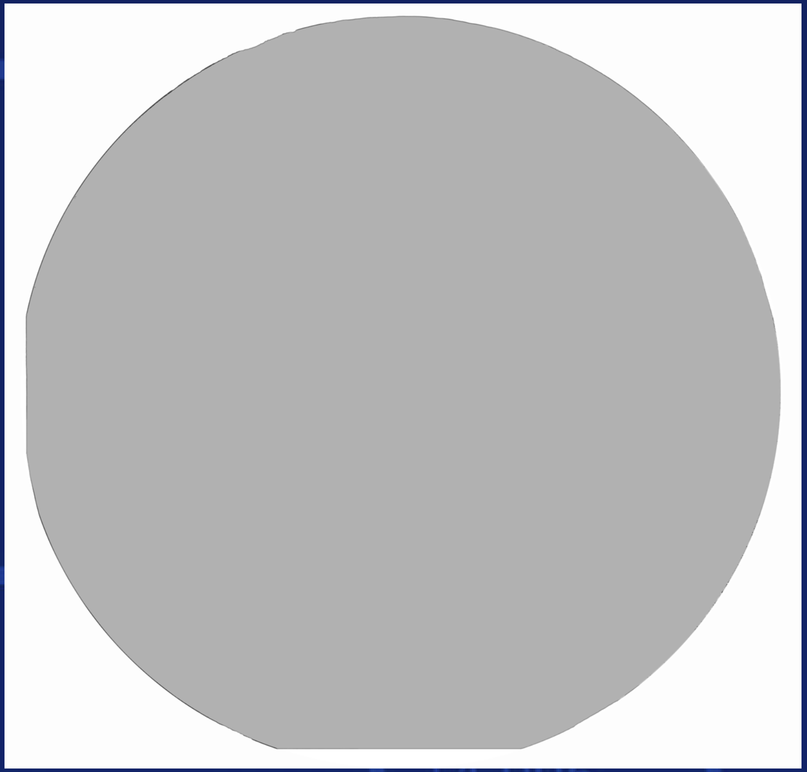
100-mm work supported by ARL MTO (W911NF-04-2-0021) and DARPA (N00014-02-C-0306)

100 mm 4HN-SiC Substrate Quality

Almost Double the Area of a 3-inch 4HN-SiC Wafer

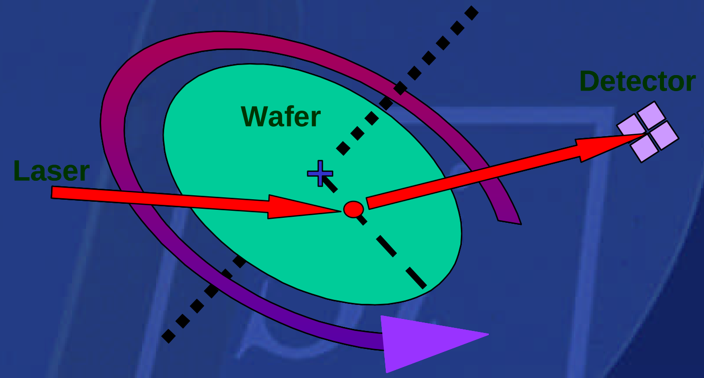


Typical 100 mm 4HN-SiC Wafer MPD ~ 0.6 cm^{-2}

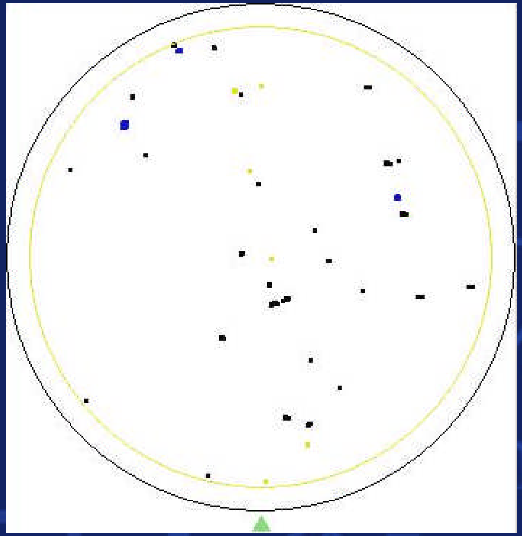


Micropipe Free 100 mm 4HN-SiC Wafer

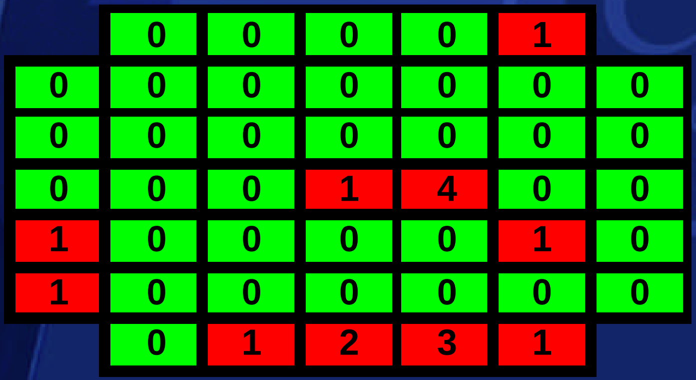
SiC Substrate and Epi Defect Mapping For Enhanced SiC Device Yield



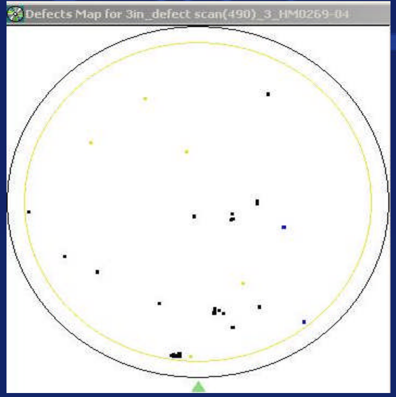
Candela Tool For Automated SiC Material Defect Mapping



- Predicted “Material” Yield for 8x8 mm SiC JBS Diodes = 63%
- Measured Yield for 10.6 x 8.3 mm SiC JBS Diodes = 72%

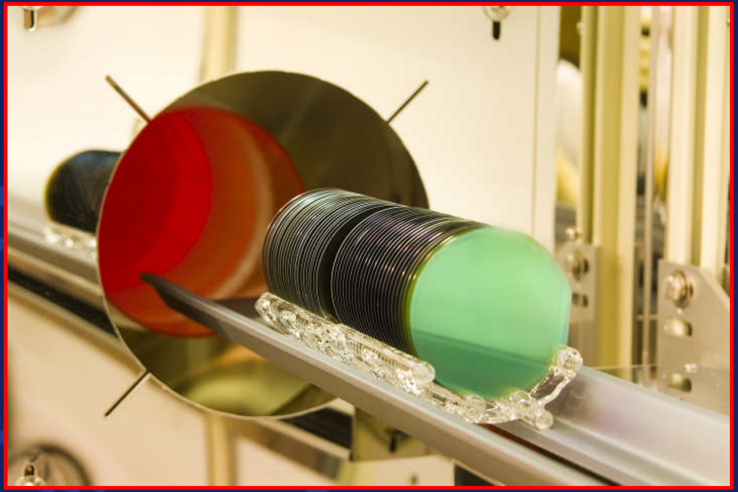


	0	0	0	0	1	
0	0	0	0	0	0	0
0	0	0	0	0	0	0
0	0	0	1	4	0	0
1	0	0	0	0	1	0
1	0	0	0	0	0	0
	0	1	2	3	1	



- Predicted “Material” Yield for 8.1x8.1 mm SiC DMOSFETs = 77%

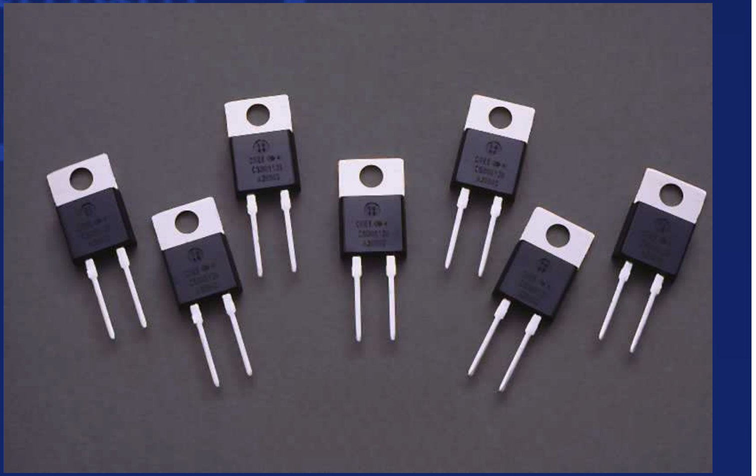
Cree WBG Technology Center of Excellence



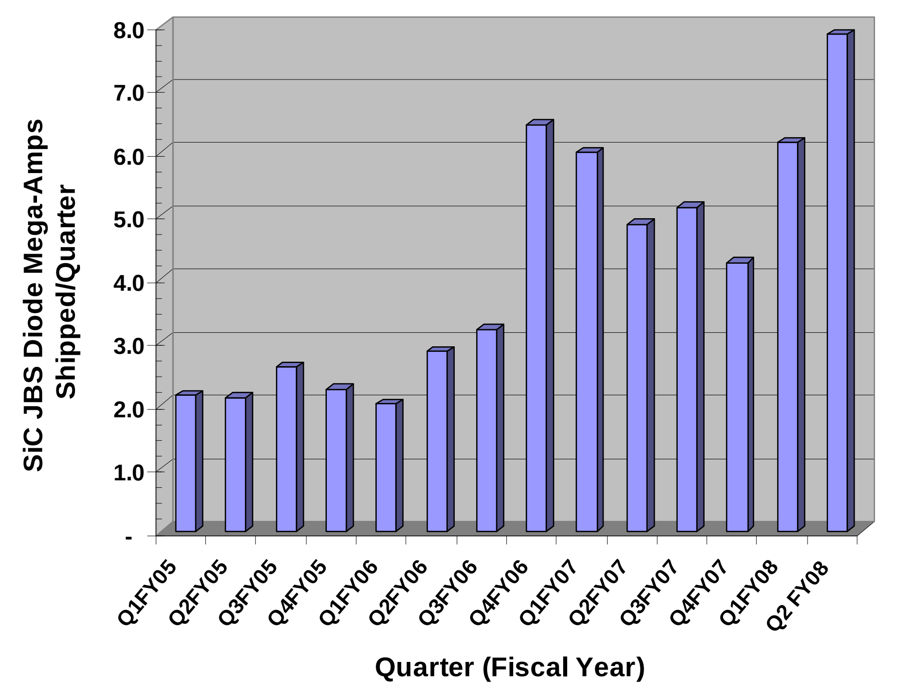
- Opened August 2006 For Large-Scale Commercial Production And Advanced Research in WBG Power and RF Products
- Located in Research Triangle Park (RTP), North Carolina
- Worlds Largest Dedicated WBG Production Device Facility
  - 40,000 total sq. ft.
  - WBG Device Fabrication Capacity: 10K Wafer Starts per Year
  - SiC Power Device Characterization & Reliability Labs
  - SiC Power On-wafer Probe and Dice
  - SiC Power Applications Support

Cree's SiC Power Product Roadmap

- SiC Power Products
  - *ZERO RECOVERY*™ Rectifiers –
    - SiC JBS Diodes
    - 300V – 10A to 20A
    - 600 V – 1A to 20A
    - 1200V - 5A to 50A
    - 10kV/10A - Product Development
  - SiC PiN Diodes
    - > 2400V - Product Development
  - SiC DMOSFETs
    - 1.2kV – 10kV / 10A - 67A
    - Product Development
  - SiC IGBTs
    - ≥ 12kV - Advanced Development

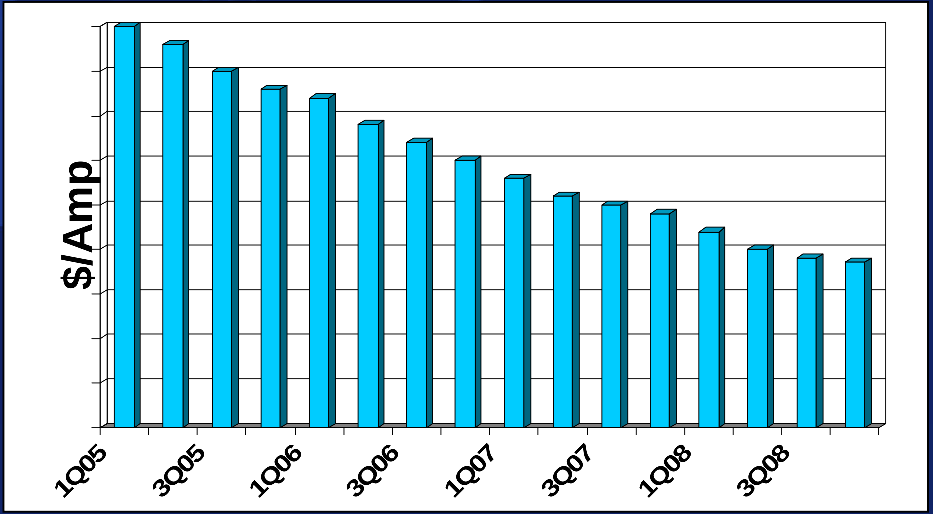


Growth in Commercial Production of SiC JBS Diodes at Cree

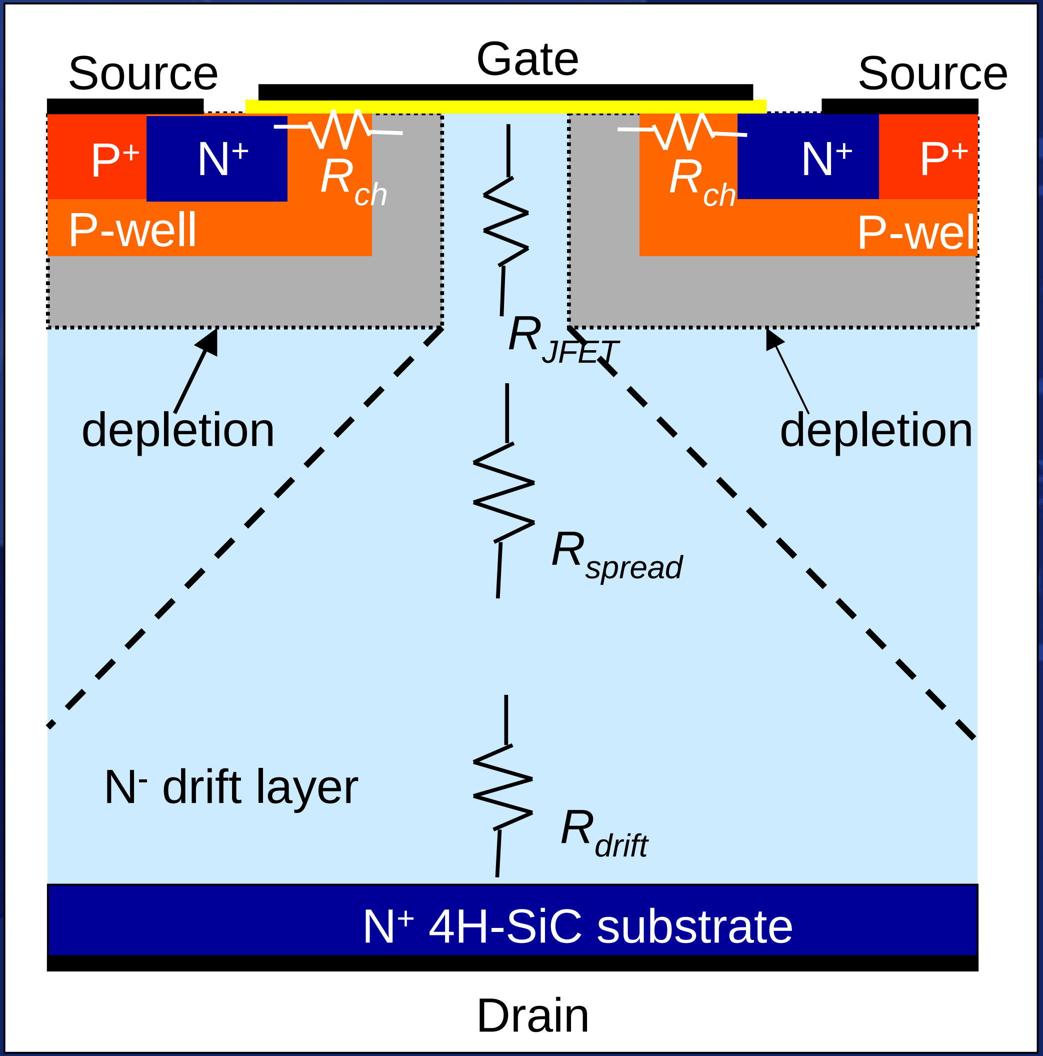

Cree SiC JBS Diode Mega-Amps Shipped Per Quarter

- **Over 2x Reduction in Price of SiC JBS Diode – 3 Factors**
  - **Higher Quality SiC Material**
  - **Larger Production Volumes**
  - **Increase SiC Wafer Size From 3 inch to 100 mm Diameter**

In Q2-FY08 (Ending 12/07) Cree Shipped 7.8 Mega-Amps of SiC JBS Diodes



Double Implanted MOSFET (DMOSFET)



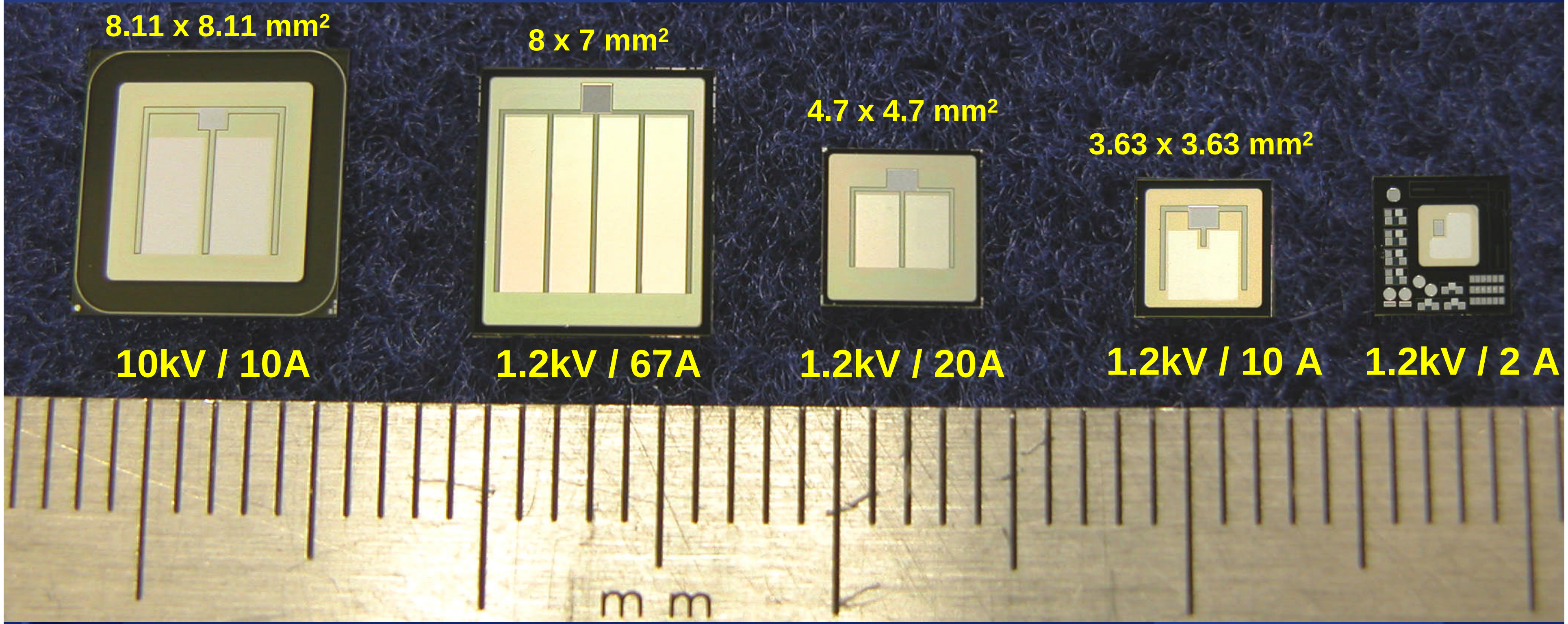
Pursuing DMOSFET As Power Switch From 1.2kV Up To 10kV

DMOSFET Requirements

- Low $R_{on,sp}$
- High Switching Speed
- Manufacturable Design/Process
- Acceptable Reliability

Scaling of SiC DMOSFET Technology

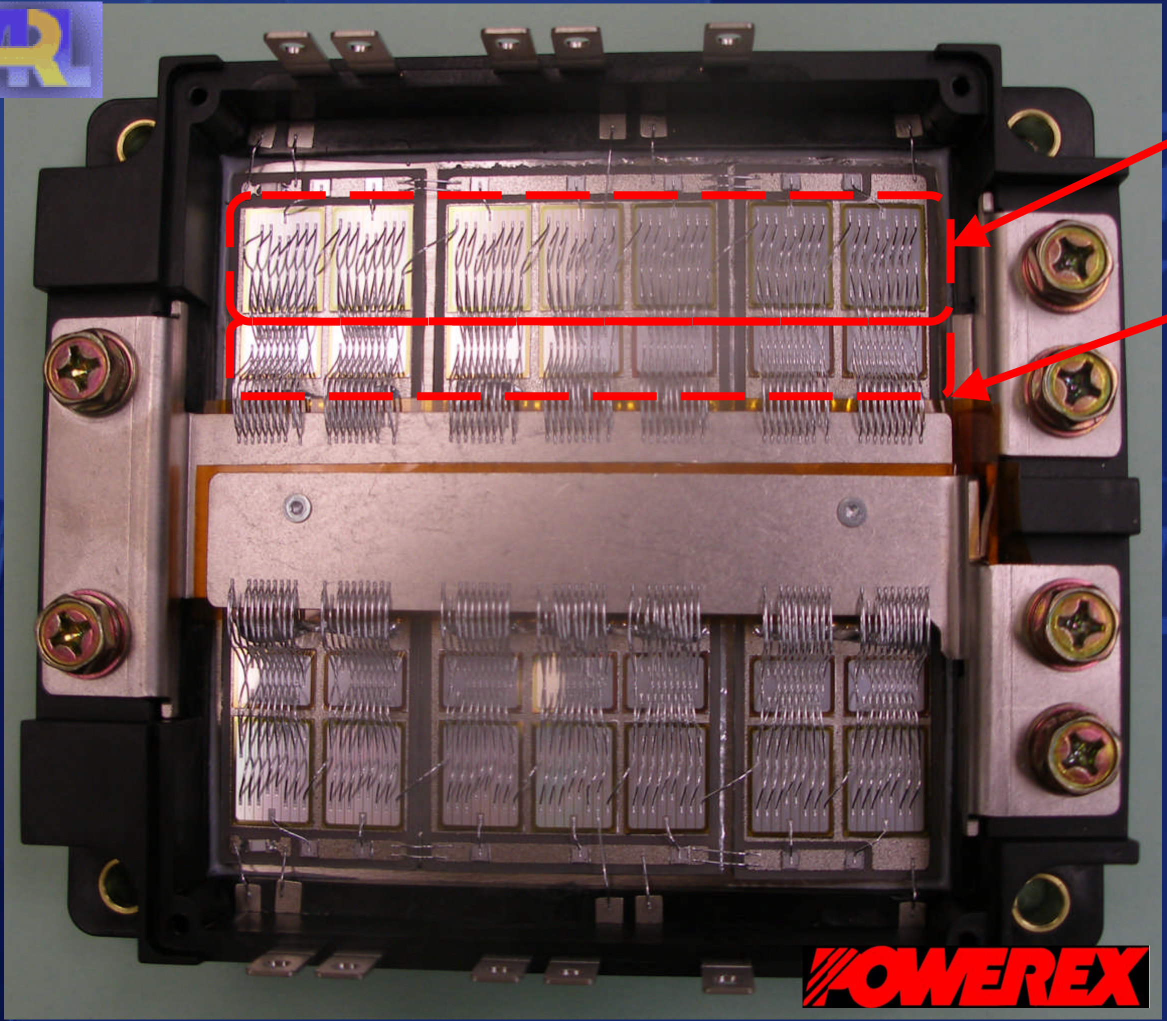
2008 ← 2004



SiC MOSFET Power Module for FCS Hybrid Electric Vehicle (HEV) Propulsion

All SiC 1.2kV / 1400A Power Module

R_G = 0.5 ohm, f = 10 kHz



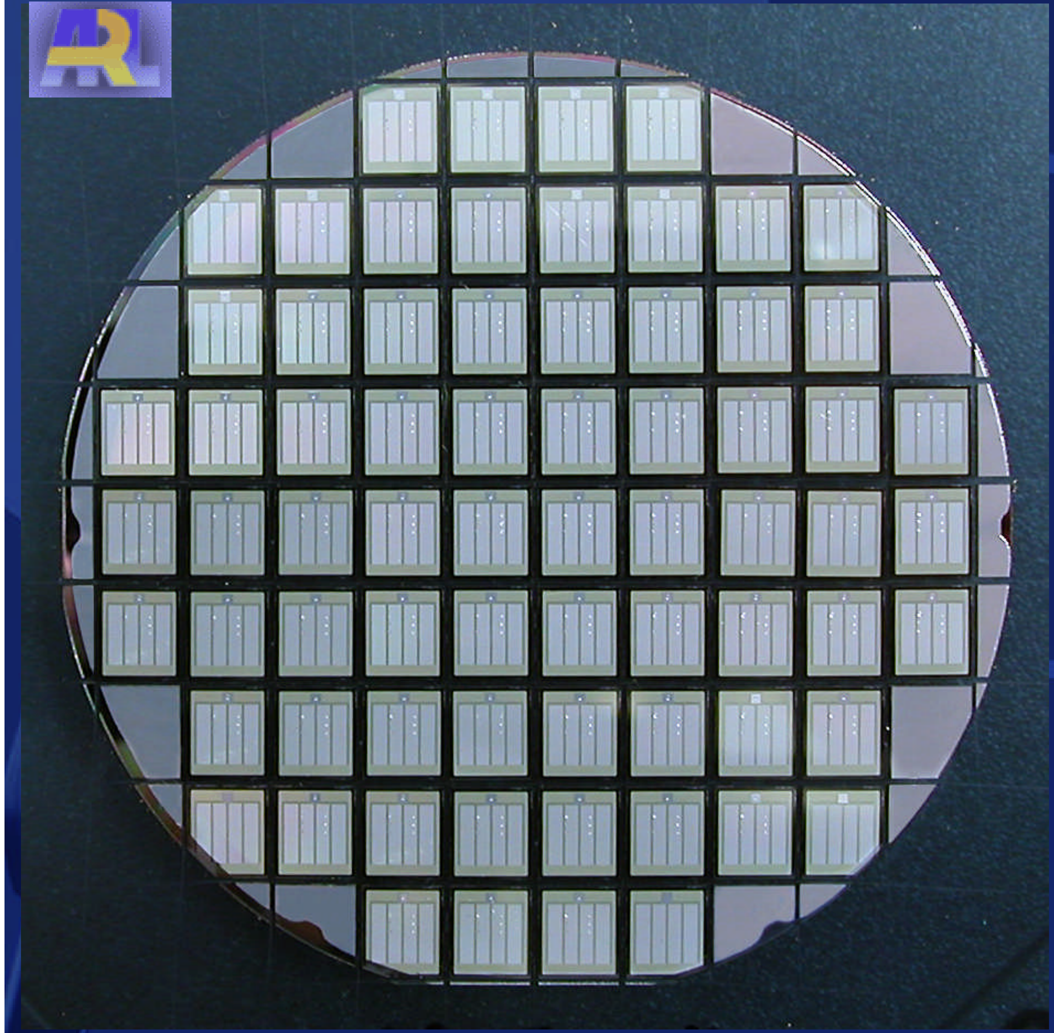
Replace Si IGBT with SiC MOSFET => 40% Reduction in Loss

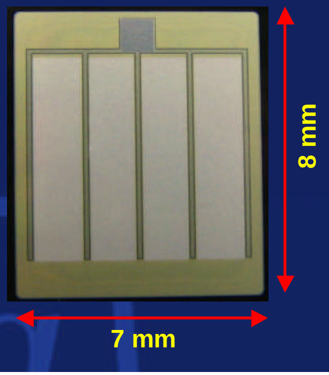
Replace Si diode with SiC JBS Diodes => 20% Reduction in Loss

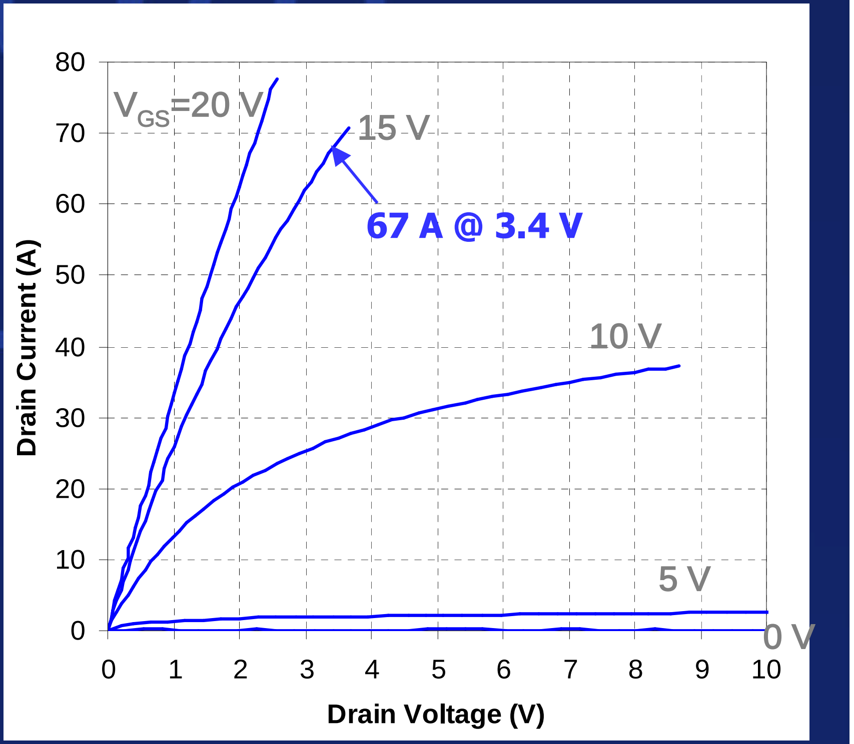
> 2x Reduction in Converter Losses
+
150 °C Operating Temperature (Si = 125 °C)

> 4x Reduction in Cooling Requirements

1.2kV/67A SiC DMOSFETs Fabricated on 3-Inch 4HN-SiC Wafer

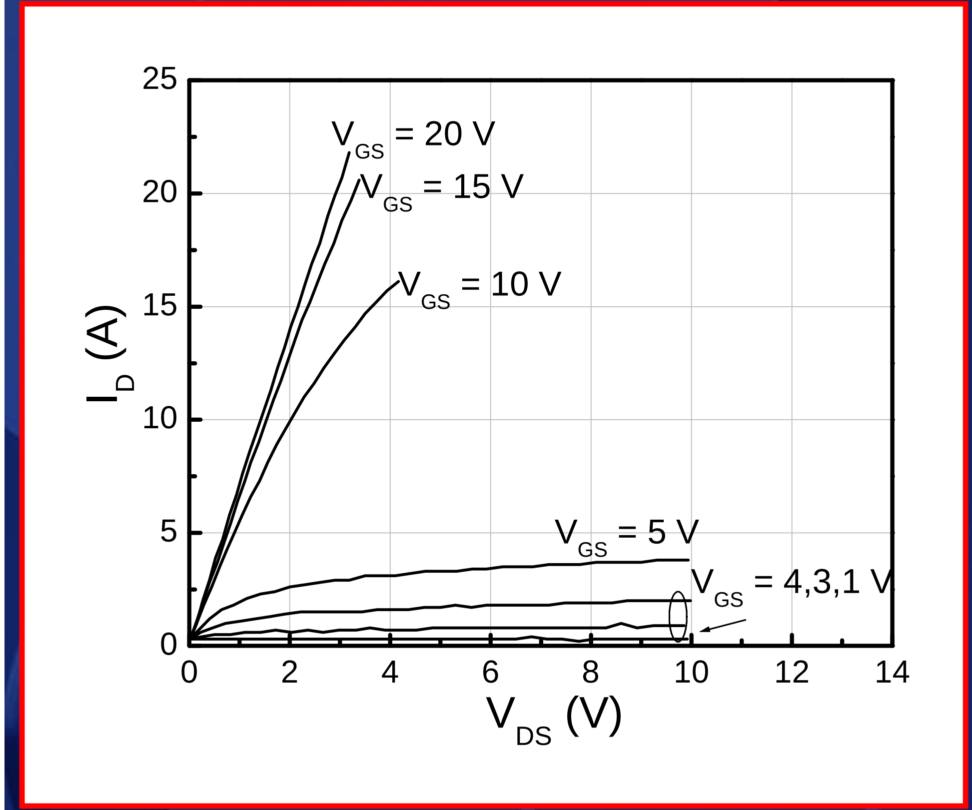


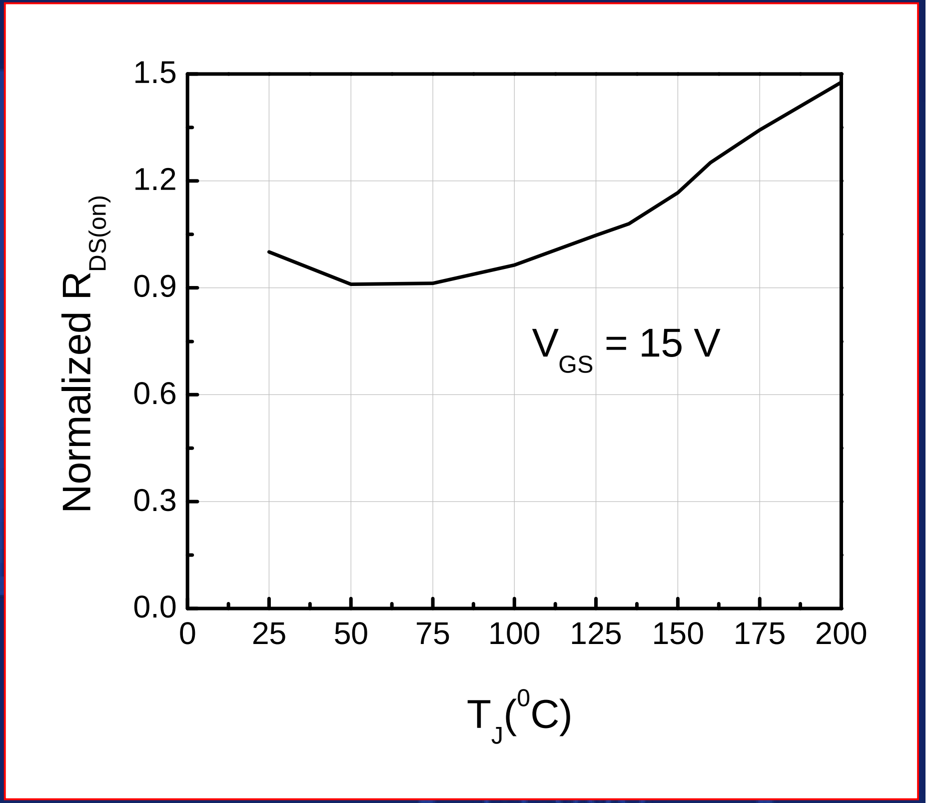




67 A @ 3.4 V

High Temperature Device Characteristics For 1.2kV/10A SiC DMOSFETs

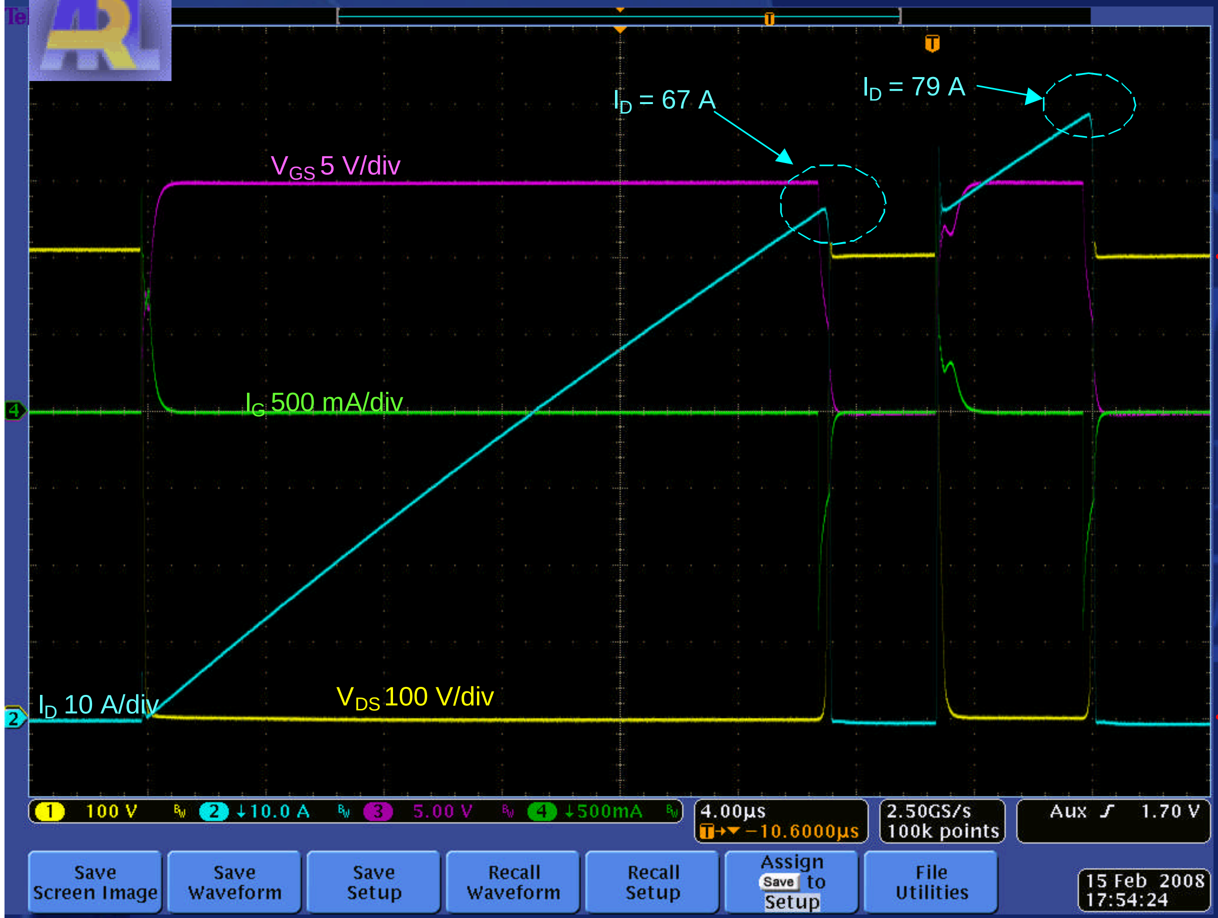


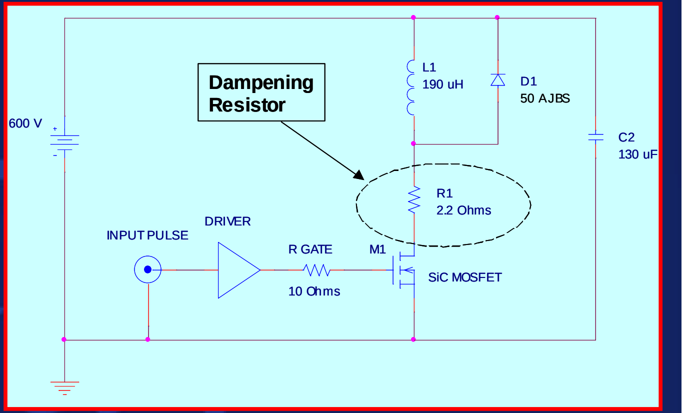


Typical Output Characteristics T_J = 150ºC

Normalized On-Resistance vs. Temperature

1.2kV/67A SiC DMOSFET Switching Measurements at 150 °C

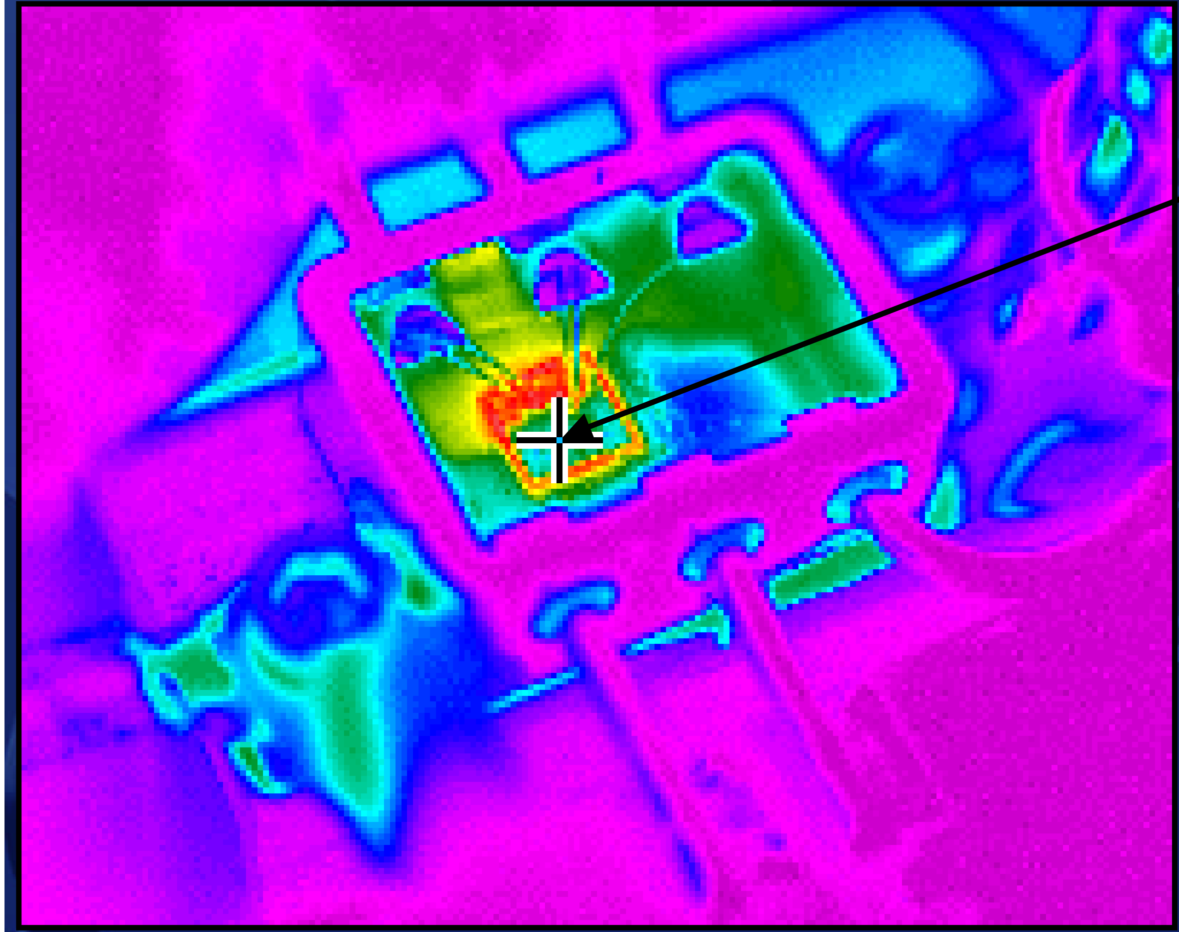




V_{DS} = 600 V

- **1.2kV/67A SiC DMOSFET Switching 67A at 150°C**
  - **E_{on} = 4.2 mJ**
  - **T_{rise} = 65 nsec**
  - **E_{off} = 3.1 mJ**
  - **T_{fall} = 68 nsec**

Boost Converter Demonstration of 1.2kV/10A SiC DMOSFET High Temperature Operation



- **Thermograph Demonstrates 1.2kV/10A SiC DMOSFET High Temperature Operation (> 183 °C) Under Hard Switching Conditions**
- **1.2kV/10A SiC DMOSFET Junction Temperature > 183 °C for 12 hrs**
  - **No failures**
  - **Stable operation**

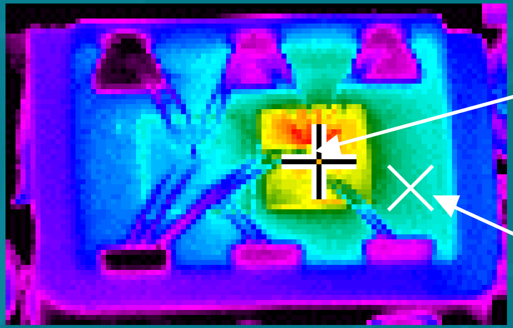
Excellent Current Sharing of Parallel 1.2kV/10A DMOSFETs in Boost Converter

Scale

227.2 °C

149.6°C

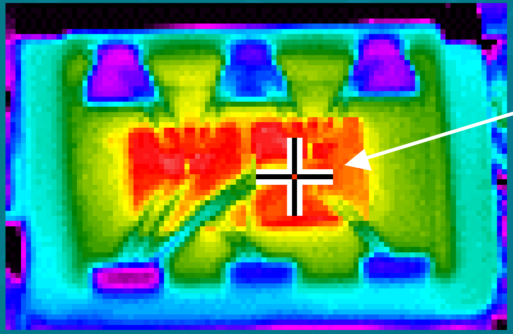
Single 1.2kV/10A SiC DMOSFET Operating @ 10.7 A RMS



T_J = 215 °C

T_C = 195 °C

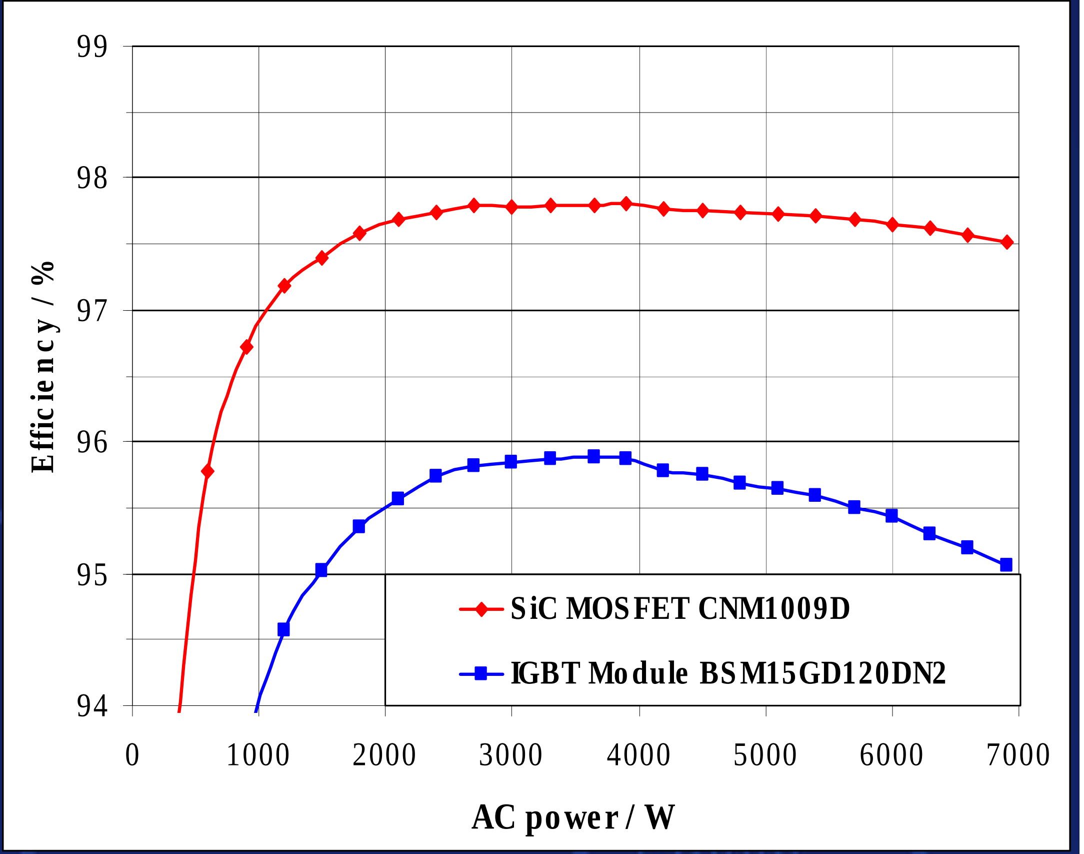
2x Parallel 1.2kV/10A SiC DMOSFETs Operating @ 15.7 A RMS



T_J = 218 °C

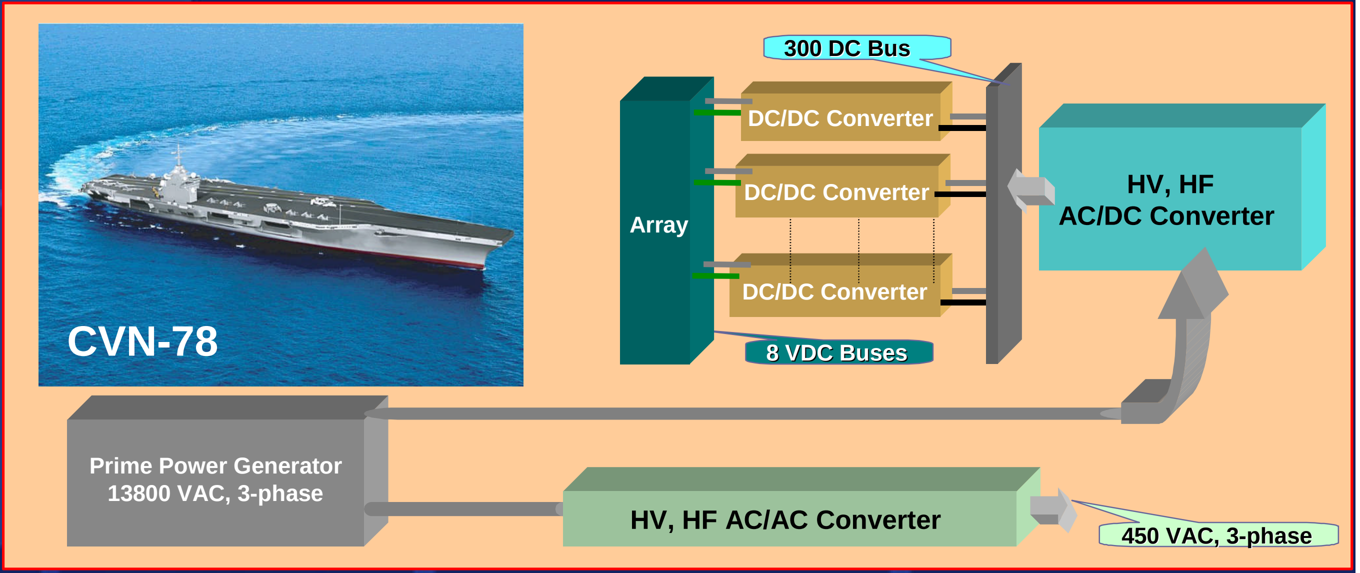
SiC 1.2 kV DMOSFETs Dramatically Improve Efficiency of 3-Phase 7kW Solar Inverter

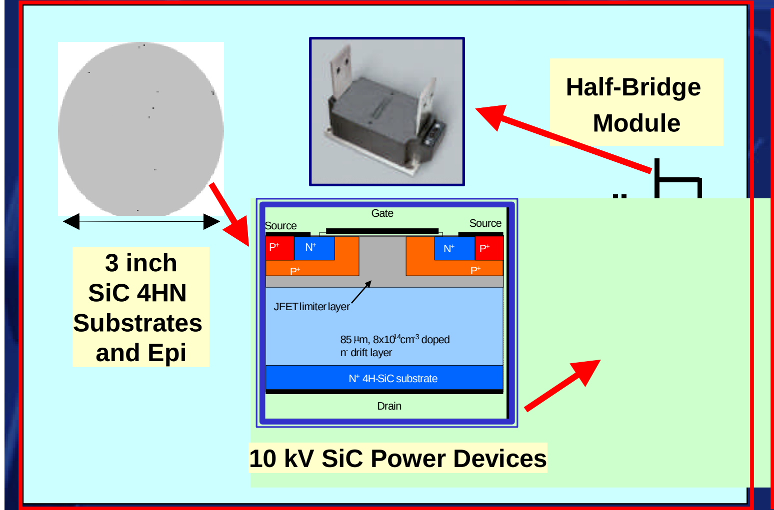
- Dr. Bruno Burger at Fraunhofer-Institute for Solar Energy Systems – 9/07
- Replaced Si IGBTs with 1.2kV SiC DMOSFETs In Existing Solar Inverter Without Further Optimization
- Efficiency Increased by 2.36%
- Huge Impact on Market - Typically Struggle for Tenths of a Percent Improvement



DARPA HPE
High Power SiC Module Development

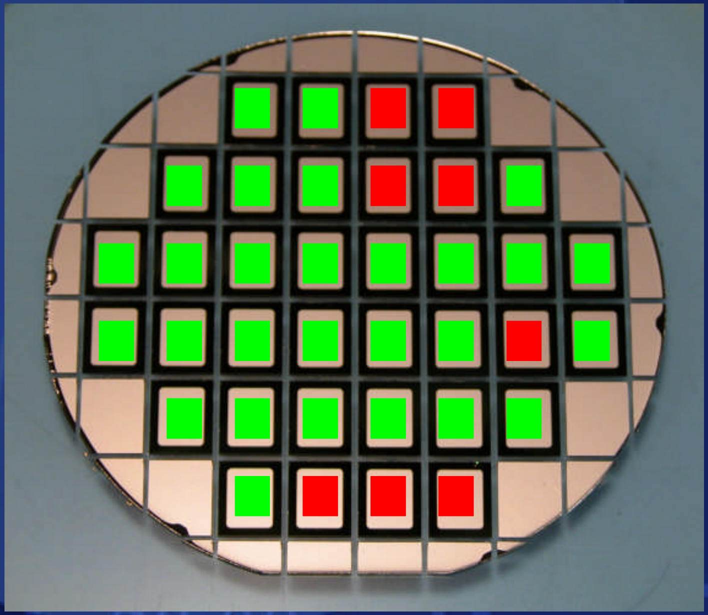
- **Develop SiC-Based Power Module for Solid State Power Substation (SSPS)**

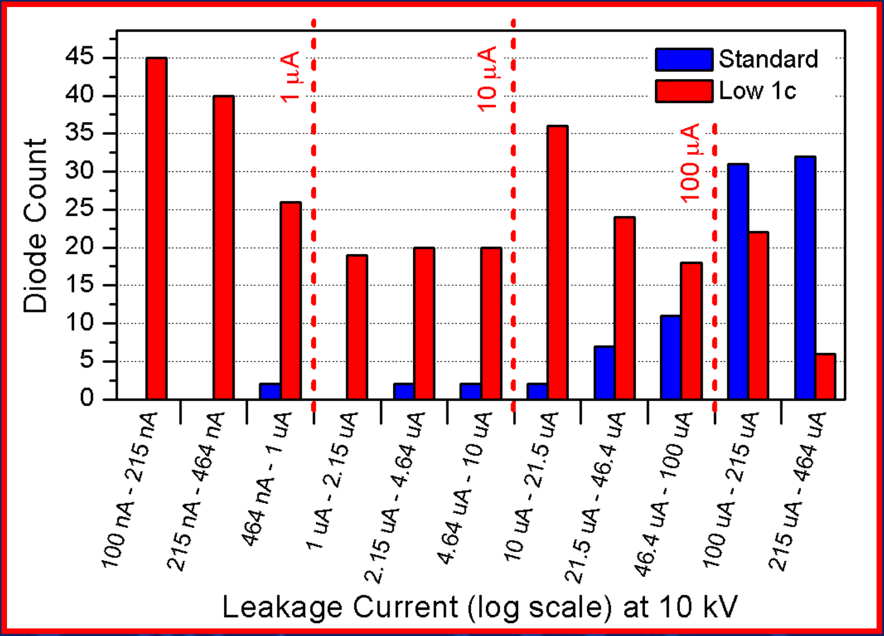




- **CVN-78 Power Distribution Uses 2.75 MVA/60HZ Power Transformers – Each Weighing Several Tons**
- **Develop SiC Power Module for Replacement SSPS 2.75 MVA 3-Phase Converter - 13.8kV AC to 465 AC**
- **Reduce System Weight by Factor of 10x**
- **Reduce System Size by Factor of 3x**
- **Demonstrate Comparable Efficiency ~ 97%**

High Yield Fabrication of 10kV/10A SiC JBS Diodes





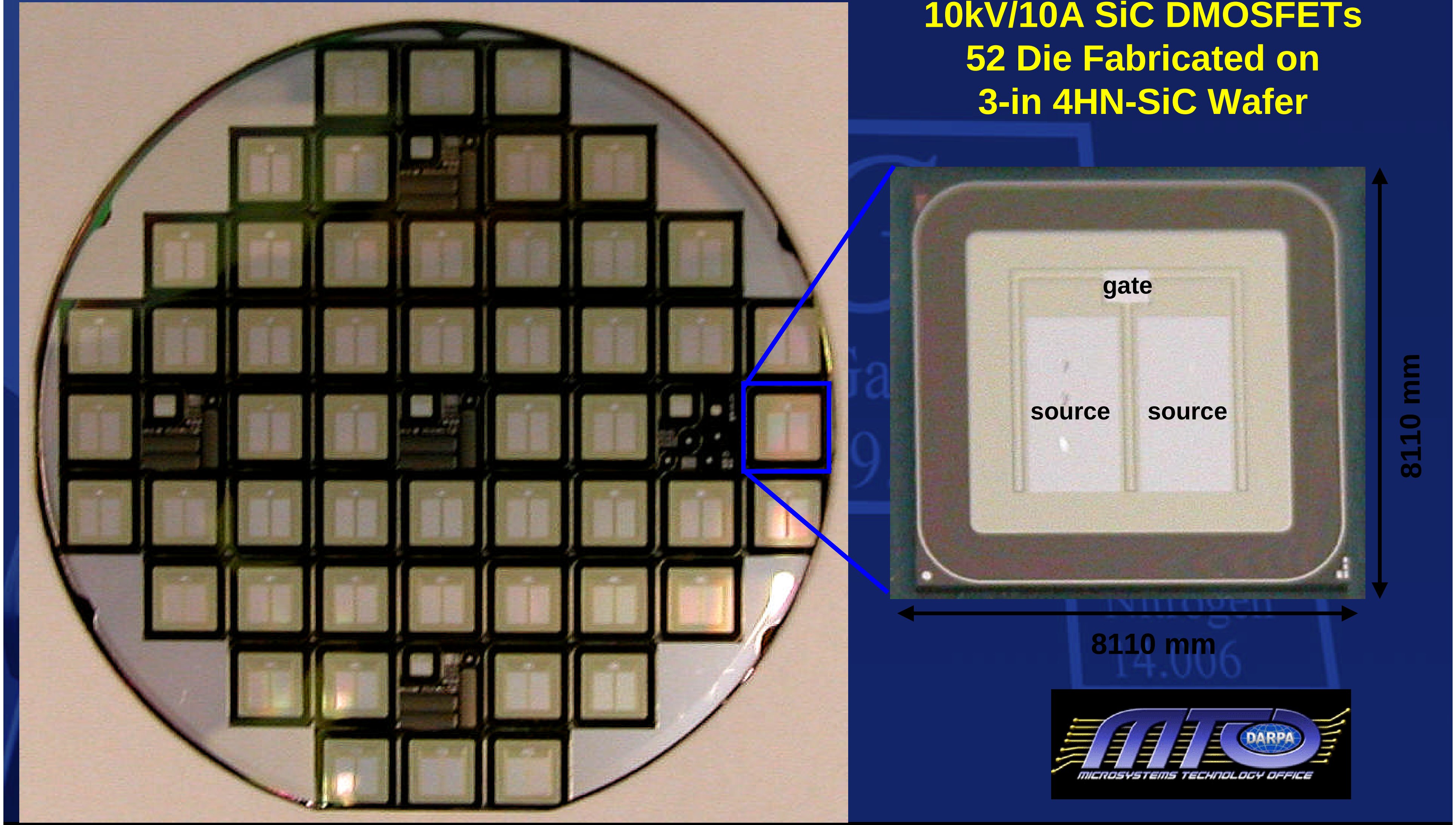
Reverse Leakage Current Histogram of 10kV/10A SiC JBS Diodes

- **High Yield Fabrication of 10kV/10A SiC JBS Diodes on 3-inch Wafers**
  - **Highest Yield = 78%**
  - **Green ⇒ Good Device on 3-inch Wafer**

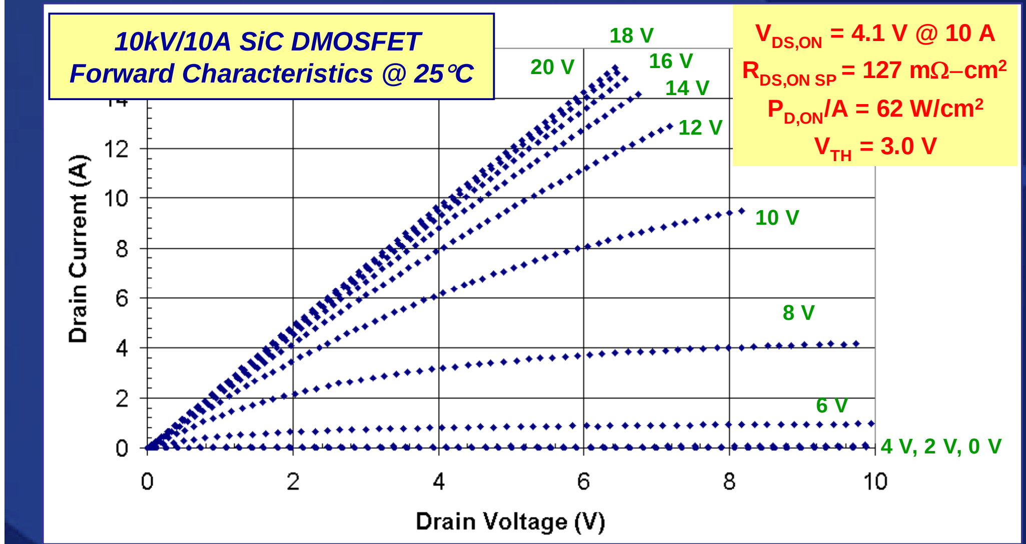
- **Low-1c SiC Wafers Dramatically Increase Yield of 10kV/10A SiC JBS Diodes**
  - **Median Reverse Leakage Current Decreased > 50X**
  - **Device Yield Increased > 3x**

10kV/10A SiC DMOSFET

10kV/10A SiC DMOSFETs
52 Die Fabricated on
3-in 4HN-SiC Wafer



High Yield Fabrication of 10kV/10A SiC DMOSFETs



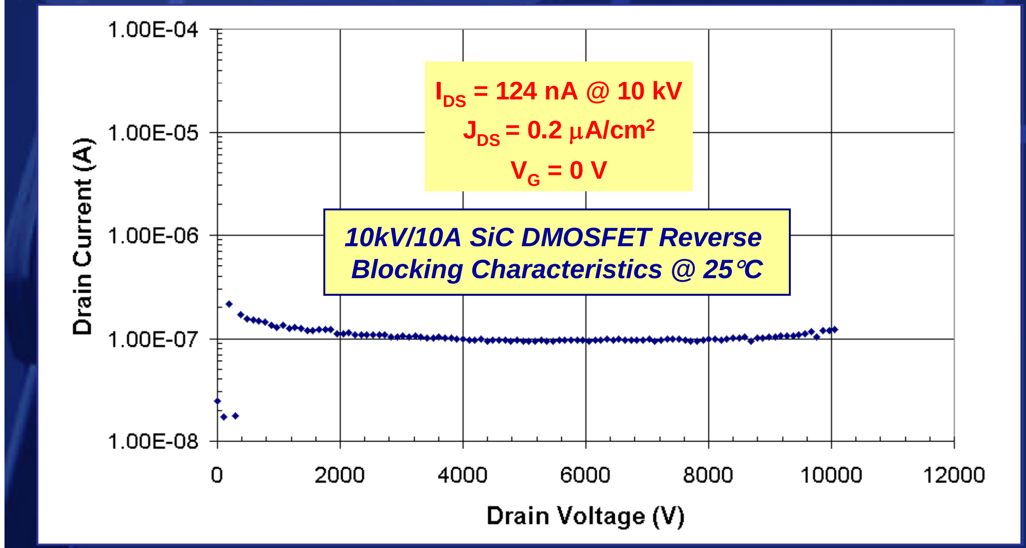
10kV/10A SiC DMOSFET Forward Characteristics @ 25°C

$V_{DS,ON}$ = 4.1 V @ 10 A

$R_{DS,ON\ SP}$ = 127 mΩ–cm²

$P_{D,ON}/A$ = 62 W/cm²

V_{TH} = 3.0 V

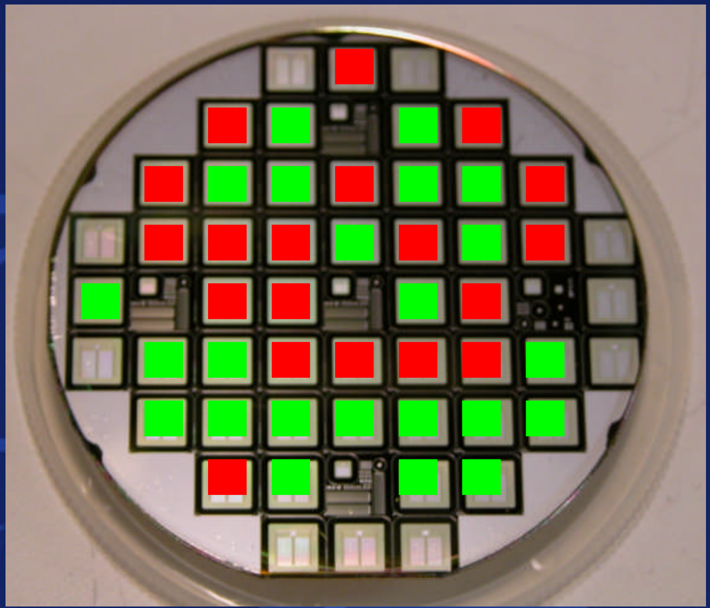


I_{DS} = 124 nA @ 10 kV

J_{DS} = 0.2 µA/cm²

V_G = 0 V

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

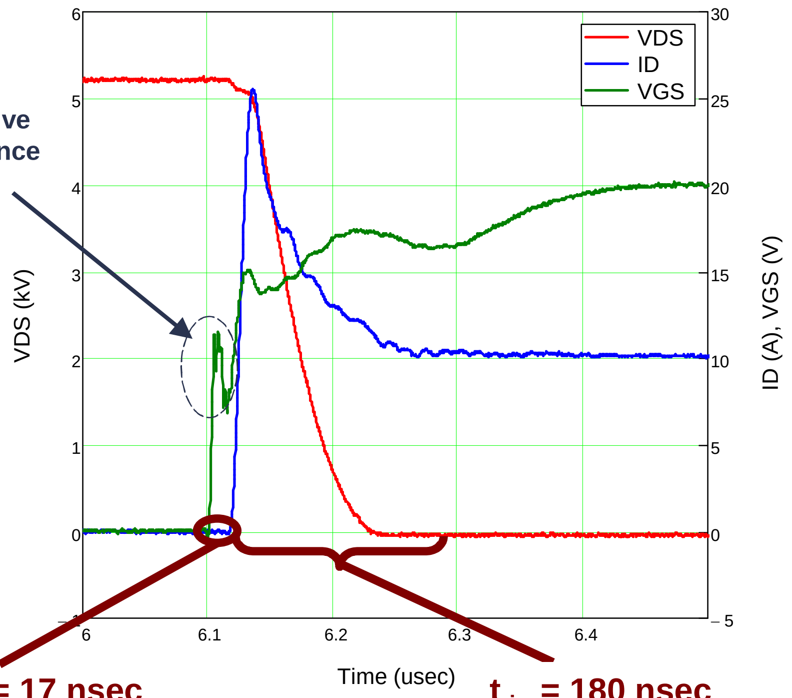


- **High Yield Fabrication of 10kV/10A SiC DMOSFETs on 3-inch Wafers**
  - **Highest Yield = 55%**
  - **Green ⇒ Good Device on 3-inch Wafer**

10kV SiC DMOSFET/JBS Diode Clamped Inductive Switching

10 A Turn-On

Gate Drive, V_{GS} = 20 V



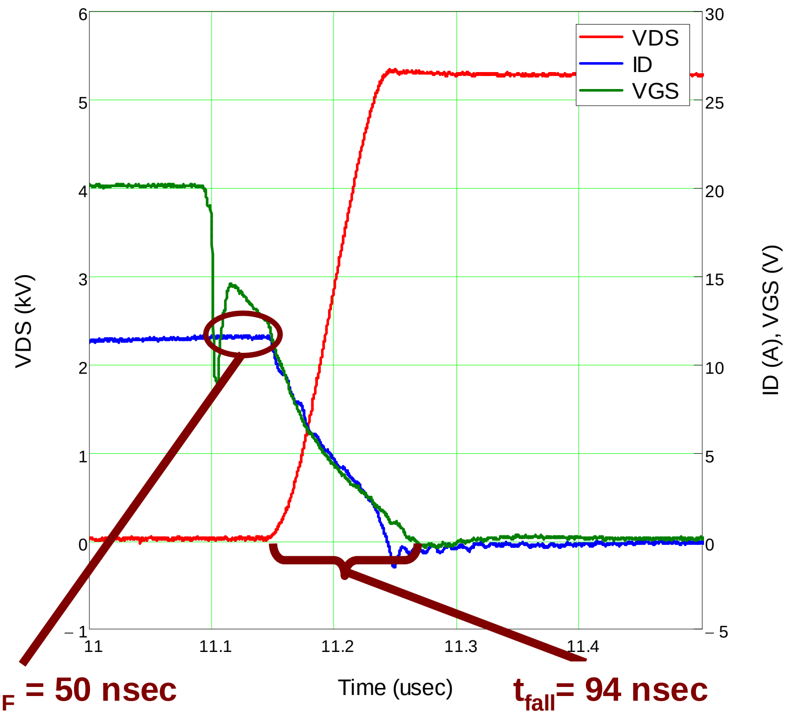
Gate drive inductance artifact

$t_{D,ON}$ = 17 nsec

t_{rise}= 180 nsec

10 A Turn-Off

Gate Drive, V_{GS} = 20 V



$t_{D,OFF}$ = 50 nsec

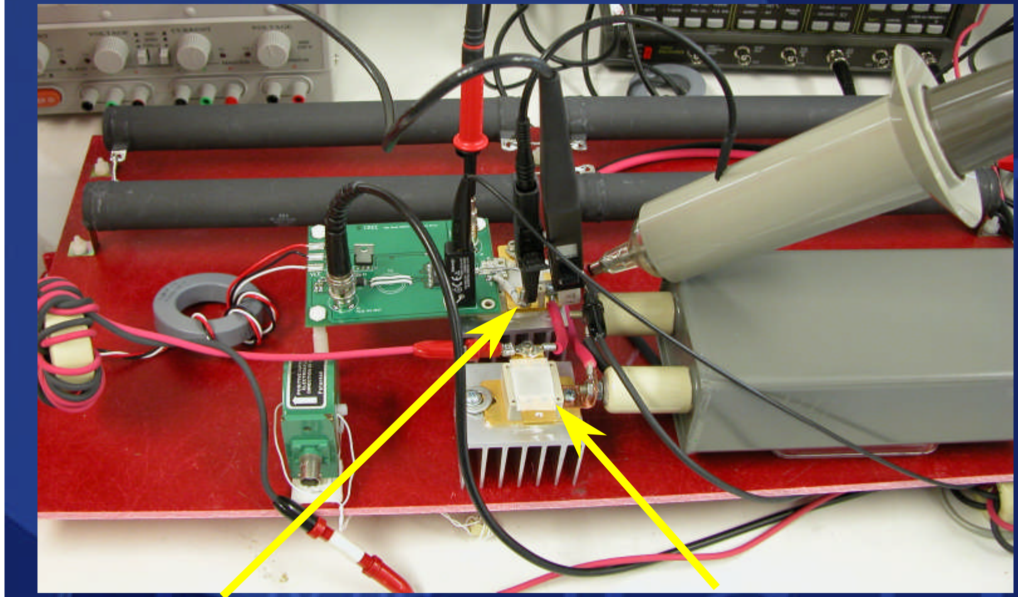
t_{fall}= 94 nsec

E_{on} = 4.48 mJ

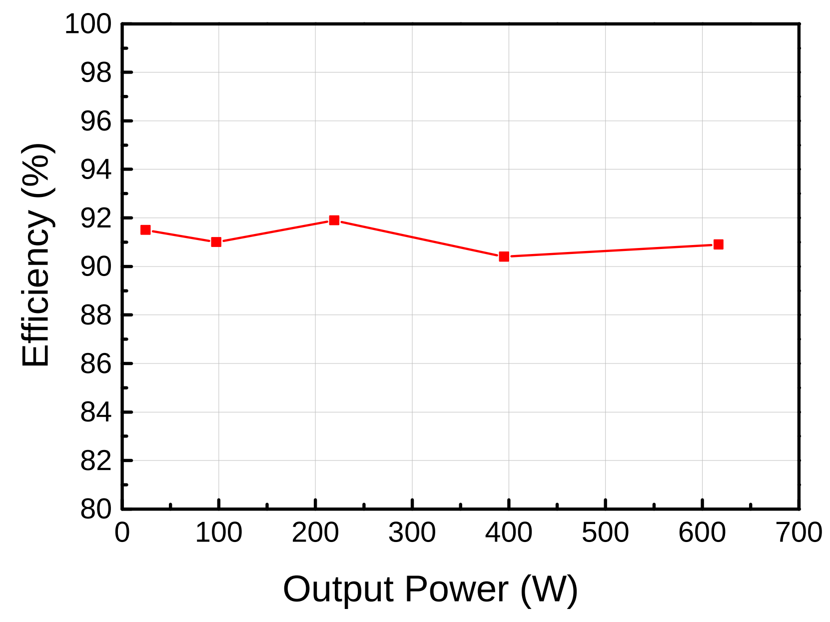
E_{off} = 0.81 mJ

160 W/cm² Switching Losses Within Module Thermal Limits

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

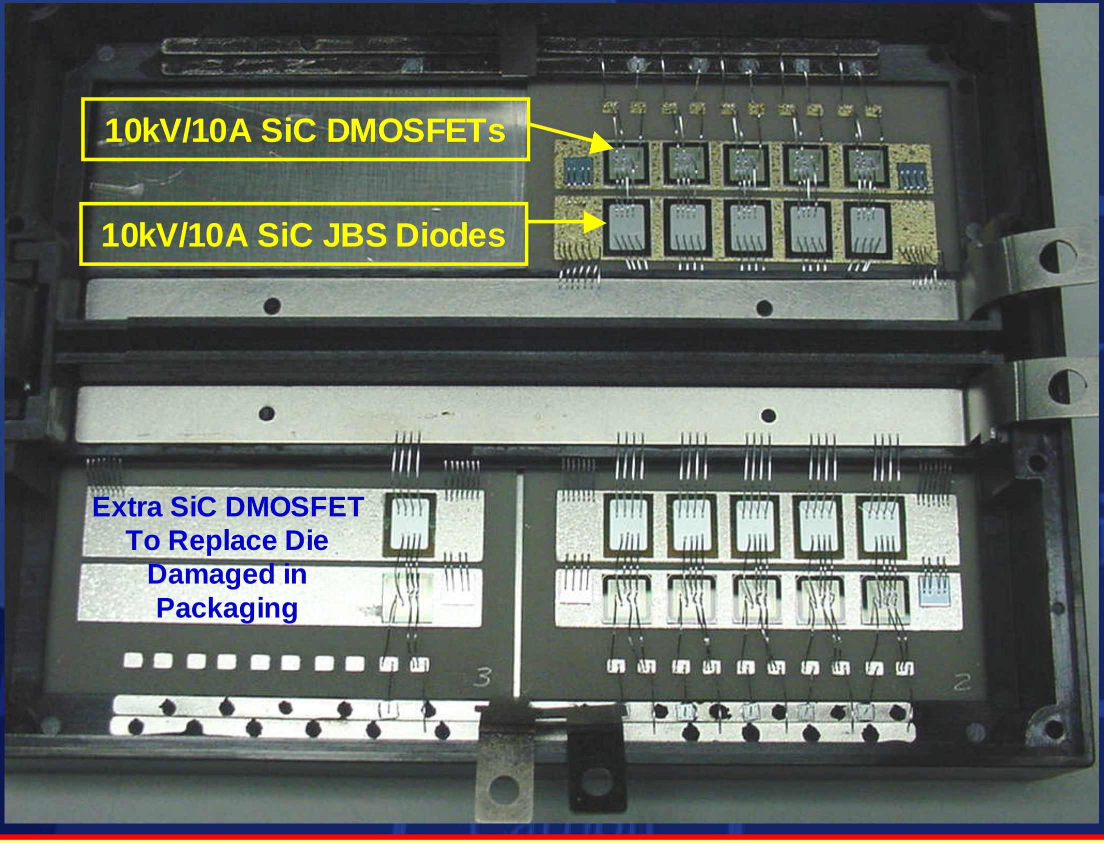


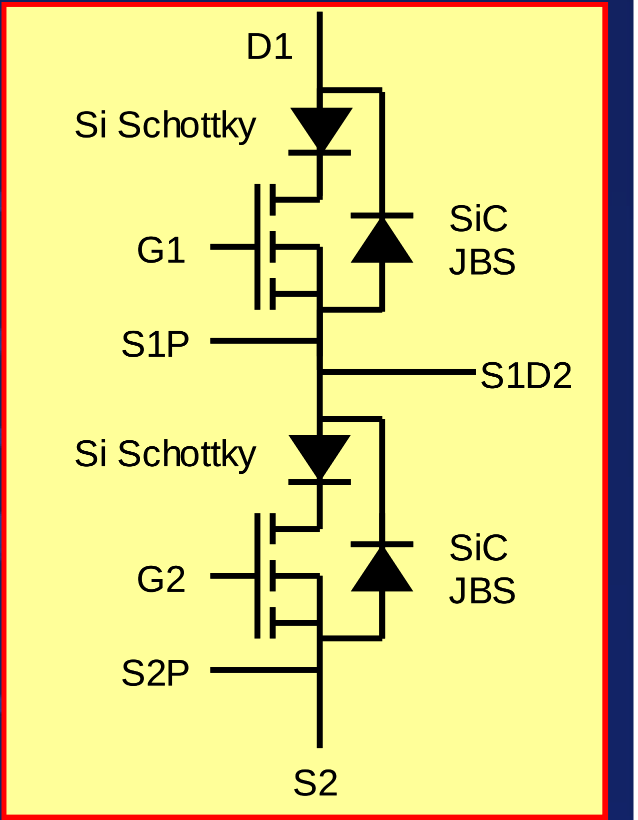
- **500V – 5kV Boost Converter Operating at 20kHz**
- **Maintained Efficiency > 90% Over Full Load Range**



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

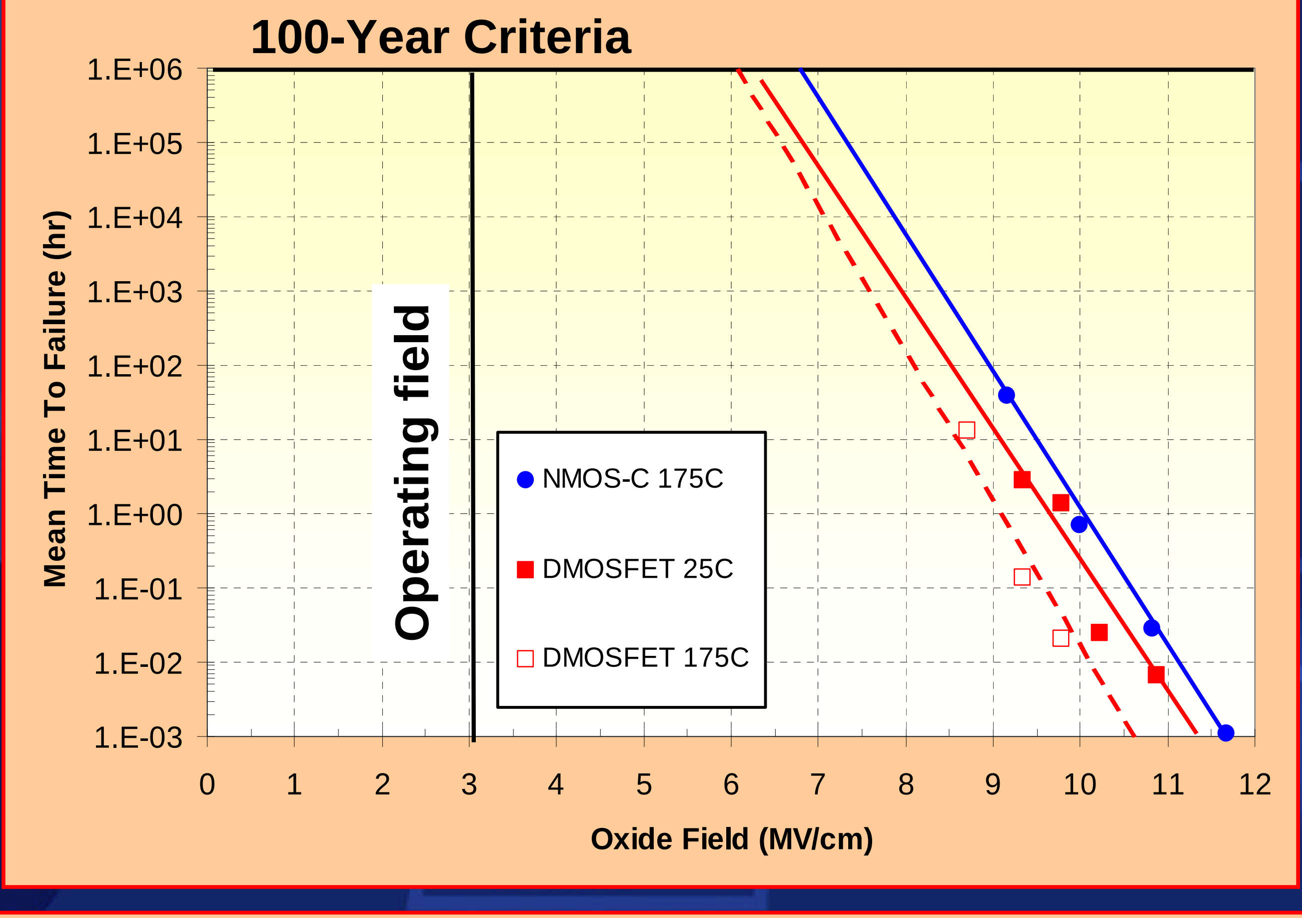
DARPA HPE-II 10kV/50A SiC Half H-Bridge Module





- **Each Switch Comprised of 5 Paralleled 10kV/10A SiC DMOSFETs**
- **Each Rectifier Comprised of 5 Paralleled 10kV/10A JBS Diodes**
- **10kV/50A Half H-Bridge Module Only Half Filled**
- **10kV Half H-Bridge Module Capable of 100A When Fully Populated**

TDDB Measurements of SiC DMOSFET Oxide Reliability

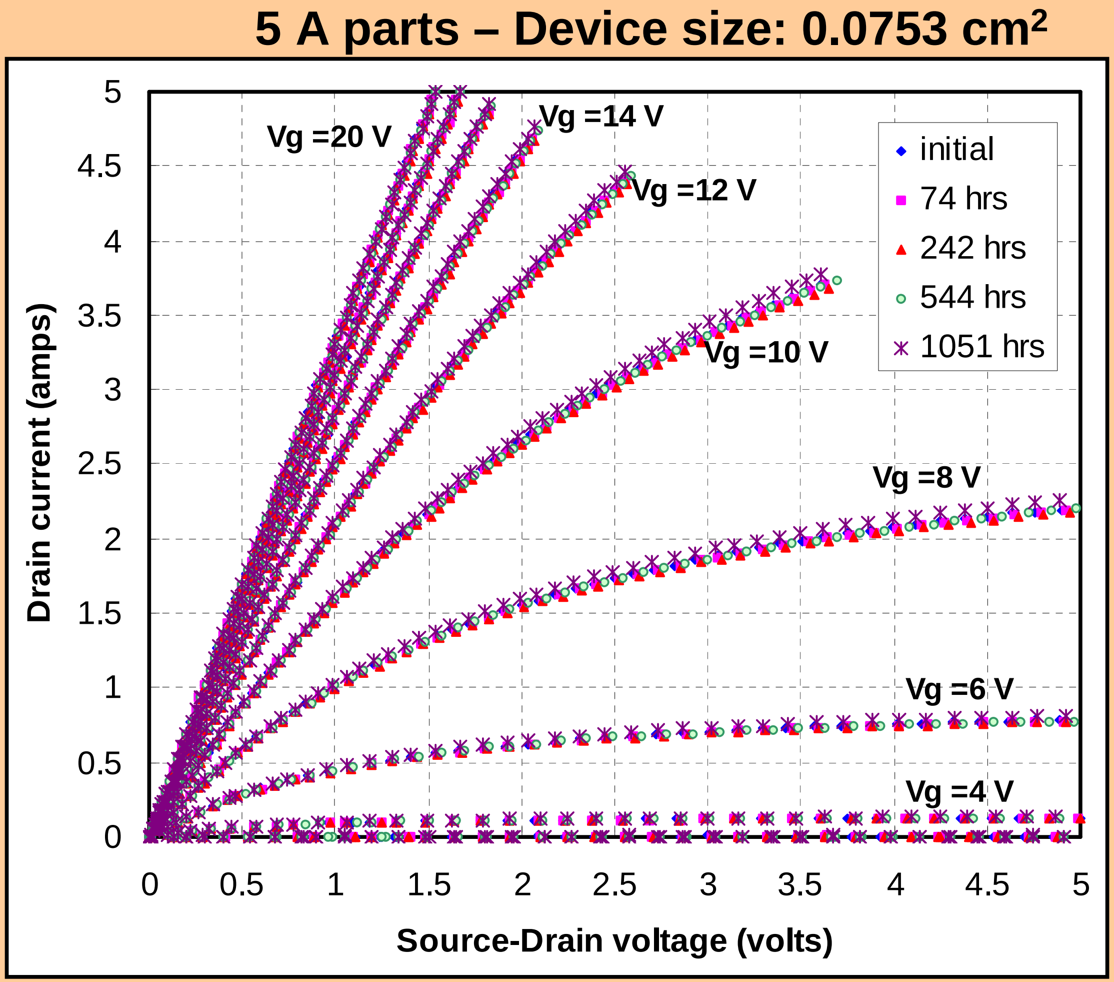


Measurements carried out on smaller DMOSFET devices fabricated without termination.

Device size: 4.9×10^{-4} cm^2

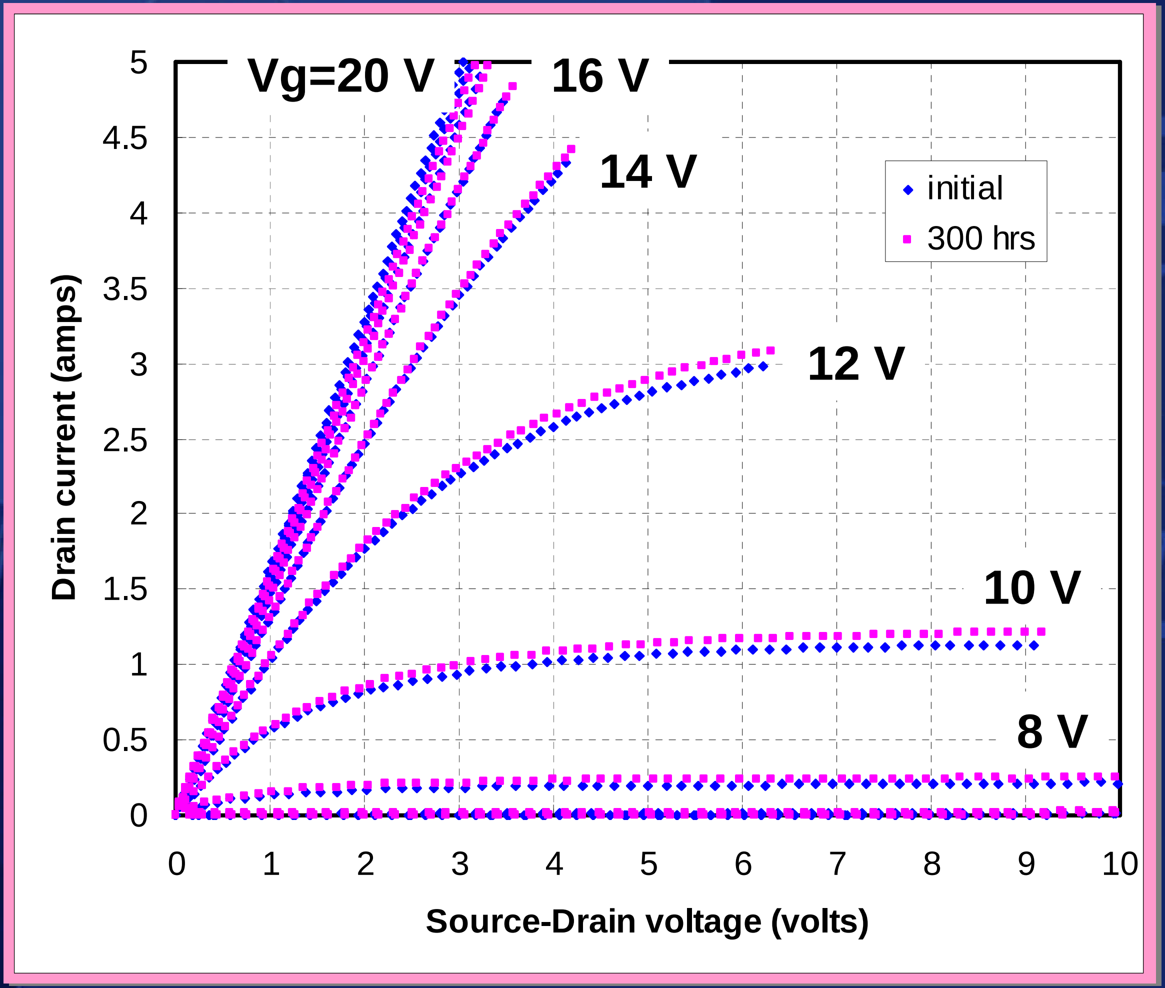
- **DMOSFETs show acceptable oxide lifetime at an operating field of ~3 MV/cm, despite ion implantation and high temperature annealing**

Stability of SiC 1200V/5A SiC DMOSFETs Under Constant Gate Stress at 175°C



- **Packaged SiC DMOSFETs Stressed at 175°C for Constant V_g = 15 V With Source & Drain Grounded**
- **Devices Cooled to RT and remeasured**
- **SiC DMOSFET I-V Curve Remains Relatively Unchanged After 1050 hrs of Stress**

10 kV / 5 A 4H-SiC DMOSFET
High Temperature Gate Stressing



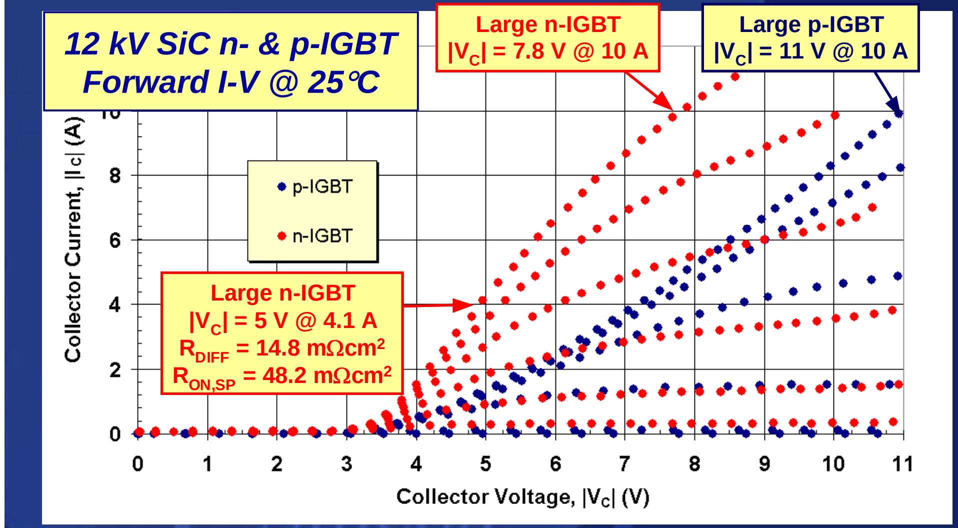
- Packaged DMOSFETs stressed with V_g = 15V at 175°C, with source and drain grounded
- Devices cooled to RT and measured
- I-V curve remains unchanged after about 300 hrs of stress

What Is Next for SiC Power Devices?

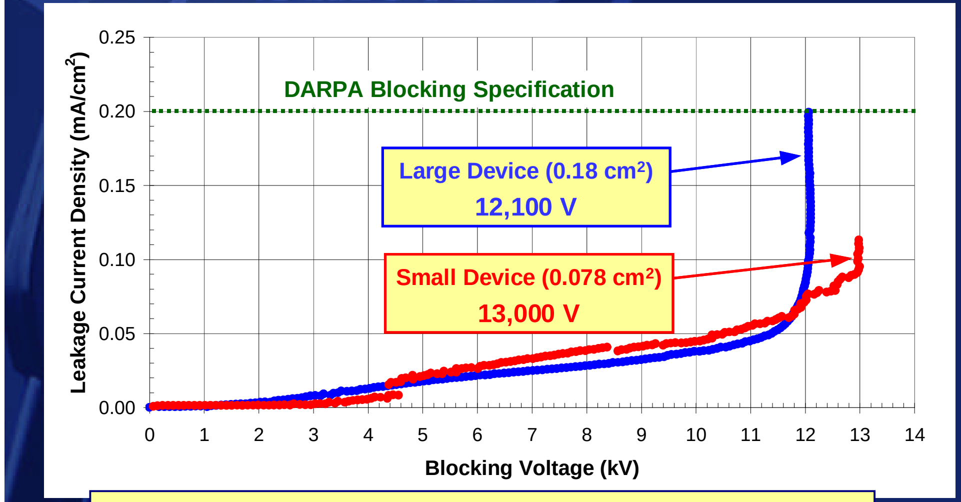
- 10 kV ~ Upper Limit of SiC Unipolar Devices
  - DMOSFETs and Schottky diodes
- Higher Voltage ⇒ Bipolar Devices
  - Si IGBT Replace Si DMOSFET at > 1kV
- For SiC devices, this holds true for >10 kV
  - SiC breakdown field 10x that of silicon

- ⇒ >10kV - We Need SiC IGBT

12kV SiC n-IGBTs and SiC p-IGBTs

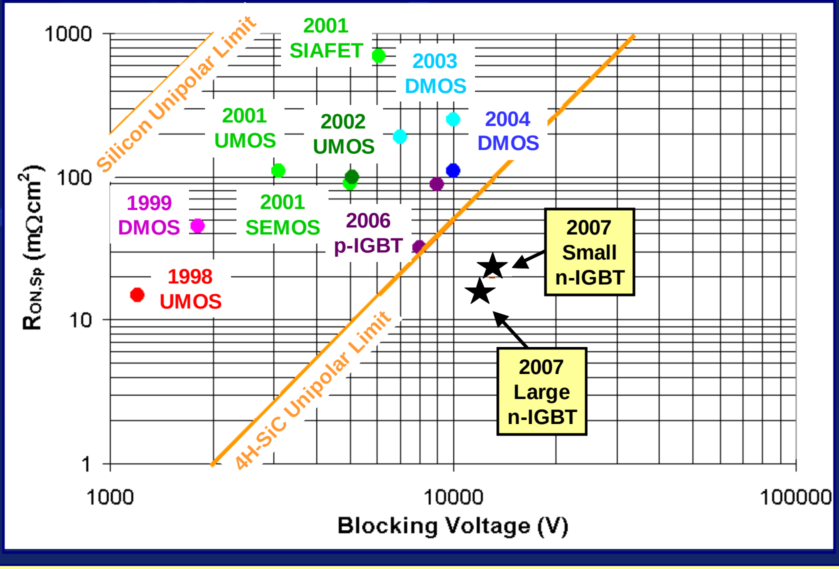


12 kV SiC n- & p-IGBT Forward I-V @ 25°C



12 kV SiC n-IGBT Reverse Blocking @ 25°C

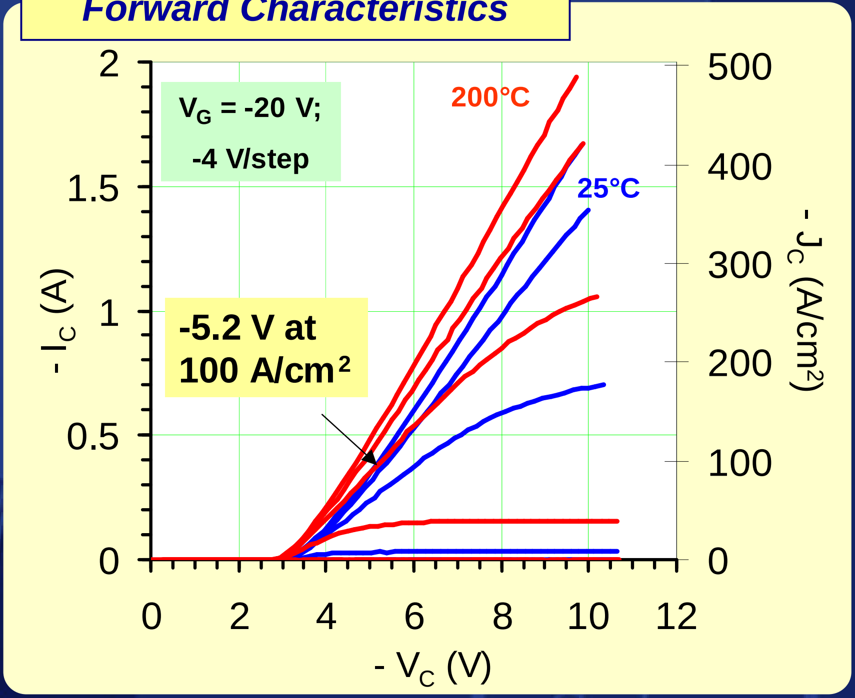
- **12kV/10A SiC n-IGBTs and SiC p-IGBTs Demonstrated**
  - **SiC n-IGBTs Already Beyond $R_{on,sp}$/BV Limits for SiC DMOSFETs**
  - **⇒ SiC IGBTs Superior to SiC DMOSFETs at BV > 10kV**
  - **n-IGBT ~ n-type SiC drift layer p-IGBT ~ p-type SiC drift layer**

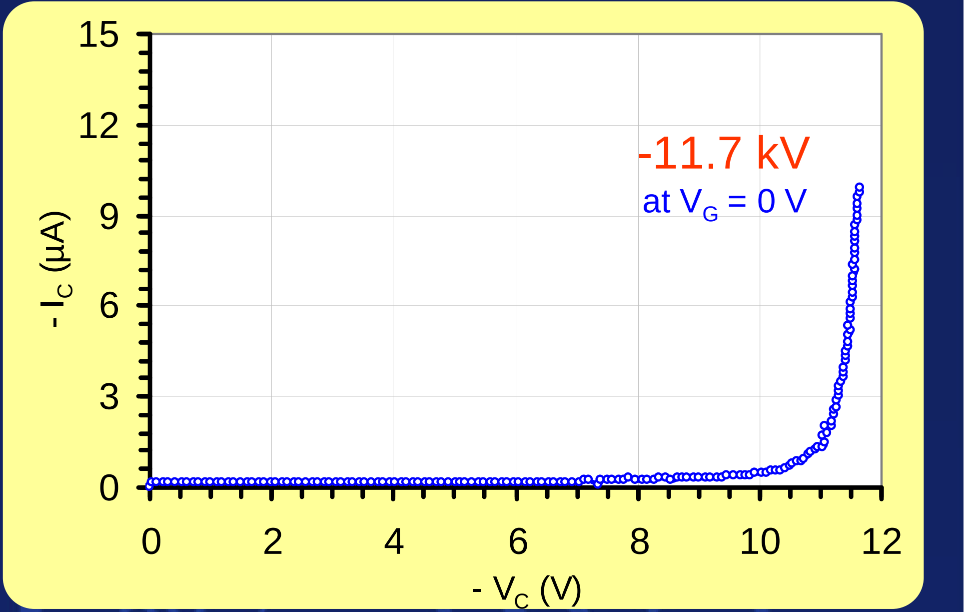


SiC n-IGBTs Beyond R_{on}/BV Limits for SiC DMOSFETs

12kV SiC p-IGBTs

12 kV SiC p-IGBT Forward Characteristics



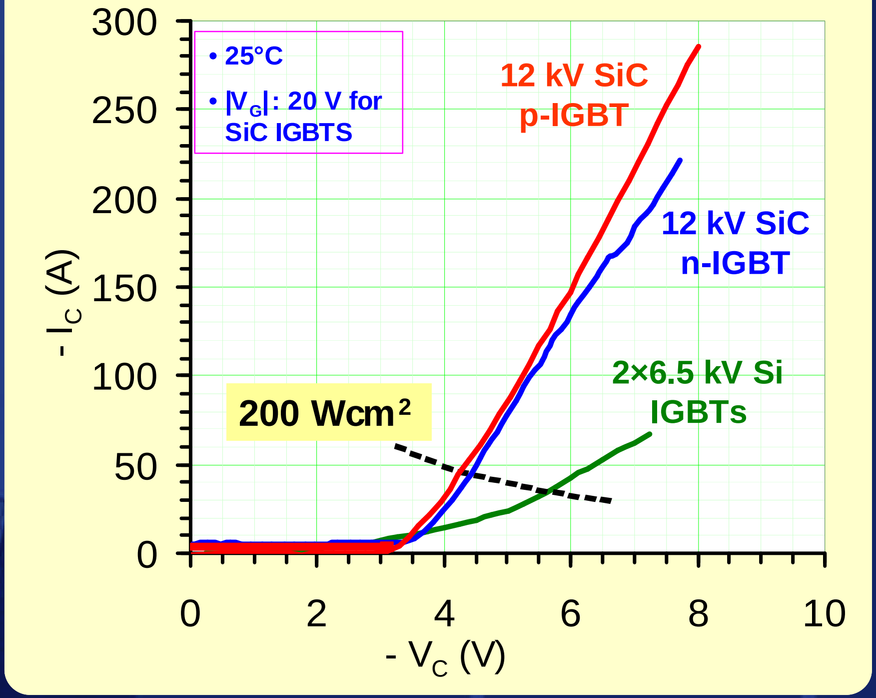


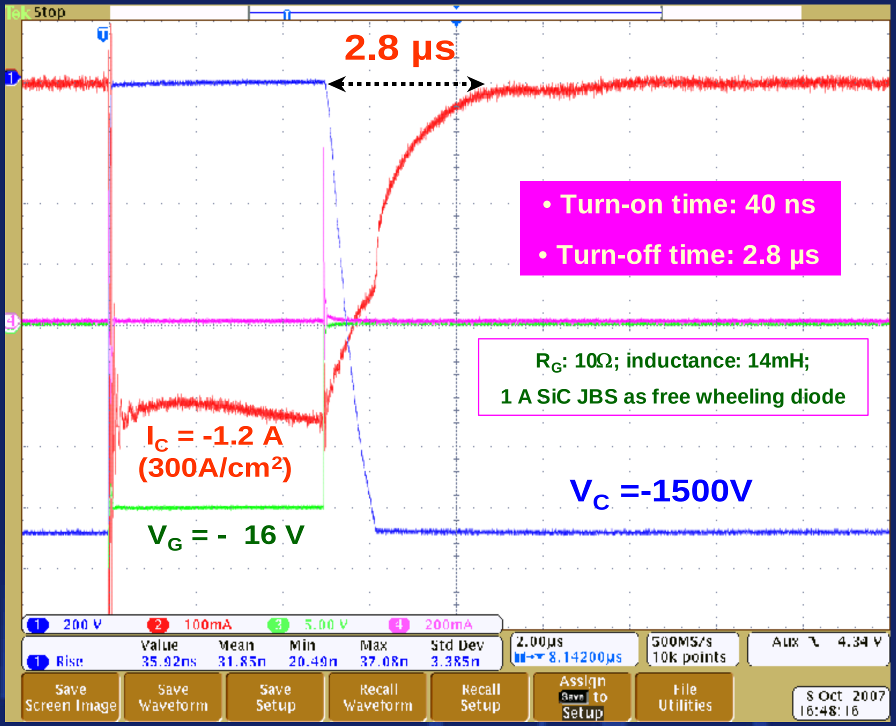
12 kV SiC p-IGBT Reverse Blocking Characteristics @ 25°C

- **12kV SiC p-IGBTs Demonstrated From 25°C to 200°C**
  - **12kV SiC p-IGBT V_f and Current Maintained From 25°C to 200°C**
  - **⇒ Reduced Conduction Losses from 25°C up to 200°C**
- **SiC IGBTs Offer Advantages over SiC DMOSFETs at Blocking Voltages > 10kV**

Comparison 12kV SiC p-IGBTs and Si IGBTs

12 kV SiC n-IGBT & p-IGBT Forward Characteristics



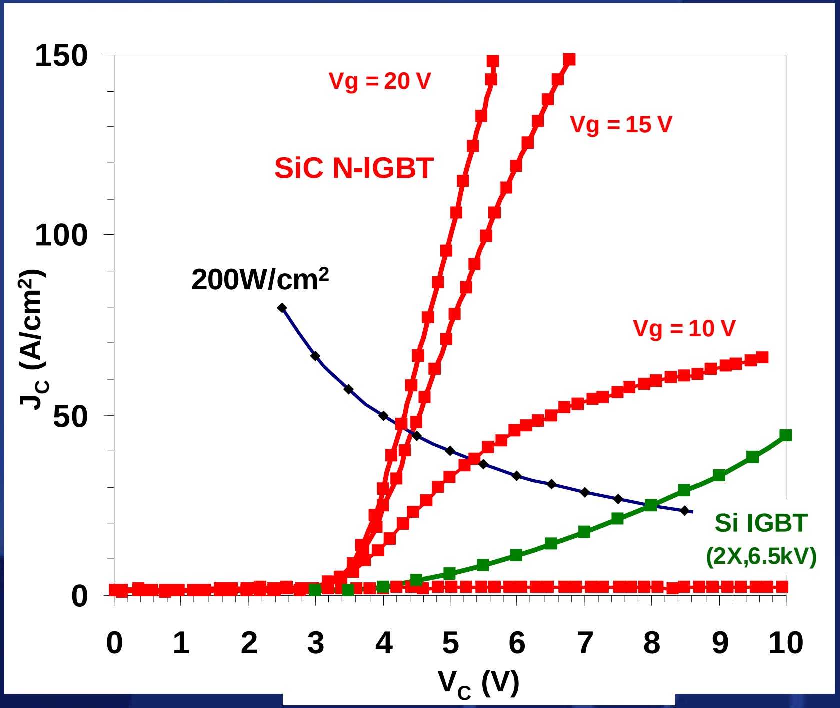


	Value	Mean	Min	Max	Std Dev
1 Rise	35.92ns	31.85n	20.49n	37.08n	3.385n

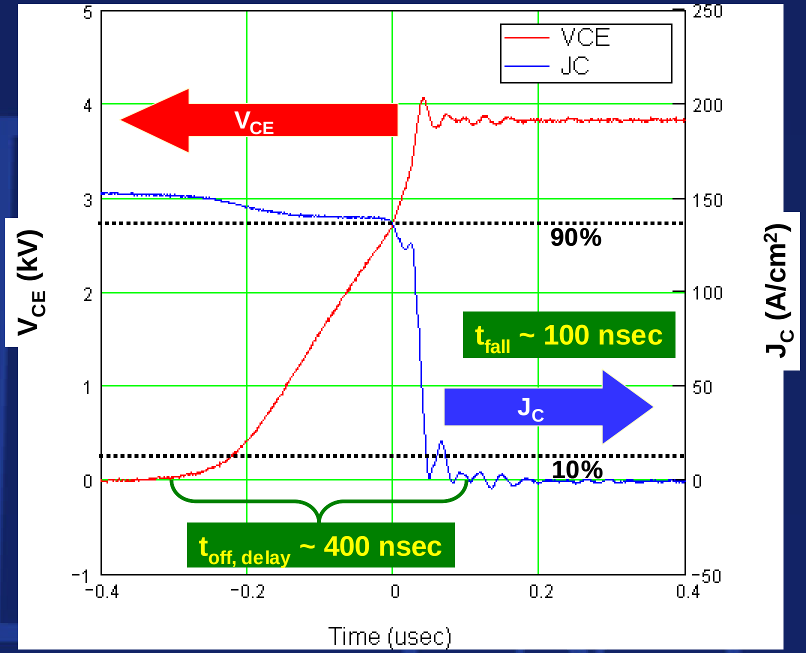
12kV SiC p-IGBT Switching Measurement

- **SiC IGBTs Are Superior to Si IGBTs at Higher Voltages**
  - **Much Lower Forward Voltage (V_F) & Higher Current Rating for Given Blocking Voltage**
  - **Dramatic Increase in Switching Speed – 12 kV SiC p-IGBT Turn-Off Time < 3 µs**

Comparison of SiC n-IGBTs and Si IGBTs



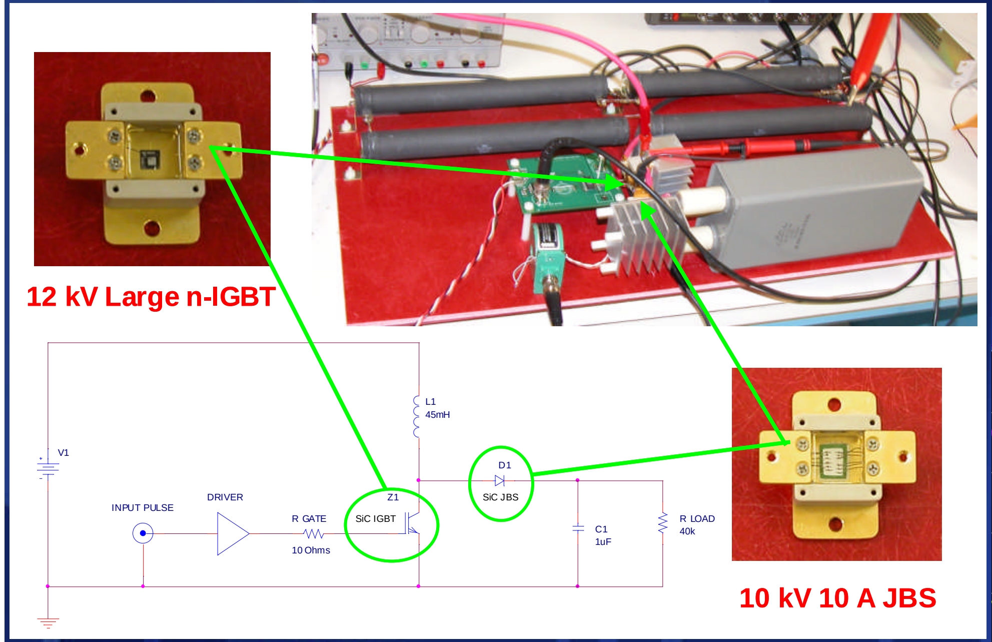
12kV SiC n-IGBT Switching Measurement



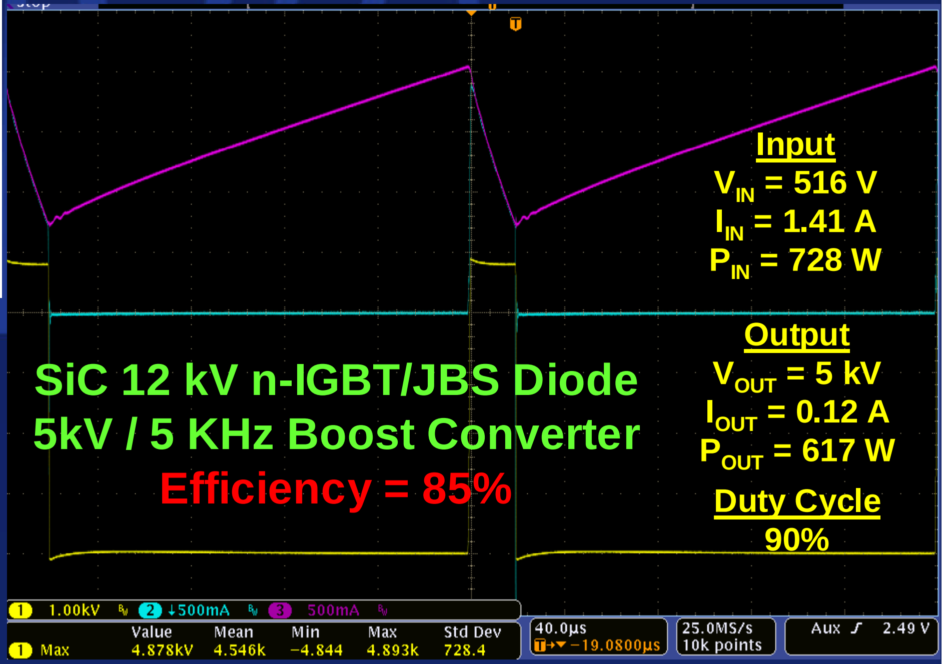
- SiC IGBTs Are Superior to Si IGBTs at Higher Voltages
  - 12kV SiC n-IGBTs Have >3x Lower $R_{on,sp}$ Than 6.5kV Si IGBTs
  - SiC n-IGBTs Have Much Lower Forward Voltage (V_F) & Higher Current Than Si IGBTs at Same BV
  - 12kV SiC n-IGBTs Have 4x Faster Switching Speed and >4x Lower Switching Loss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

12kV SiC n-IGBTs Boost Converter

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



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



```
     Value    Mean    Min     Max     Std Dev
1 Max 4.878kV  4.546k  −4.844  4.893k  728.4
```

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%

Its Time for SiC Power Technology!

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

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