Advanced SiC Power Technology for High Megawatt Power Conditioning

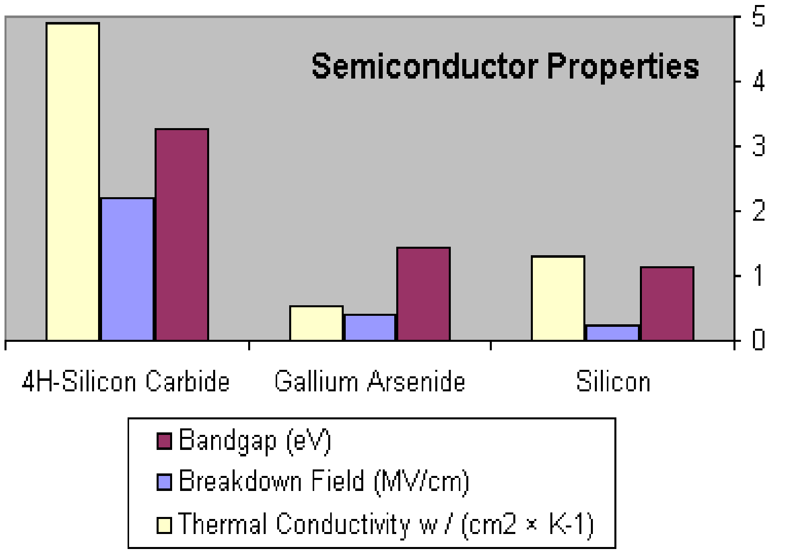
David Grider, Anant Agarwal, Sei-Hyung Ryu, Lin Cheng, Craig Capell, Charlotte Jonas, Al Burk, Michael O'Loughlin, Mrinal Das, John Palmour

Cree, Inc.

May 24, 2012

Why SiC Power?
SiC's Material Difference

- **10X Breakdown Field of Si**
  - Lower specific on-resistance and faster switching for the same breakdown voltage
- **3X Thermal Conductivity of Si**
  - Higher current densities
- **3X Bandgap of Si**
  - Higher temperature operation



For more than 60 years, silicon has been the "go-to" material for power semiconductors.

But in terms of delivering additional efficiency, silicon is nearing its limit.

{ Thank you silicon—we'll take it from here. }

Silicon Carbide is the most efficient and highest reliability power semiconductor material in the world today

—and it will power our future.

MOTOR & MOTION CONTROL SOLAR TRACTION WIND ENERGY SERVERS AND MANY MORE

Cree Commercial SiC Power Product Portfolio

ZERO RECOVERY™ Rectifier Product Family

600V Z-Rec SiC JBS Diodes
1, 2, 3, 4, 6, 8, 10 & 20

650V Z-Rec SiC JBS Diodes
4, 6, 8, 10 & 20A

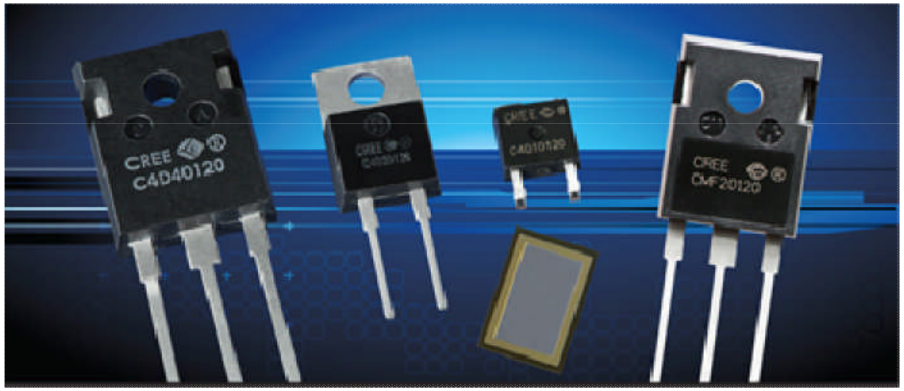
New! Z-Rec 1200V SiC JBS Diodes
2, 5, 7.5, 10, 15, 20, 30 & 40A

1200V SiC JBS Diodes
5, 10, 20 & 50A

1700V Z-Rec SiC JBS Diodes
10 & 25A

The Z-FET™ MOSFET Product Family

1200V SiC DMOSFET
80mΩ & 160mΩ available today



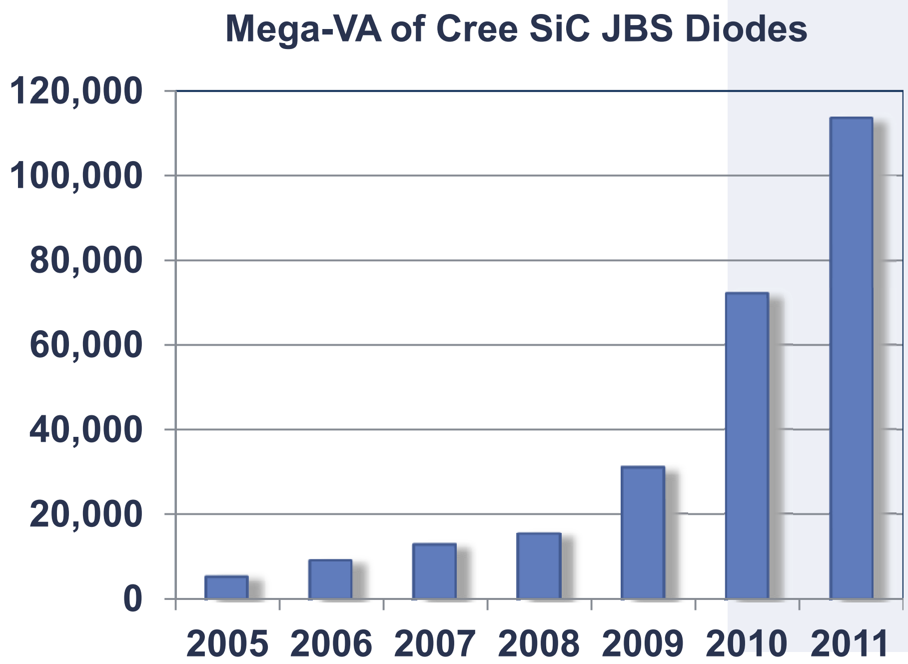
Packages

THROUGH HOLE: TO-247 TO-220,
Fully molded TO-220,
SMT: TO-252 (D-Pak), TO-263 (D^2-Pak)

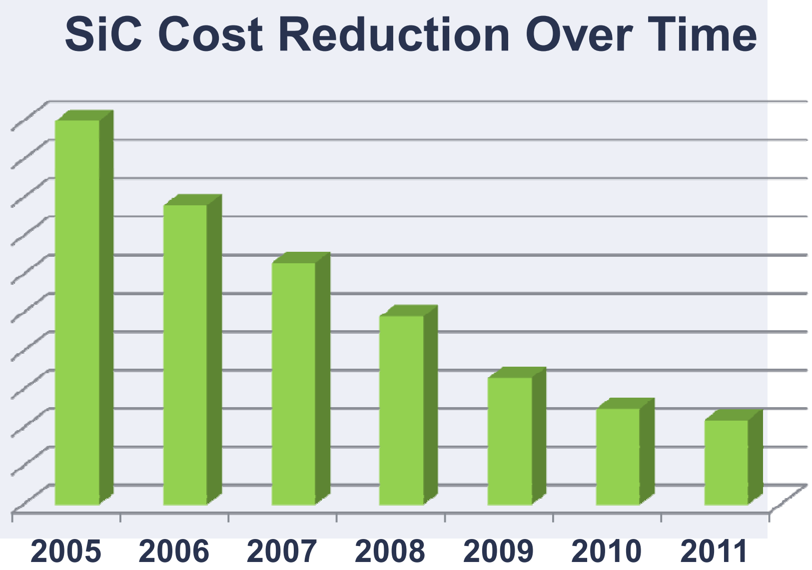
CREE

Cree Commercial JBS Diode Production

- In FY2011 Cree Shipped >113 GVA
  - 61% Increase Over 2010
  - 66% CAGR Since 2005



- Over 5x Cost Reduction Result of 3 Factors
  - Higher Quality SiC Material
  - Larger Production Volumes
  - SiC Wafer Size Increased From 3 inch to 100 mm Diameter



Industry-Lowest Field Failure Rate of Cree SiC JBS Diodes

Cree Field Failure Rate Data since Jan. 2004

Product	Device Hours	FIT (fails/billion hrs)
CSDxxx60	205,000,000,000	0.16
C3Dxxx60	81,000,000,000	0.09
C2Dxx120	46,000,000,000	1.35
Total	**332,000,000,000**	**0.31**

- **This rate is 10 times lower than the typical silicon**

330 billion device hours in the field with an industry-leading FIT rate of only 0.31

Z-FET™

Industry's First SiC MOSFET Available in Volume Production

CMF20120D-Silicon Carbide Power MOSFET

Z-FET™ MOSFET

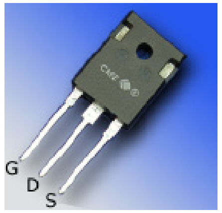
N-Channel Enhancement Mode

V_{DS}	= 1200 V
$R_{DS(on)}$	= 80 mΩ
$I_{D(MAX)}$ @ T_c=25°C	= 33 A

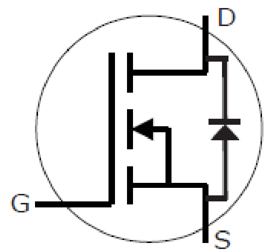
Features

- Industry Leading $R_{DS(on)}$
- High Speed Switching
- Low Capacitances
- Easy to Parallel
- Simple to Drive
- Pb-Free Plating, RoHS Compliant, Halogen Free

Package



TO-247-3



Benefits

- Higher System Efficiency
- Reduced Cooling Requirements
- Avalanche Ruggedness
- Increased System Switching Frequency

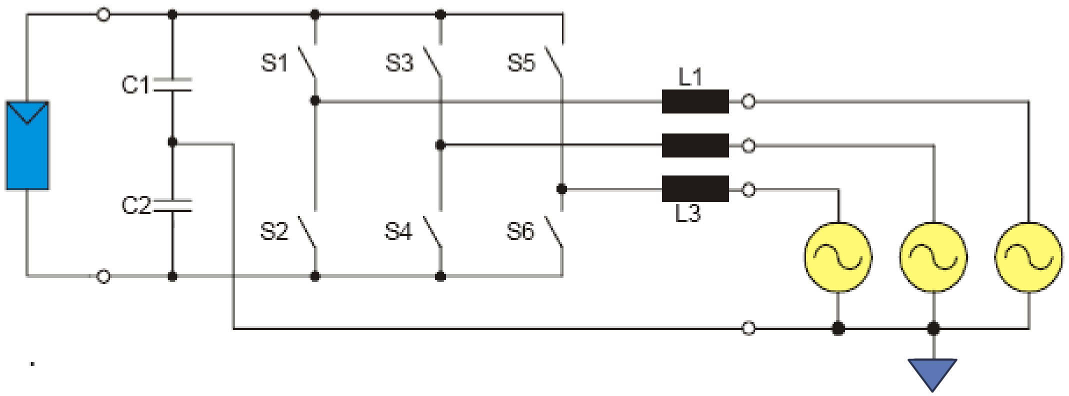
Part Number	Package
CMF20120D	TO-247-3

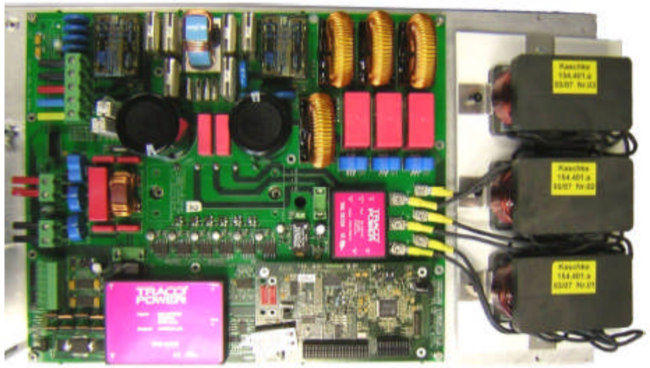
Applications

- Solar Inverters
- High Voltage DC/DC Converters
- Motor Drives

Avalanche Energy = 2.2 J

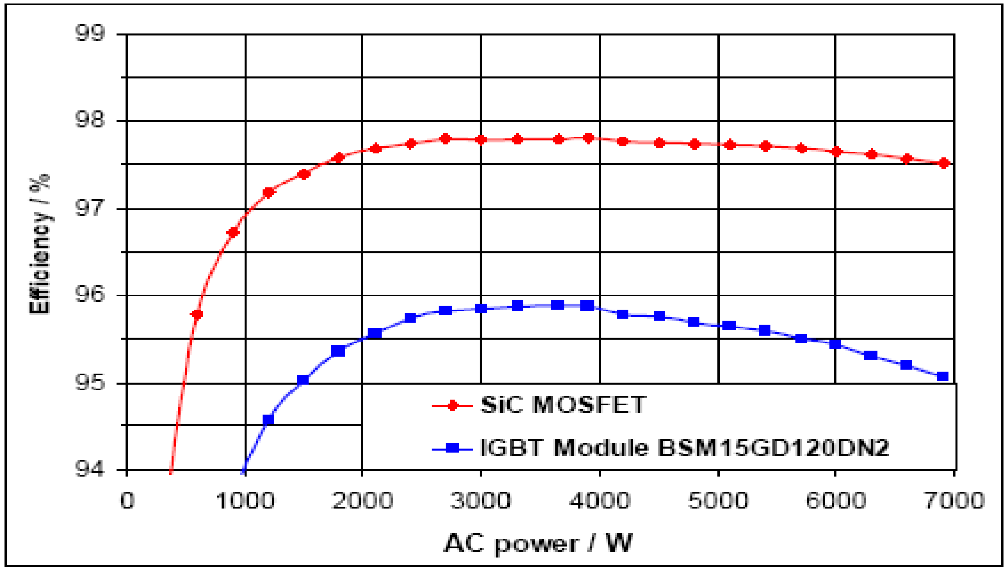
Solar Inverter Example Using 1200 V/20A SiC MOSFETs





7kW 750V DC link 3-Phase Solar Inverter

(Fraunhofer Institute, Freiberg Germany)



~ 2% Efficiency Improvement vs. Si IGBT

Record PV efficiency since demonstrated at 99.05% with SiC power devices

1200V SiC MOSFET Results in Dramatic Improvement in APEI All-SiC Inverter

Actual Size Comparison

Heat Sink

28”

Characteristics	Commercial Si Inverter	APEI, Inc. SiC Inverter	Comparison
Power	5 kW	5 kW	Same
Cooling	Free Air Convection	Free Air Convection	Same
Peak Efficiency @ Pk Power	95.50%	96.75%	APEI increased efficiency 1.25%
Power Loss	205 watts	162 watts	APEI reduces losses 27%
Size	28.5" x 16" x 5.75"	4.5" x 9" x 9"	APEI > 7x smaller volume
Volume	2,622 cubic inches	365 cubic inches	APEI > 7x smaller volume
Mass	58 lbs.	7.25 lbs.	APEI > 8x lighter
Pk Temperature Capability	< 125 °C	> 225 °C	APEI 2x temperature capability

14”

Heat Sink

7”

Commercial Si Inverter

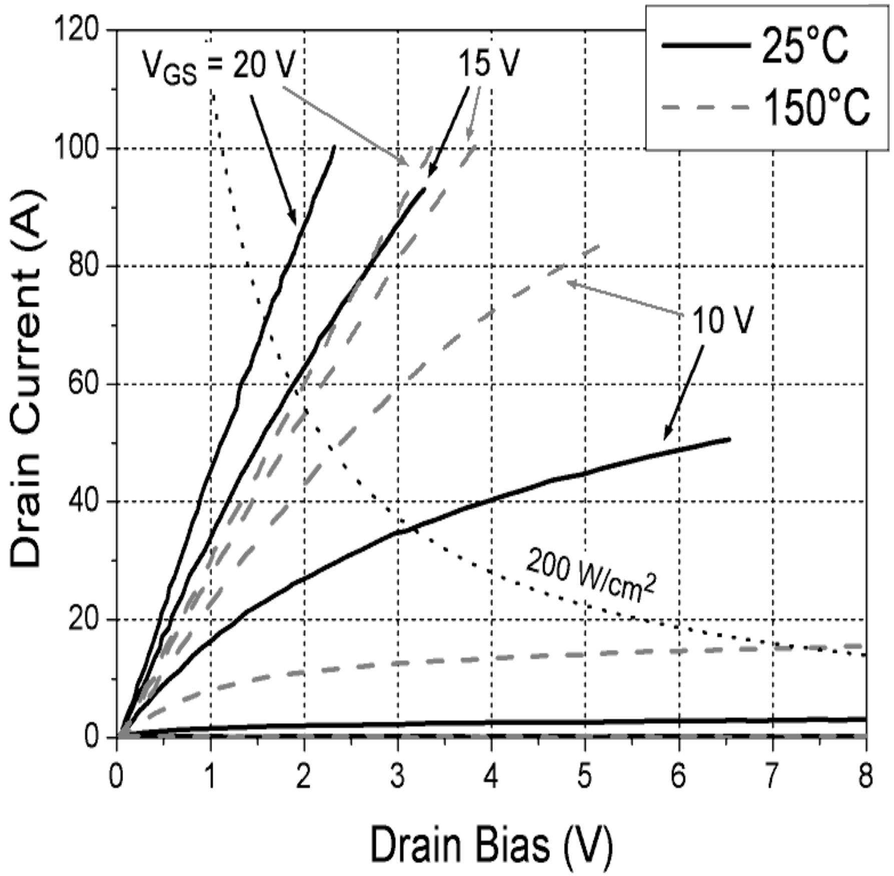
APEI, Inc. SiC Inverter

All-SiC inverter
- operates at 225C
- 7x smaller
- 8x lighter
- has 27% lower losses

1200V Gen2 SiC DMOSFET With Dramatically Reduced On-Resistance

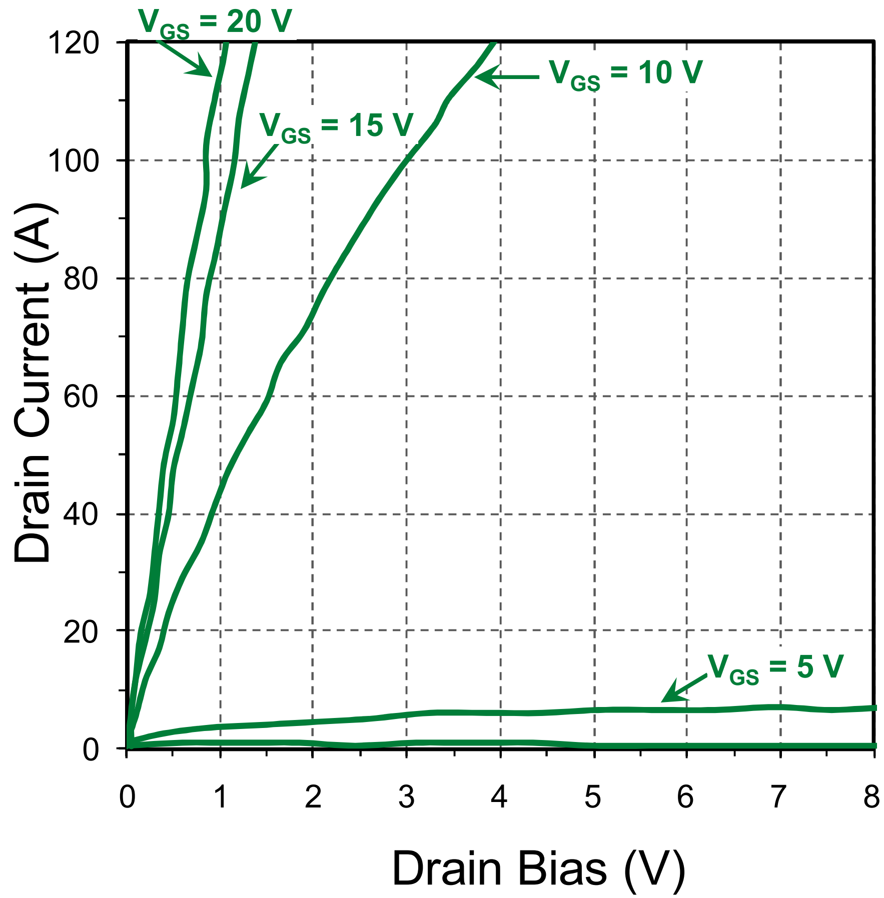
Forward I-V characteristics

1200 V Gen1 SiC DMOSFET



$R_{sp,on}$ = 9.0 mΩ-cm² at V_{GS} = 20V

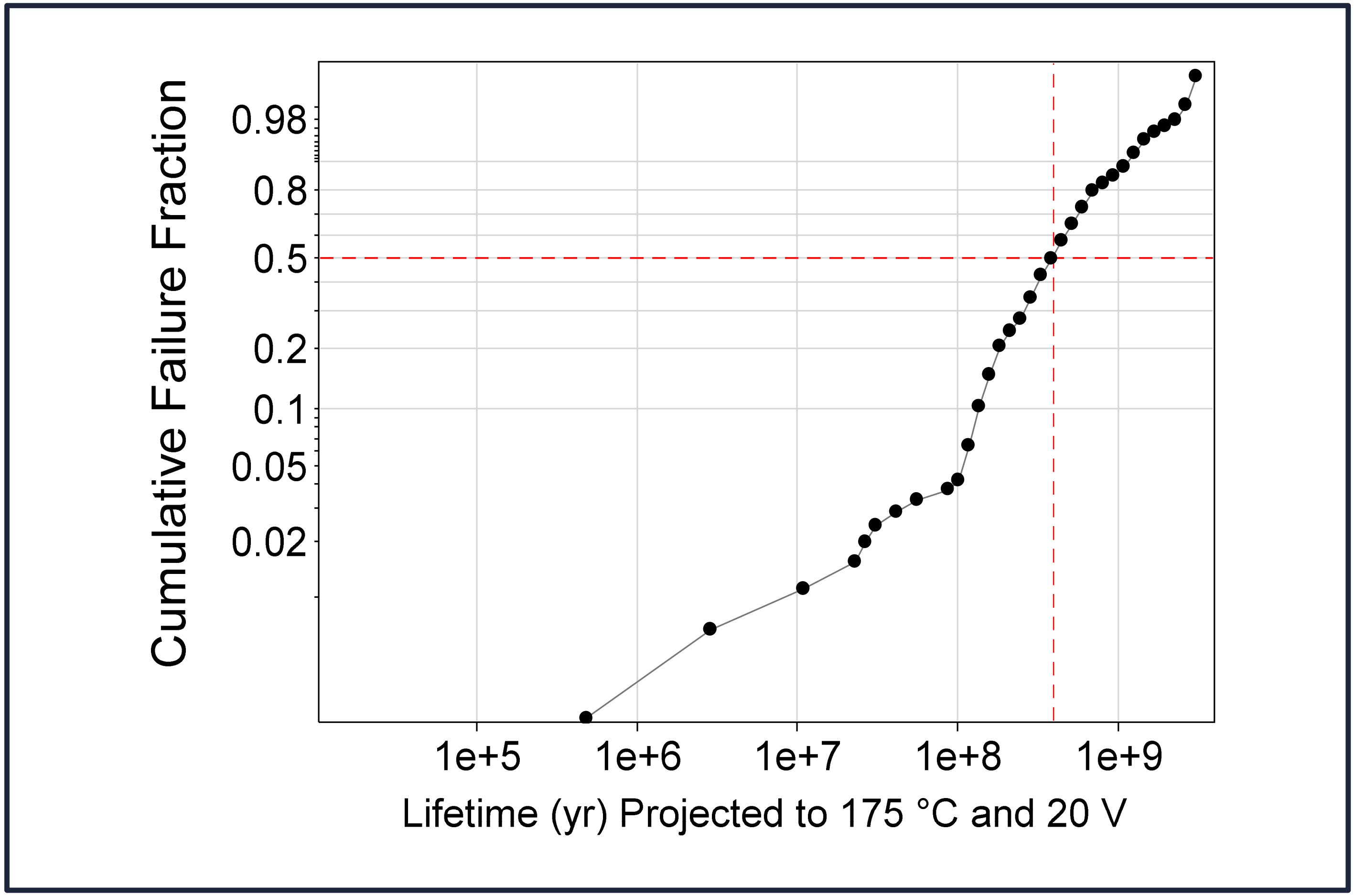
1200 V Gen2 SiC DMOSFET



$R_{sp,on}$ = 3.6 mΩ-cm² at V_{GS} = 20V

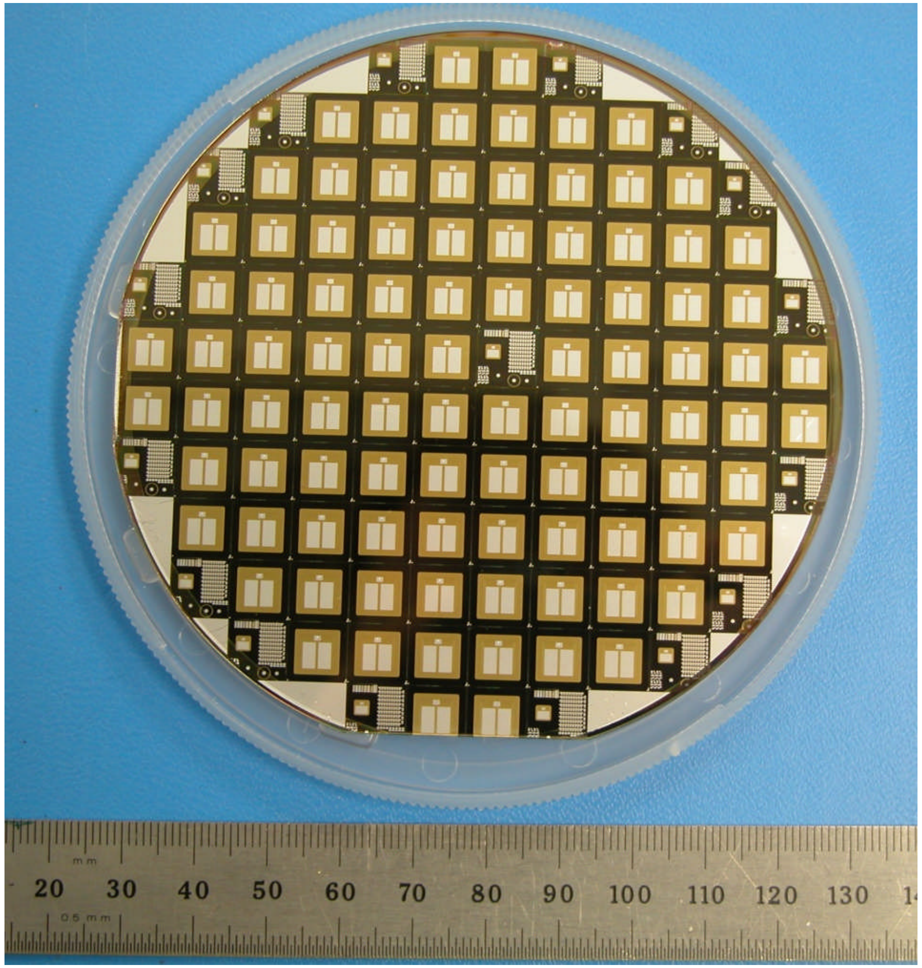
Reliability of Cree's SiC Gate Oxide for SiC MOSFETs

Ramped TDDB at 175°C

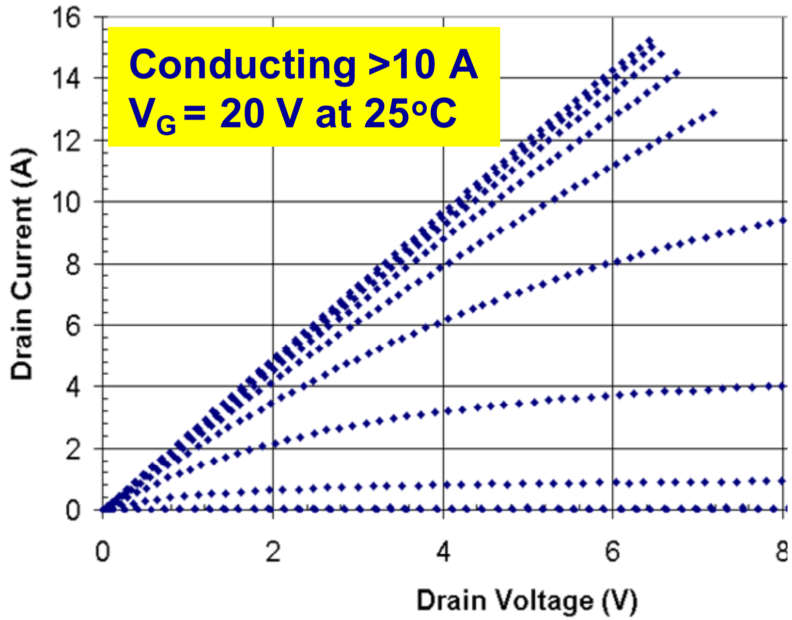


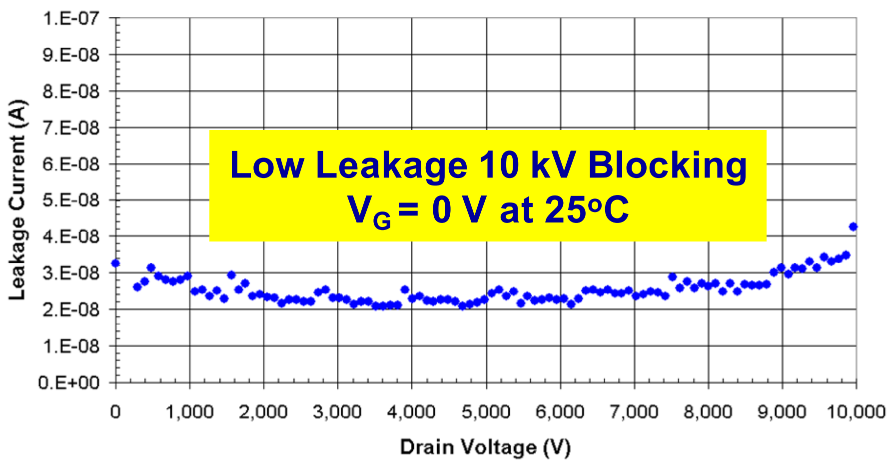
- **Projects to a MTTF of ~ 400 million years for SiC MOS capacitors at V_{GS} = 20 V gate bias**

10 kV/10 A SiC DMOSFETs Developed Under DARPA/ONR HPE Program

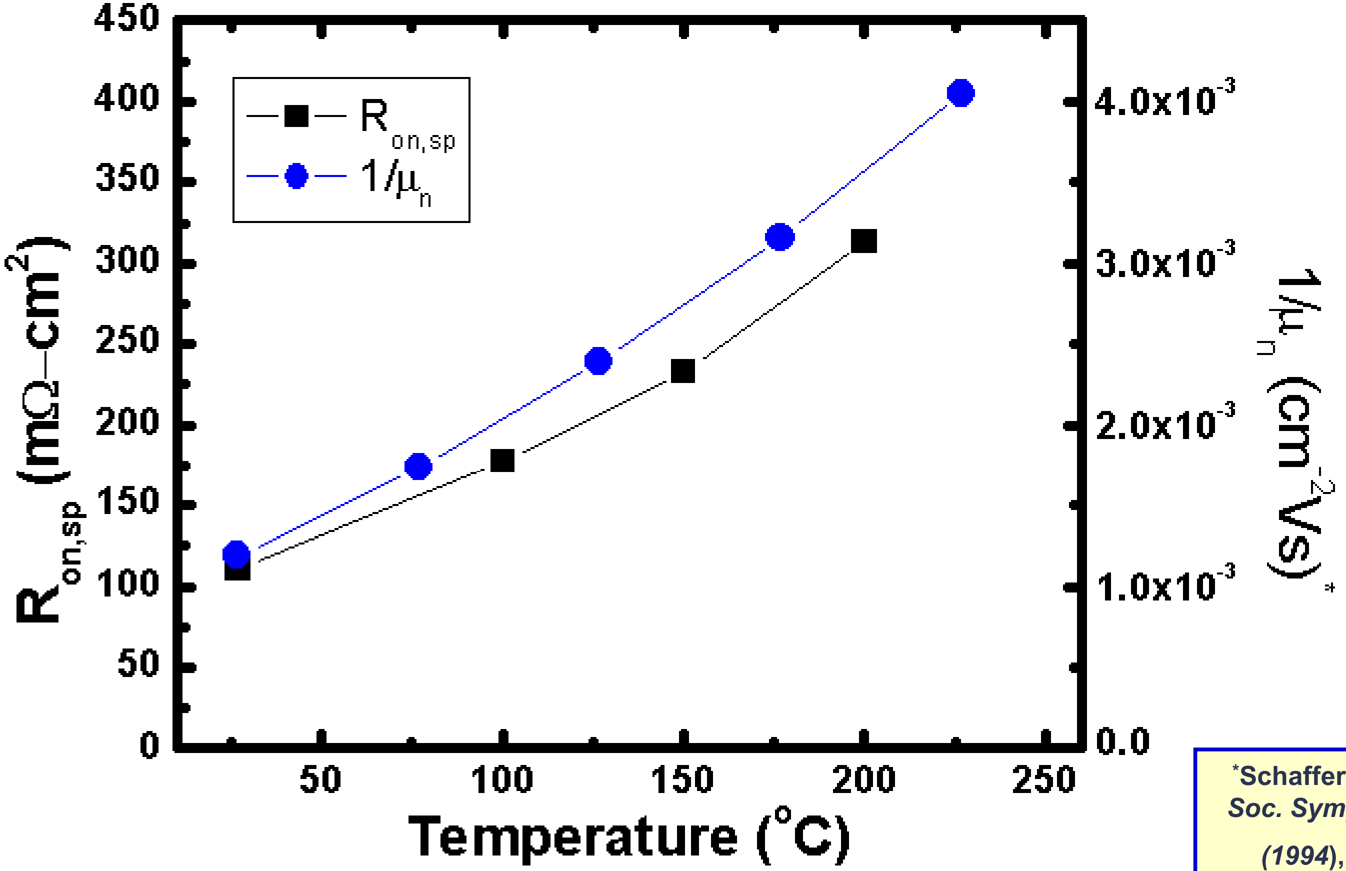


10 kV/10 A SiC DMOSFETs
Fabricated on 100 mm 4HN-SiC Wafer





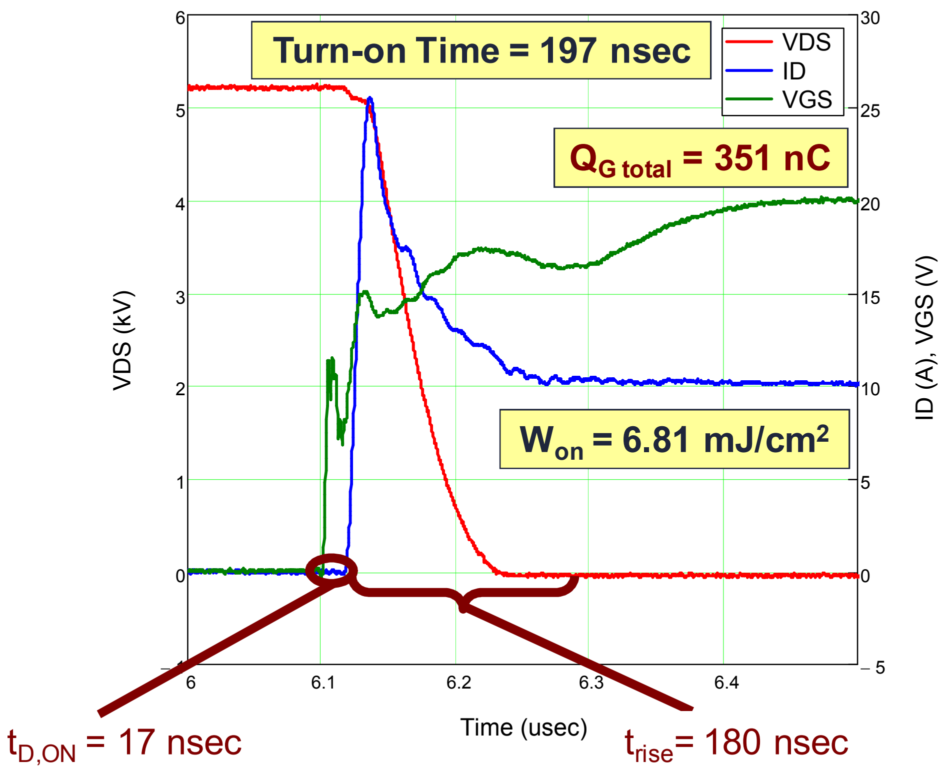
10kV/10A SiC DMOSFET On-Resistance vs. Temperature - Means Good Current Sharing Between Devices in Parallel



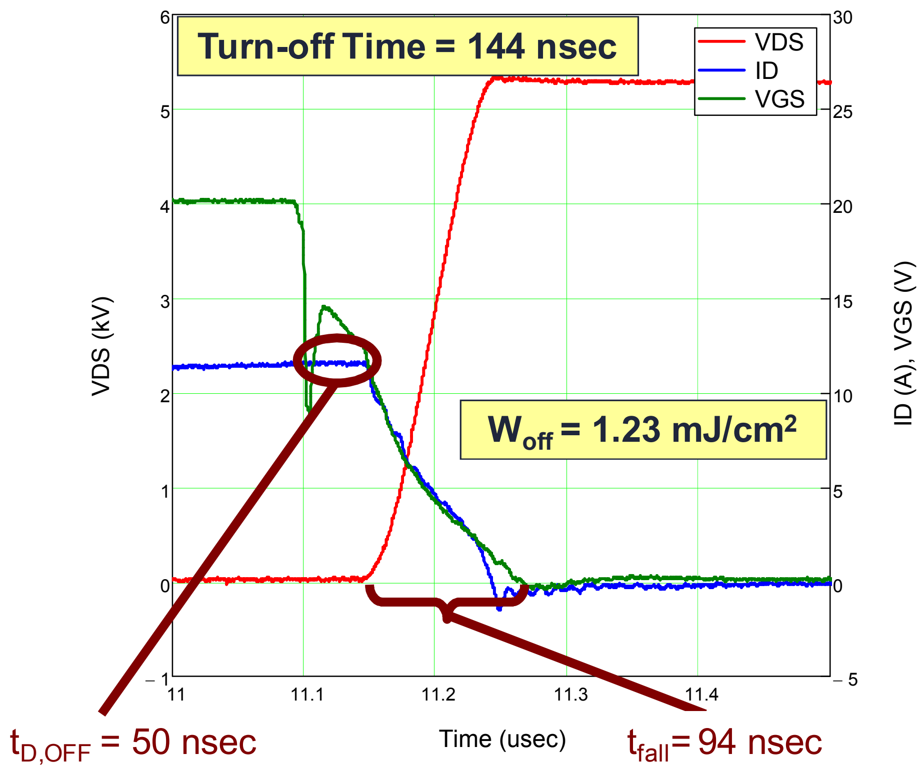
*Schaffer et al., *Mat. Res. Soc. Symp. Proc. Vol. 339 (1994)*, pp. 595 – 600

$R_{on,sp}$ increases about 3x with a temperature increase to 200°C
Increase dominated by drift layer resistance

10 kV/10 A SiC DMOSFET Clamped Inductive Switching



10 kV/10 A SiC DMOSFET Turn-On Waveform



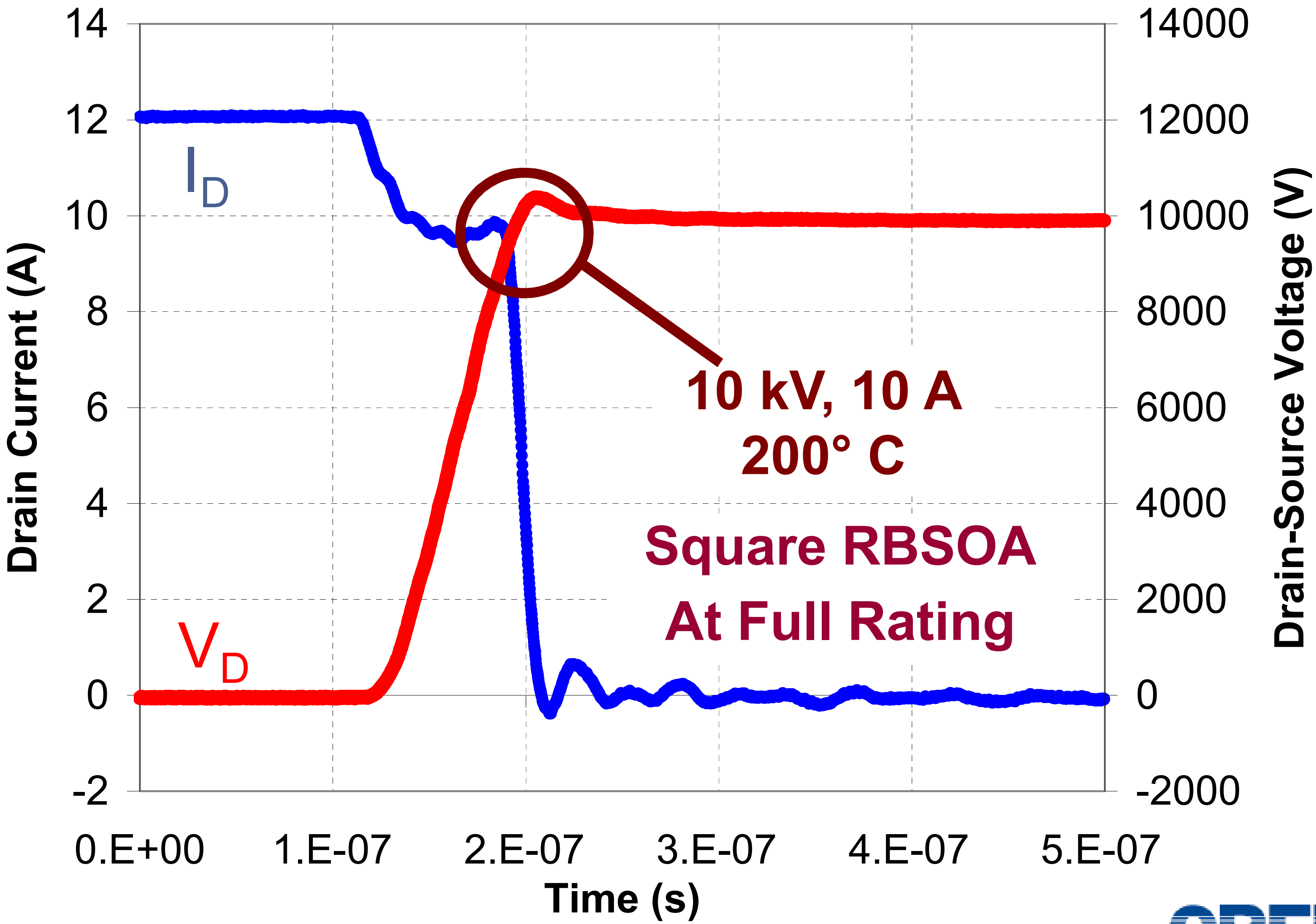
10 kV/10 A SiC DMOSFET Turn-Off Waveform

Power Loss Comparison Between SiC 10 kV Switches and Si IGBTs

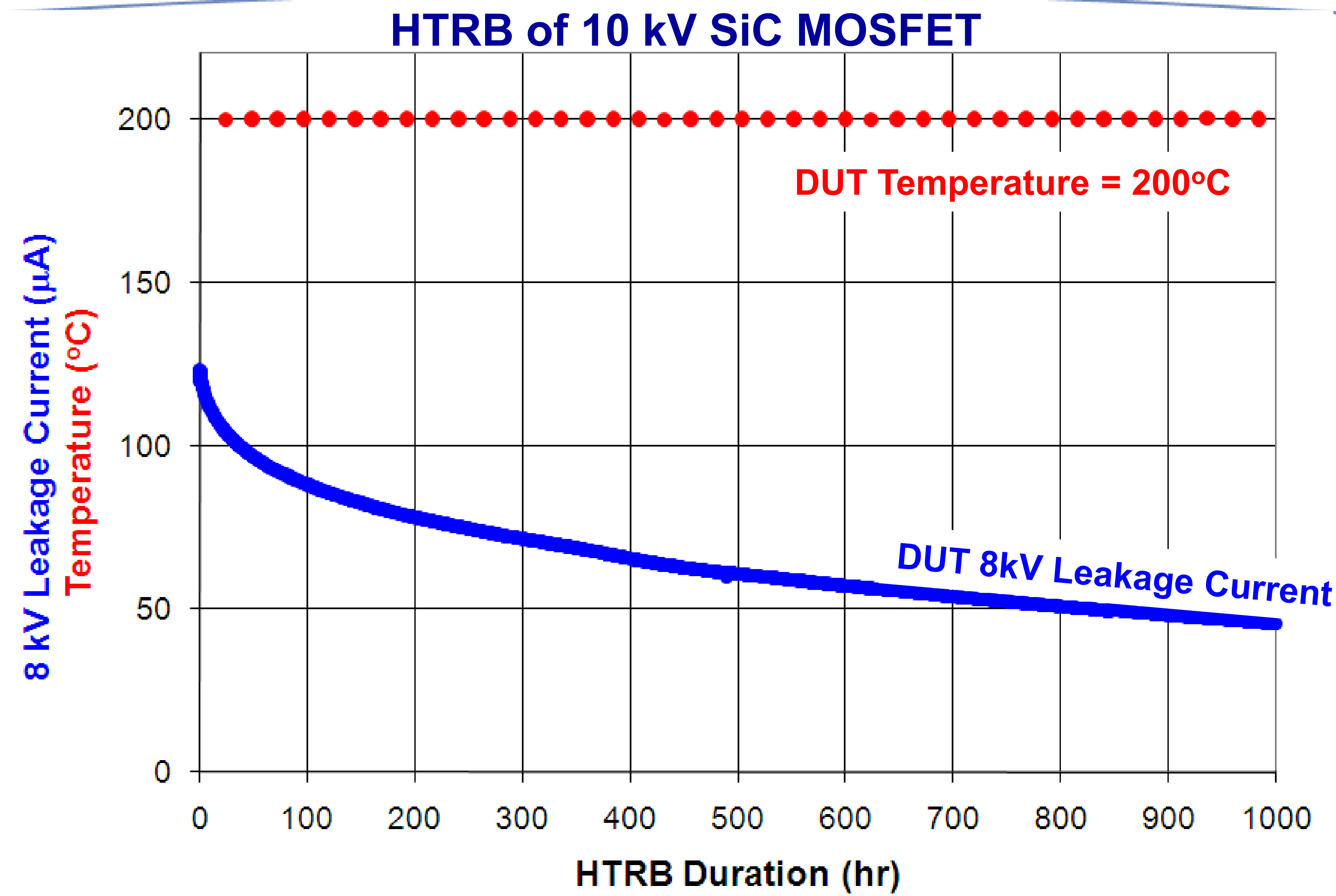
Device	BV (kV)	500 Hz 5 kV $P_{sw,sp}$ (W/cm²)	5 kHz 5 kV $P_{sw,sp}$ (W/cm²)	20 kHz 5 kV $P_{sw,sp}$ (W/cm²)	33 A/cm² 50% Duty 100°C $P_{cond,sp}$ (W/cm²)
Cree SiC DMOSFET	10	4	40	160	100
Cree SiC n-IGBT	12	6.5	65	260	66
ABB Si IGBT 5SMX 12M6500	2x 6.5	72.5	725	2900	182

Excellent Reverse Bias Safe Operating Area For 10 kV/10 A SiC DMOSFET

Courtesy: Dr. Allen Hefner, NIST

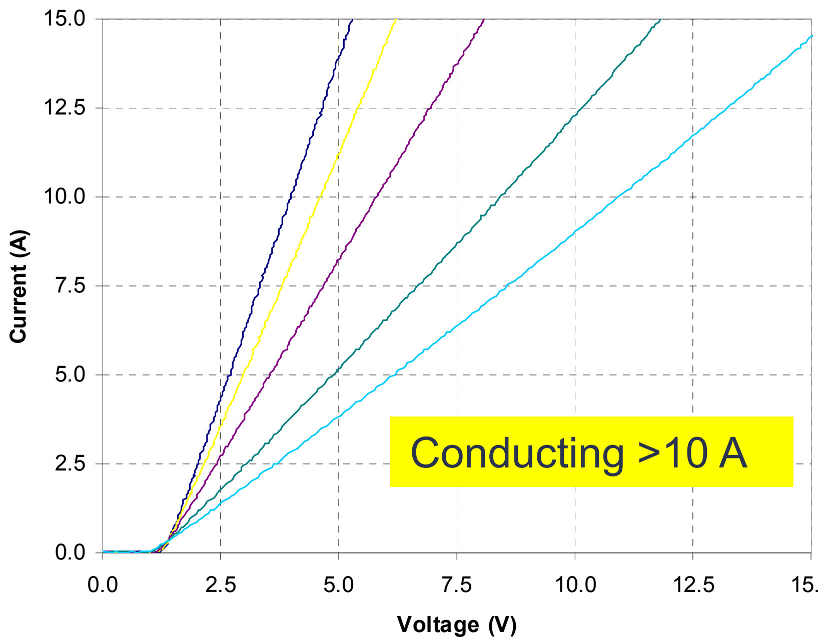


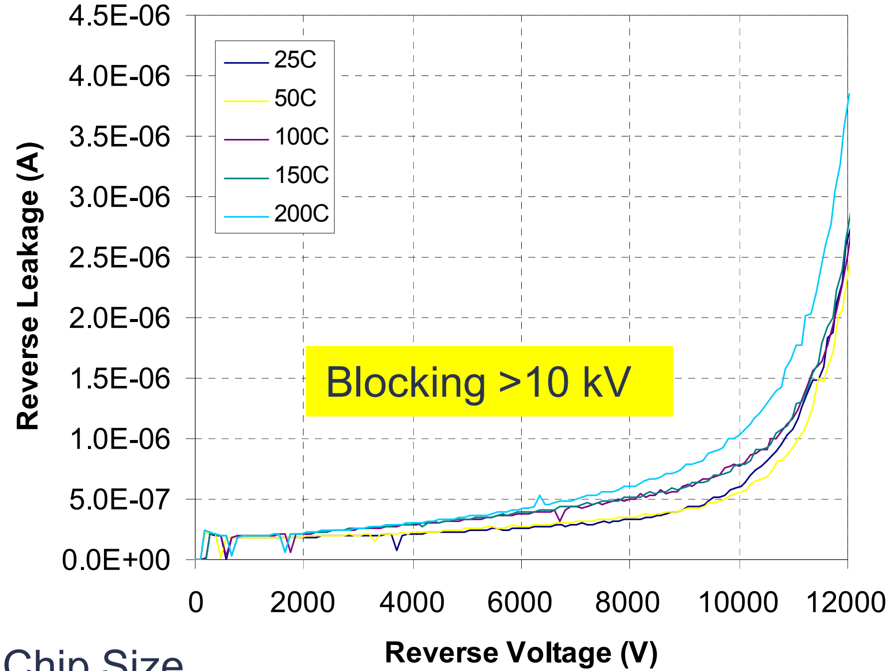
Off-State Blocking Reliability Of 10 kV SiC DMOSFET

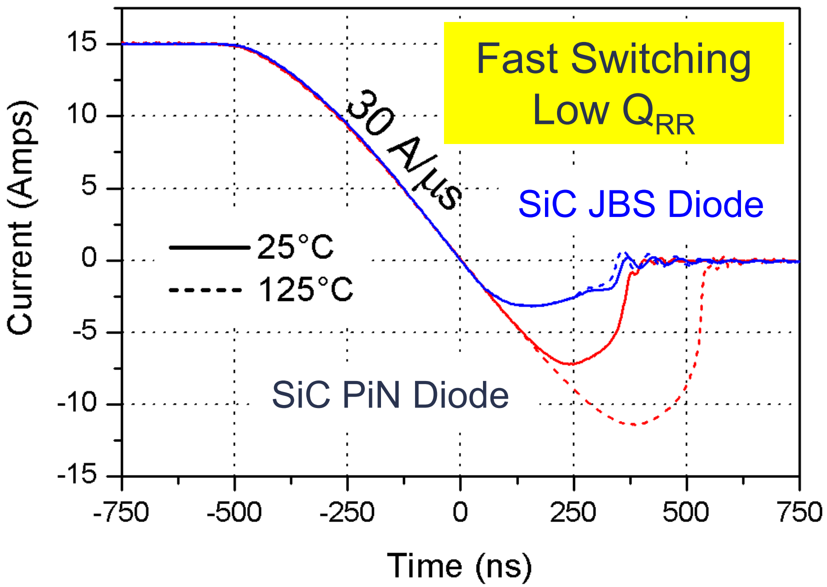


Courtesy of Penn State EOC
Prof. Joe Flemish & Mike Horgan

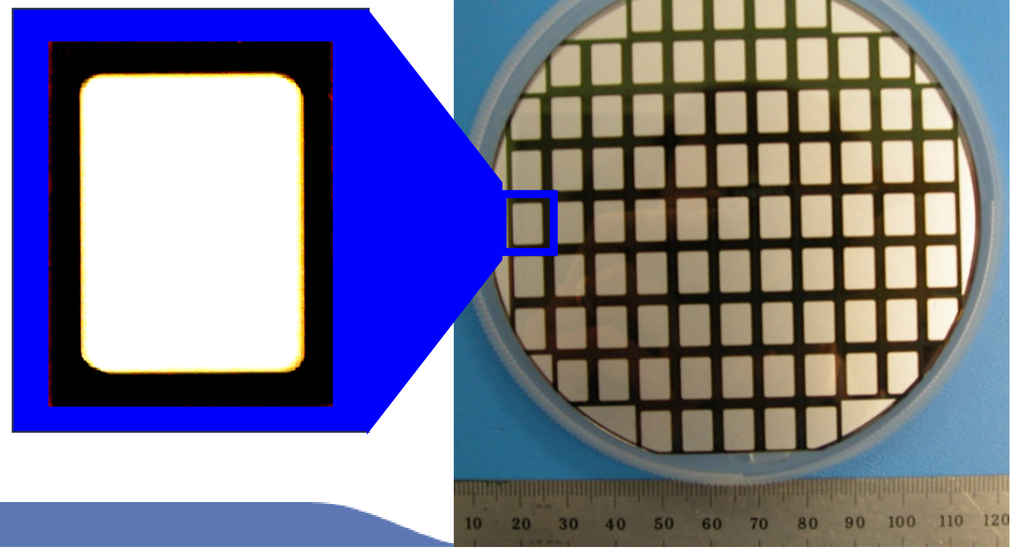
Highest Voltage Schottky Diode
10 kV/10 A SiC Junction Barrier Schottky Diodes





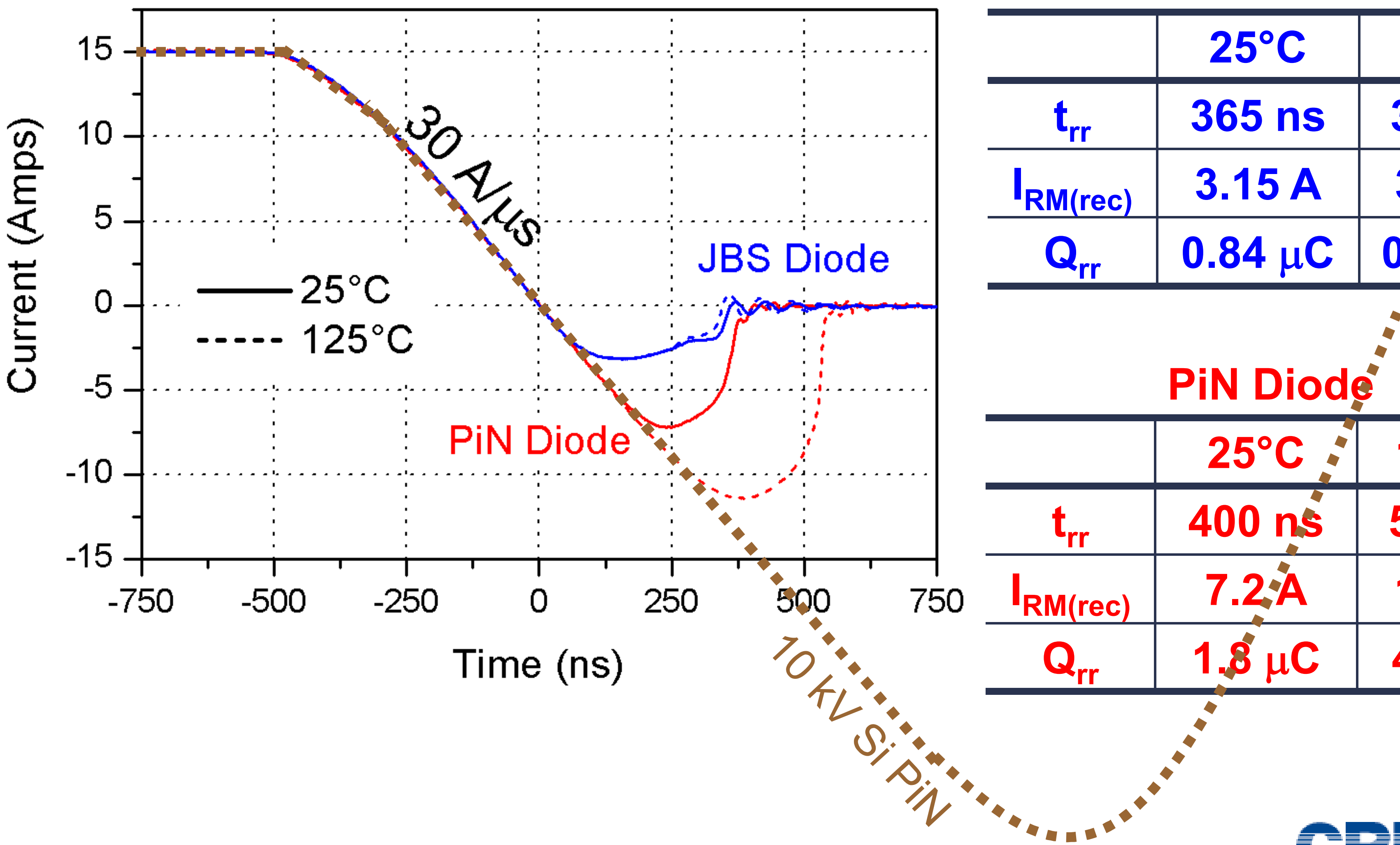


Chip Size
10.6 mm x 8.3 mm



10 kV/10 A SiC JBS Diode Switching

Inductive Switching Characteristics



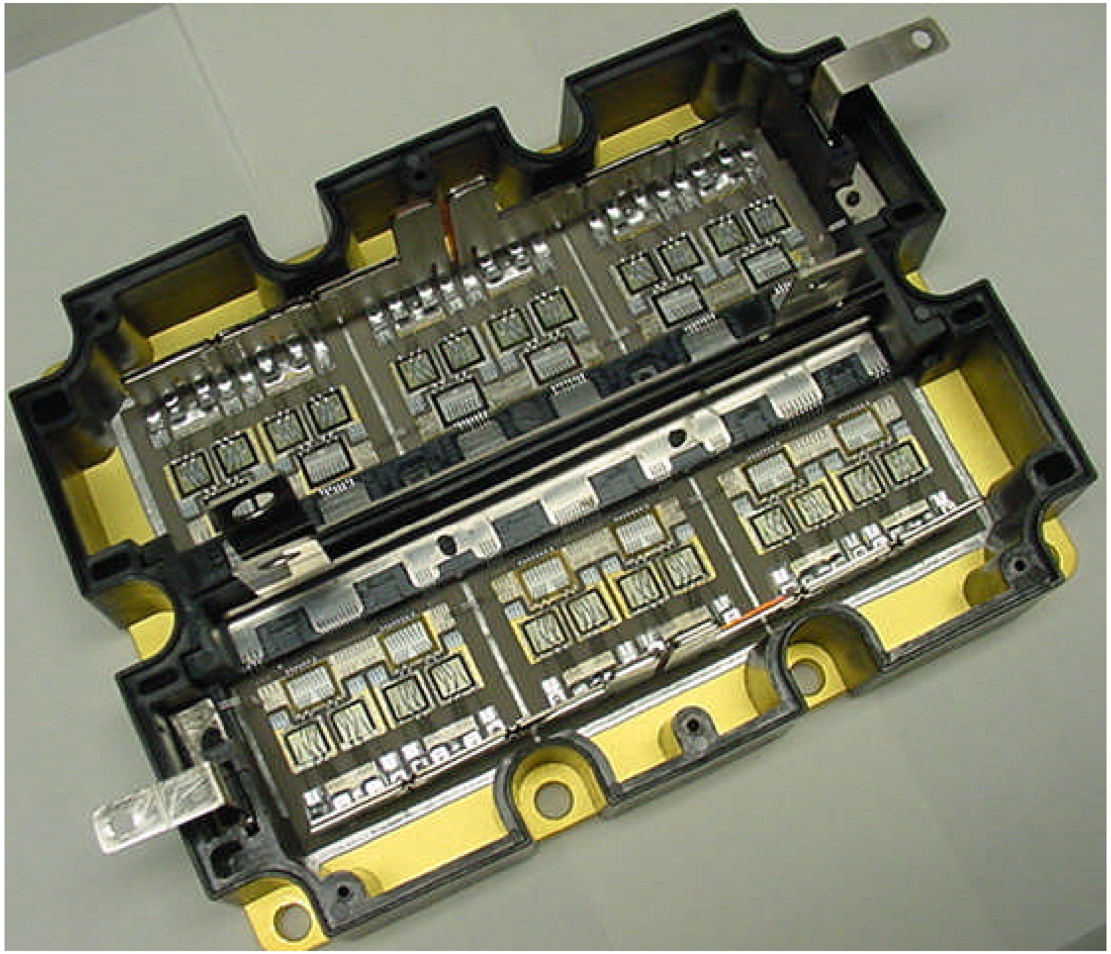
JBS Diode

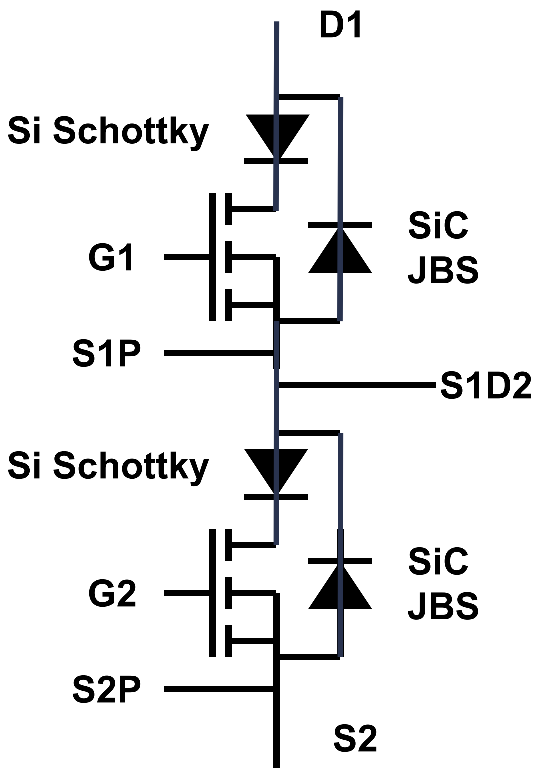
	25°C	125°C
t_{rr}	365 ns	350 ns
$I_{RM(rec)}$	3.15 A	3.15 A
Q_{rr}	0.84 µC	0.79 µC

PiN Diode

	25°C	125°C
t_{rr}	400 ns	550 ns
$I_{RM(rec)}$	7.2 A	11.4 A
Q_{rr}	1.8 µC	4.0 µC

10kV/120A SiC DMOSFET - JBS Diode
Half H-Bridge Module Capable of 20 kHz Operation





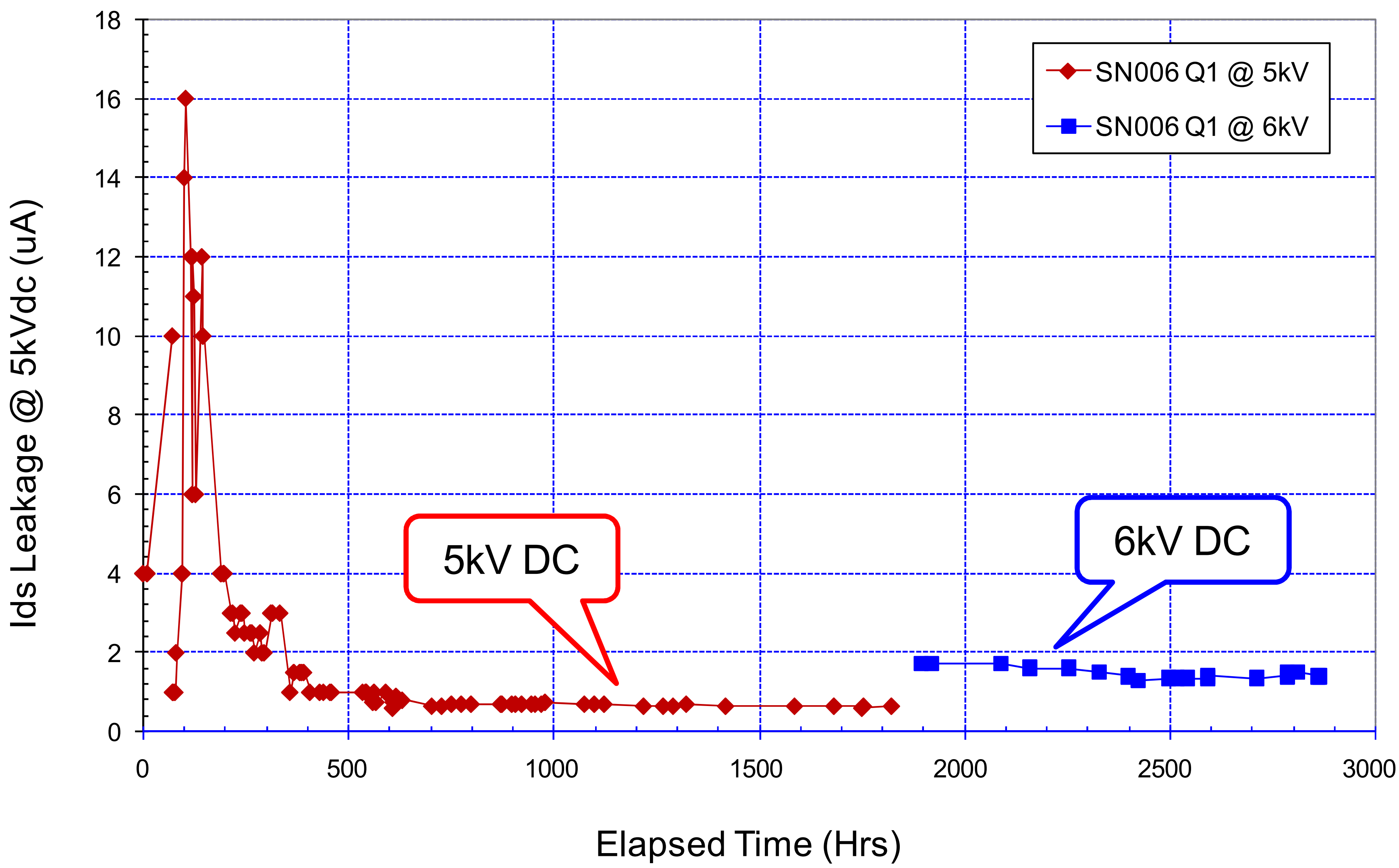
Each switch comprised of 12 paralleled 10kV/10A SiC DMOSFETs

Each rectifier comprised of 6 paralleled 10kV/10A SiC JBS Diodes

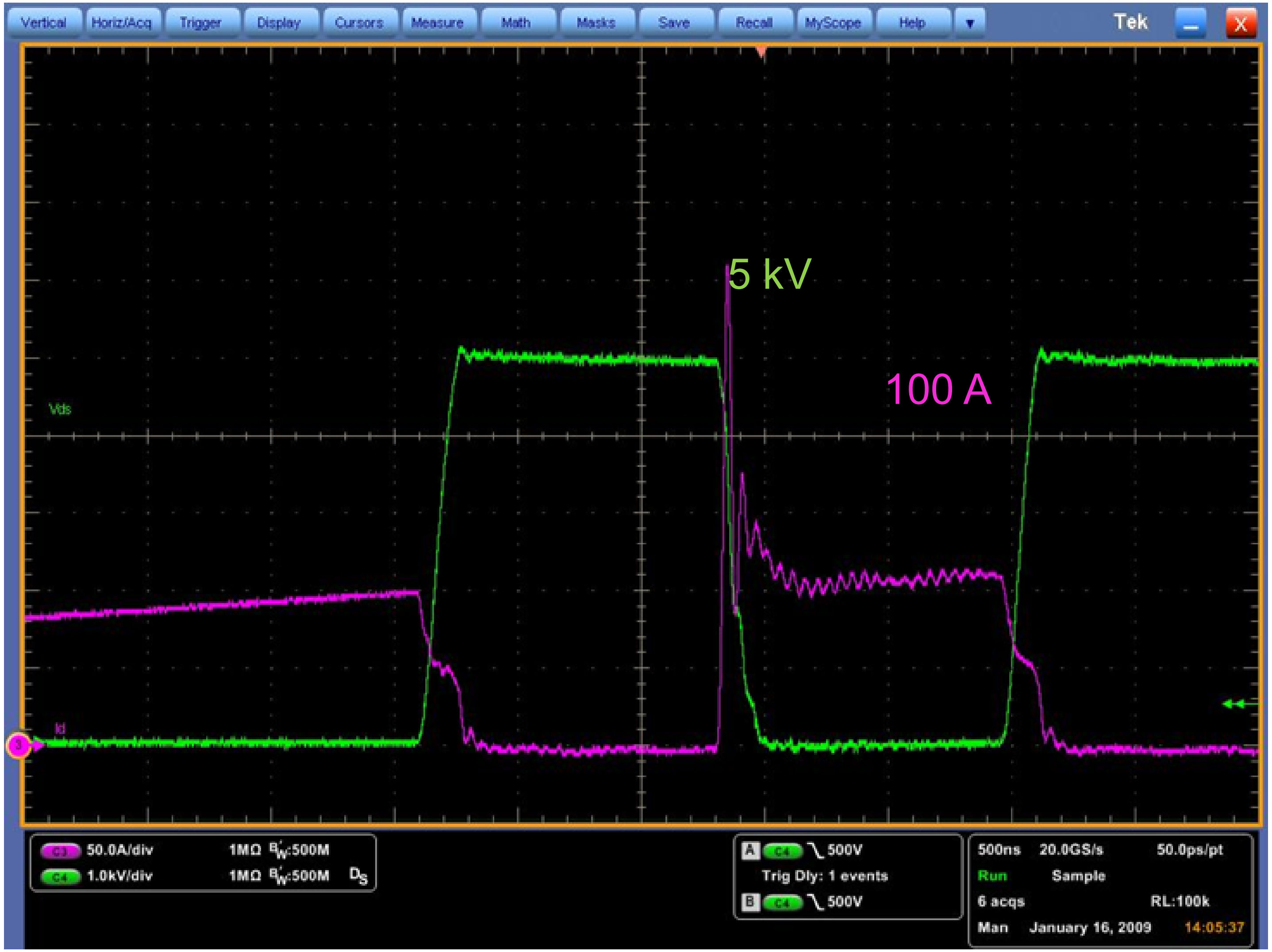
Series Si Schottky to bypass SiC DMOSFET body diode

HPE III 10 kV/120 A Half H-Bridge Module

Static HTRB Verifies High Voltage Capability



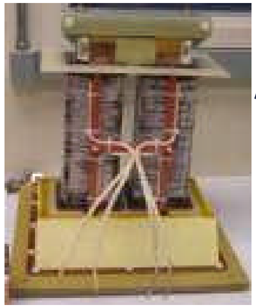
10 kV, 120 A SiC Half H-Bridge Module Switching Waveforms

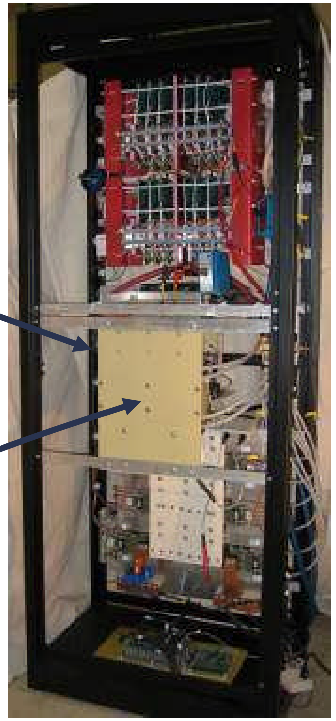


4 Stage - Single Phase (13.8 kV AC to 465/√3 V AC) SSPS Demonstratrated by GE and Tested at NSWC

One Stage AC-AC Building Block

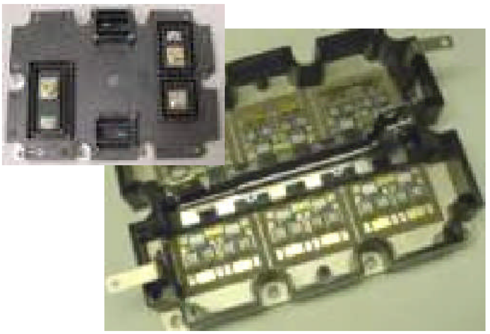
HF transformer





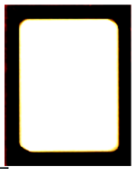
x 4

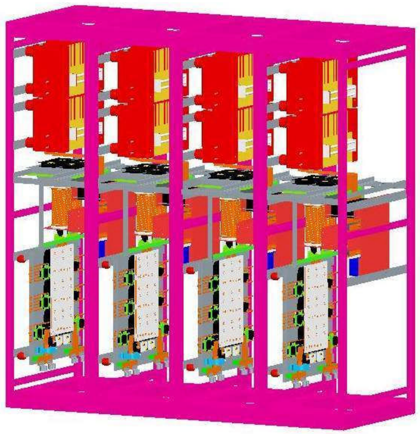
SSPS installed for testing at NSWC, Philadelphia (picture courtesy of NSWC & GE)



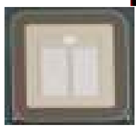
10 kV SiC Module

10 kV SiC JBS





10 kV SiC DMOSFET



Single Phase 1 MVA SSPS

Stacks tested to full power at GE

imagination at work

POWEREX

CREE

Dramatic Reduction in SiC Module Size and Weight In 13.8 kV AC to 465/√3 V AC SSPS

SiC 10 kV Modules are 9% of the Weight and 12% of the Volume of Si IGBT 13.5 kV Module

SiC MOSFET Module
10 kV, 120amps

Si IGBT Module
13.5 kV, 100amps

imagination at work

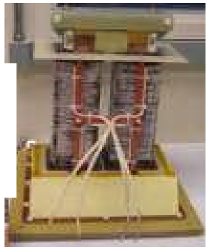
Dramatic Reduction in Transformer Size and Weight In 13.8 kV AC to 465/√3 V AC SSPS

OTS Transformer

330 kVA 60 Hz transformer
55” high
2700 lb

Los Alamos National Laboratory
High Frequency Transformer

Los Alamos NATIONAL LABORATORY EST. 1943



Courtesy of Bill Reass

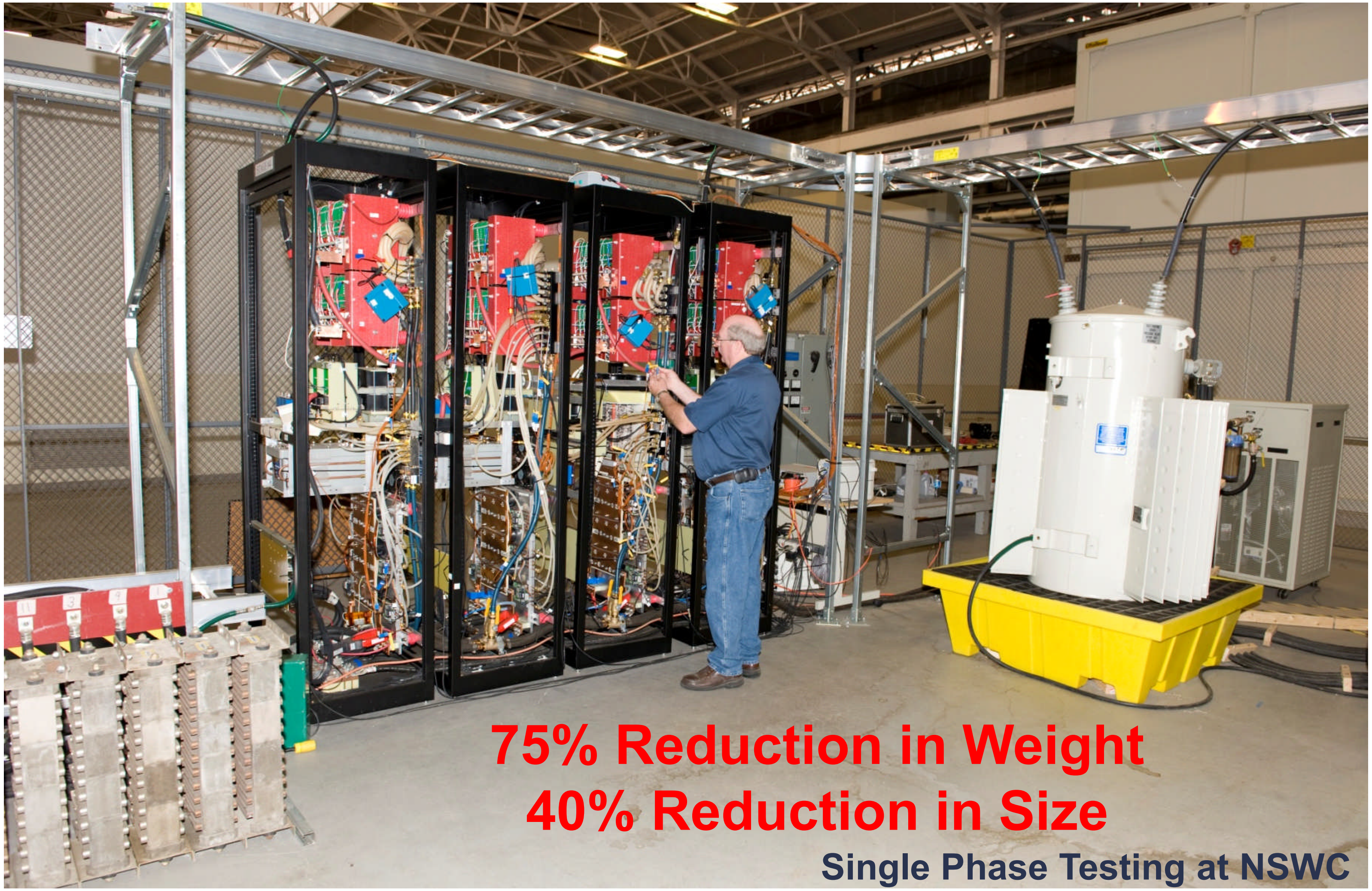
250 kVA - 20 kHz transformer
16” high
75 lbs

imagination at work

CREE

4 Stage - Single Phase (13.8 kV AC to 465/√3 V AC) SSPS Based on 10 kV/120 A SiC DMOSFET Modules

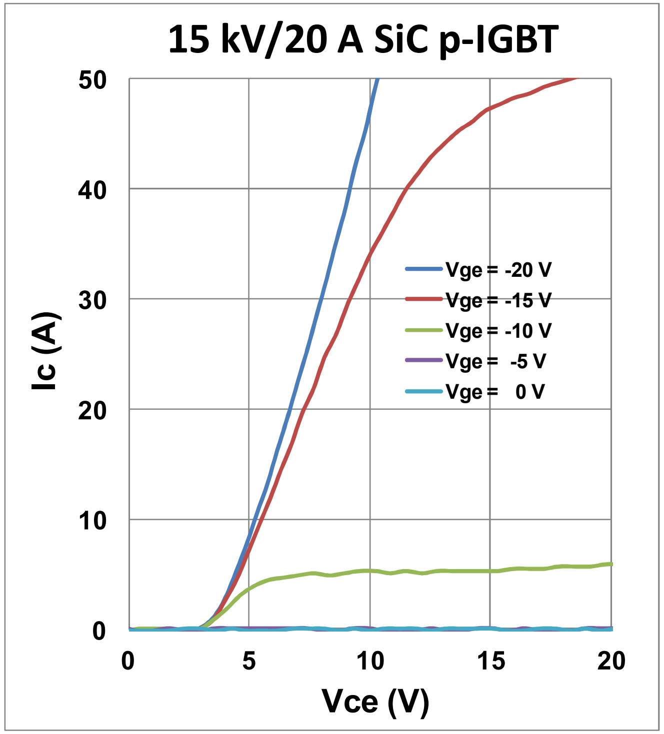
Single Phase SSPS – Demonstrated 860 kVA Operation



Single Phase Testing at NSWC

15 kV/ 20 A SiC p-IGBT
World's First 15 kV Semiconductor Switch

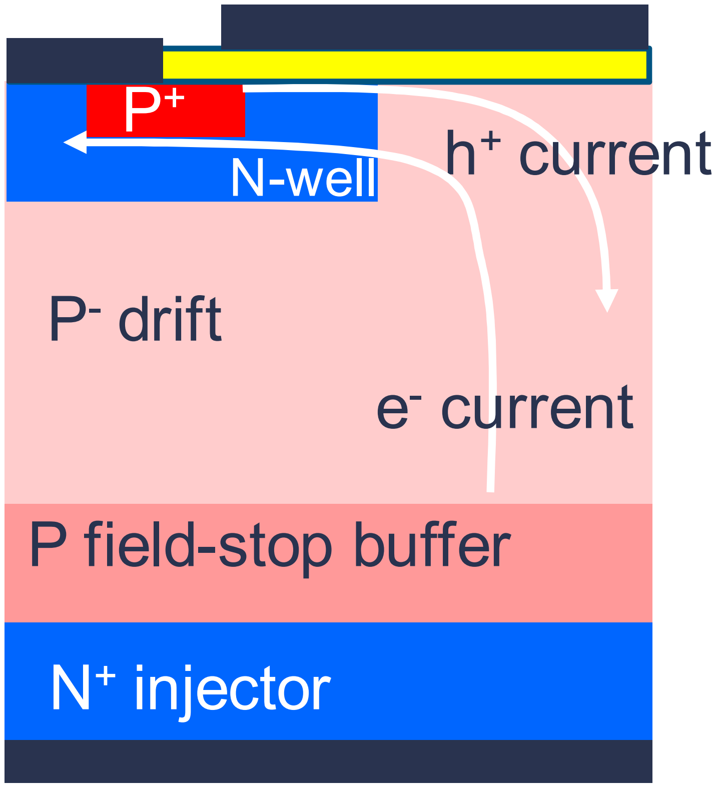
SiC IGBT Power At Your Fingertips!



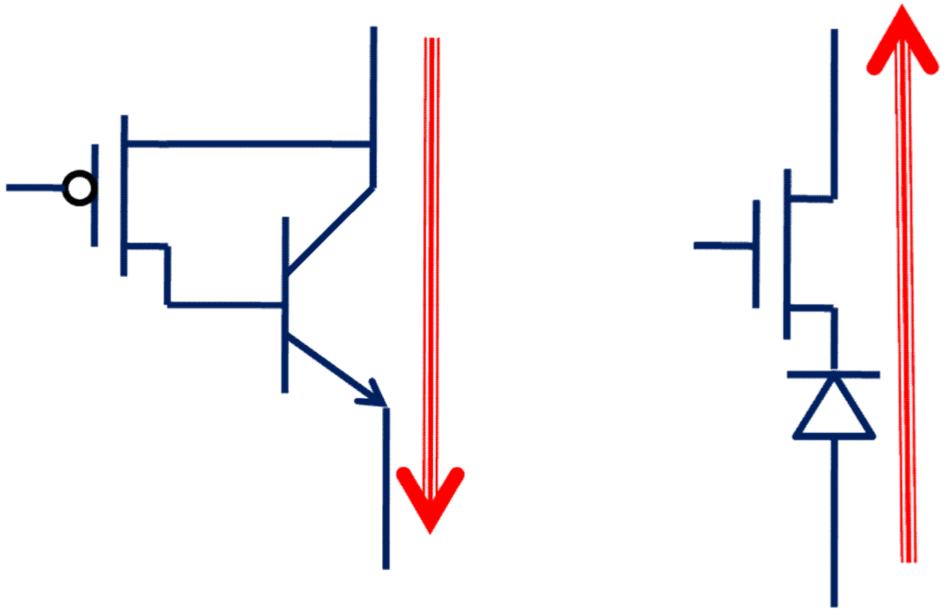
- **15 kV/20 A SiC p-IGBT**
- V_F = 6.5 V @ 20 A, V_{GE} = 20V
- State-of-the-Art SiC p-IGBT Developed Under ARPA-E ADEPT Program

15 kV SiC p-IGBT – World's Highest Voltage Semiconductor Switch

SiC p-IGBT and SiC n-IGBT Operation



$I_e : I_h = \mu_e : \mu_h$
$= 10 : 1$ in 4H-SiC



P-IGBT:
Small PMOS driving a big NPN BJT

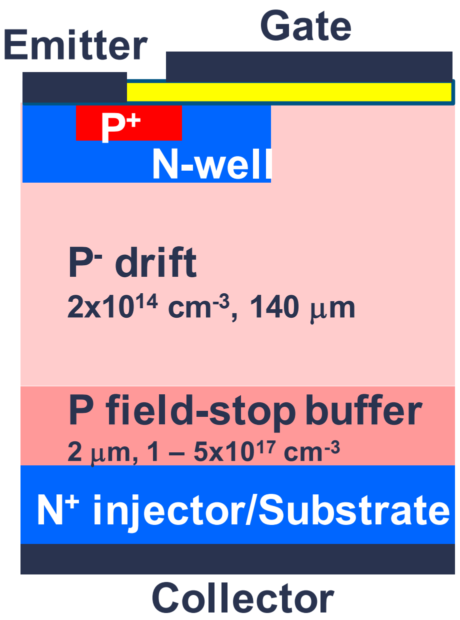
N-IGBT:
NMOS with cond. mod. drift layer

arpa·e

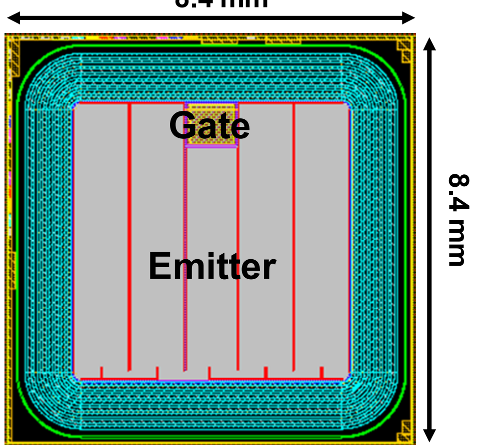
CREE

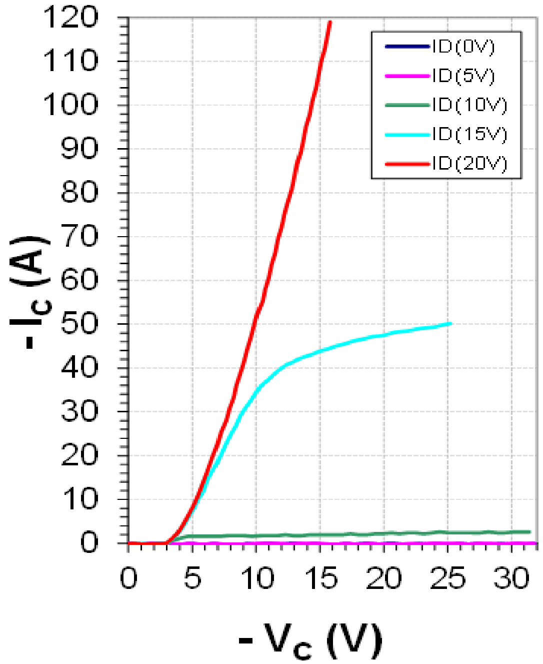
15kV/20A SiC p-IGBT
DC Device Characteristics at 25ºC

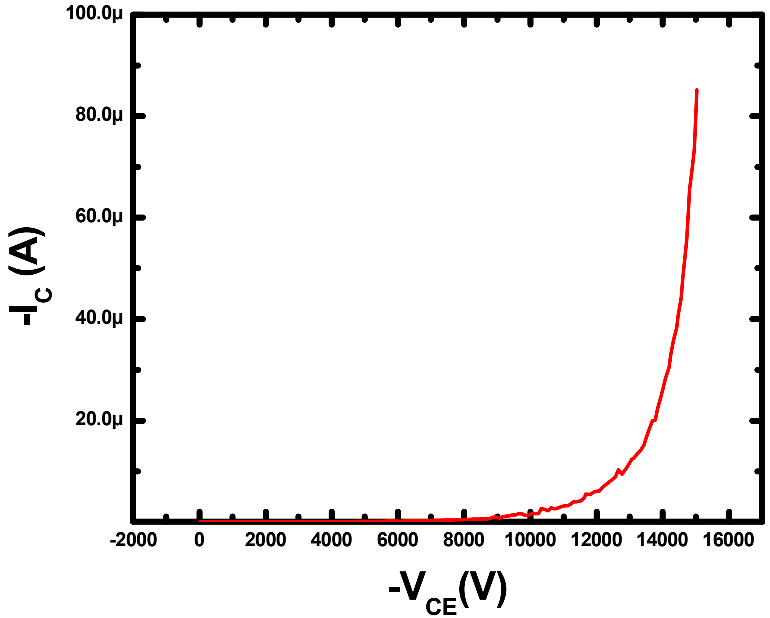
15 kV SiC p-IGBT - Highest Breakdown Voltage Ever Reported for a Semiconductor Switch!



SiC P-IGBT Structure







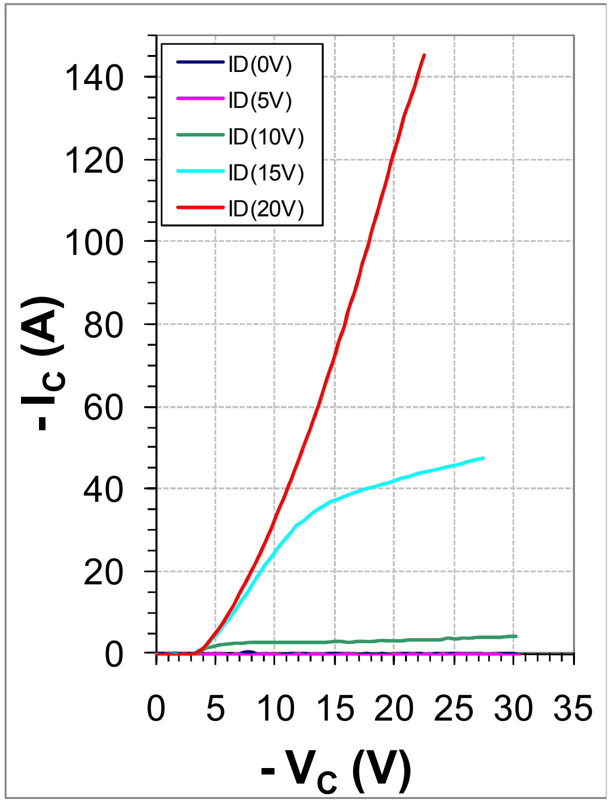
V_F = 6.5 V @ 20 A, V_{GE} = -20V

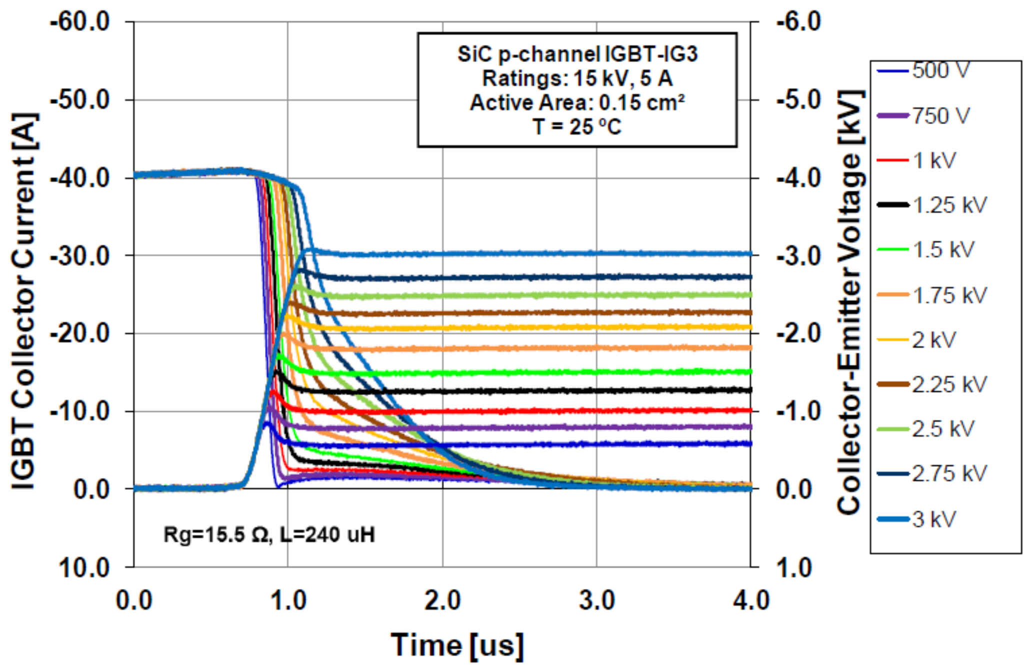
15 kV Blocking (V_{GE}=0V)

Room Temperature Device Characteristics

No Latch-Up Observed In 15kV/10A SiC p-IGBT

Dr. A. Hefner, NIST

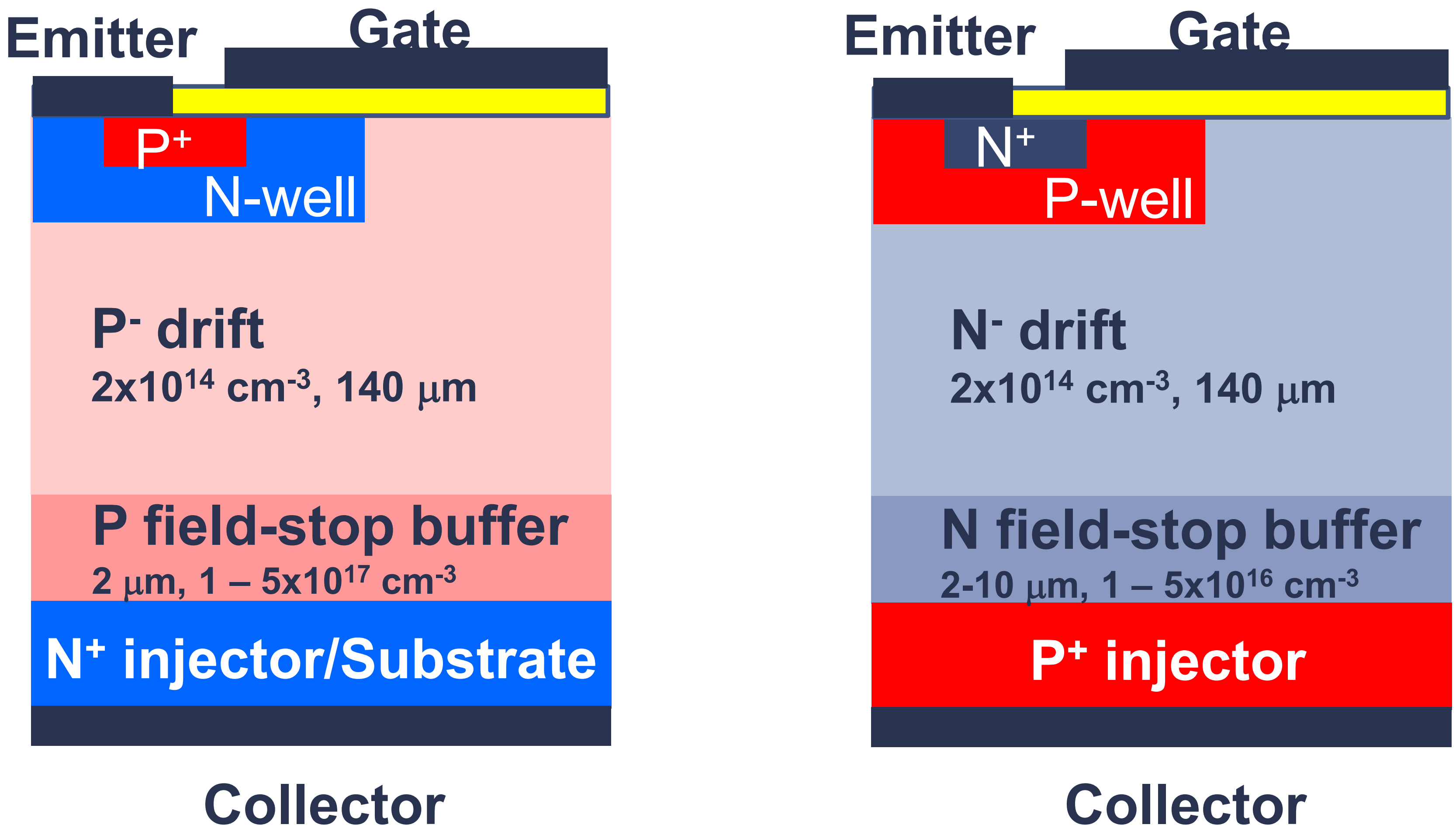




No Static Latch-up @ I_C= 145 A @ 22.5 V
=> Current density: 906 A/cm²
=> Power density: 45 kW/cm²

No Dynamic Latch-up during turn-off transients: I_C = -40A

15 kV SiC p-IGBT and n-IGBT Device Structures
(Based on SiC DMOSFETs)

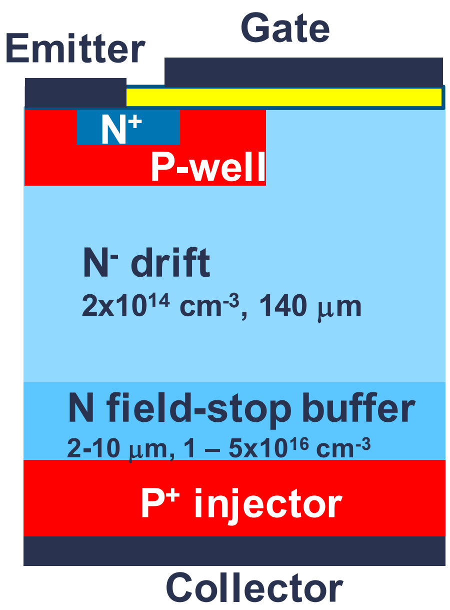


SiC P-IGBT structure

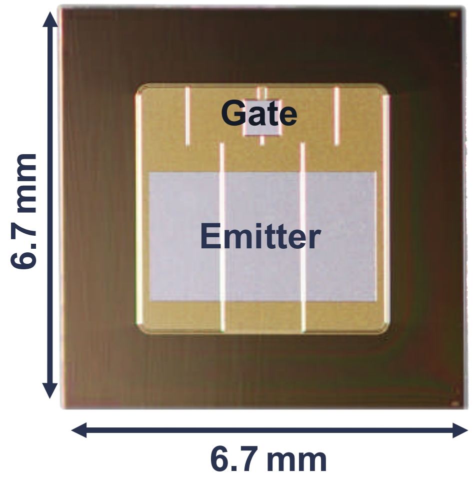
SiC N-IGBT structure

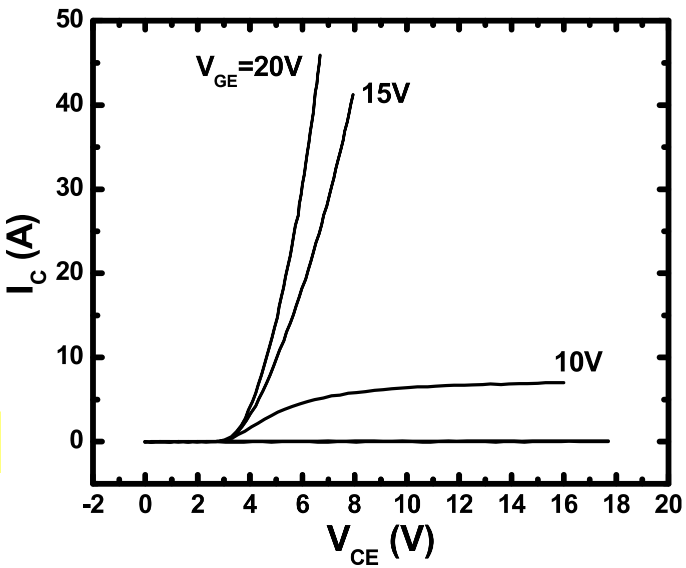
12.5kV/35A SiC n-IGBT
DC Device Characteristics at 25°C

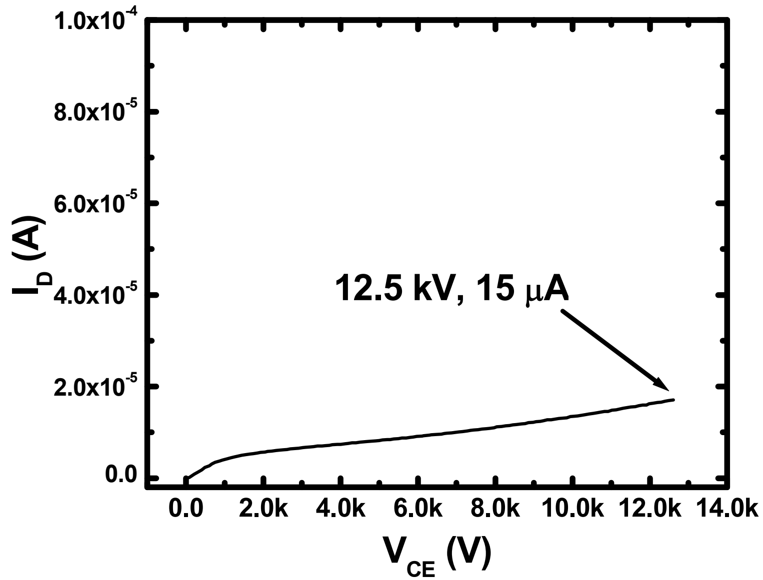
12.5 kV SiC n-IGBT With Specific On Resistance ($R_{on,sp}$) of Only 5.3 mΩ-cm² !



SiC N-IGBT Structure







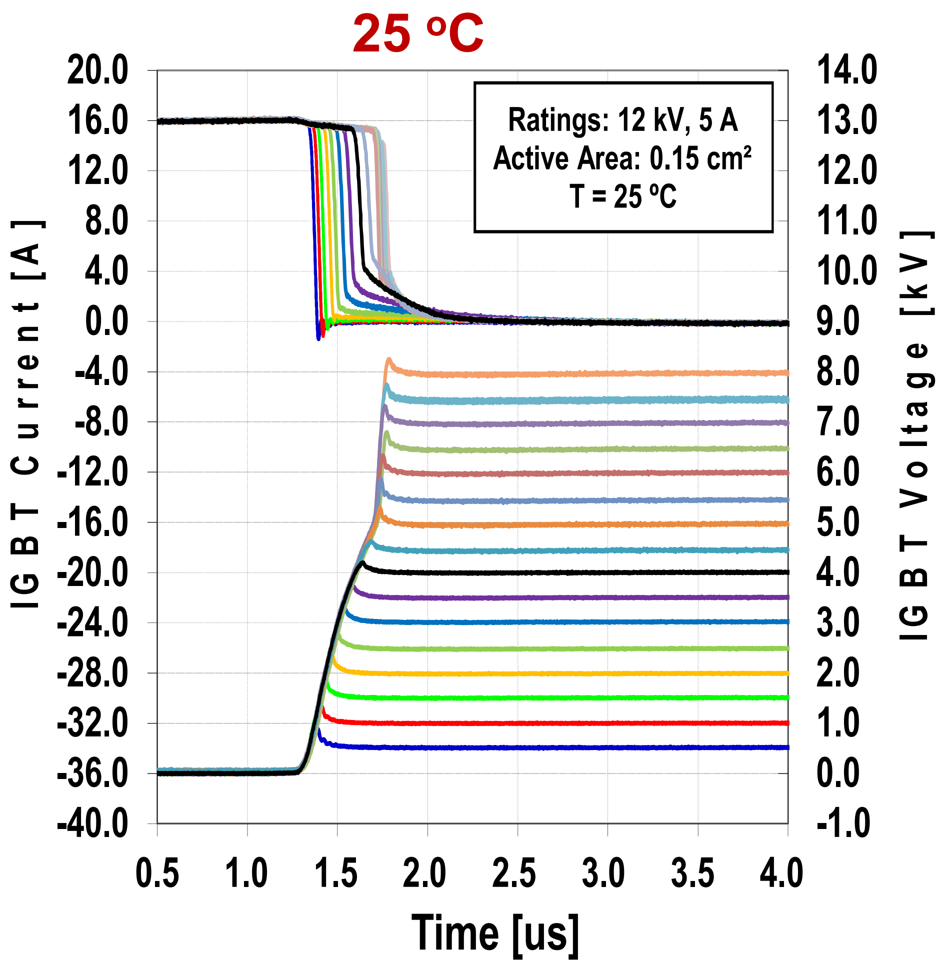
V_F = 4.1V @ 5 A, V_{GE} = 20V
= 6.1 V @ 32 A (200 A/cm²)

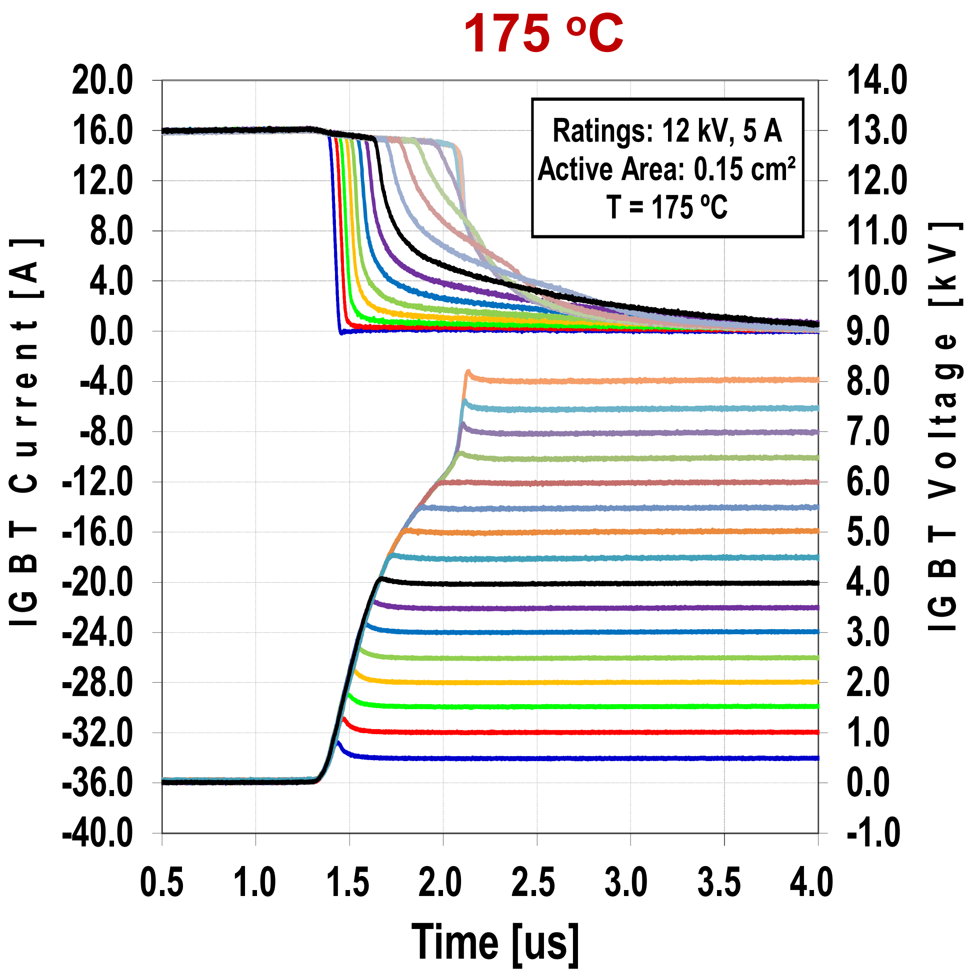
$R_{on,sp}$ = 5.3 mΩ-cm²
(V_{GE}= 20V, V_{CE}= 6.1V)

12.5 kV blocking
(V_{GE}=0V)

Room Temperature Device Characteristics

12.5kV SiC n-IGBT Turn-Off Switching
Up to 8 kV at 25^{0}C and 175^{0}C

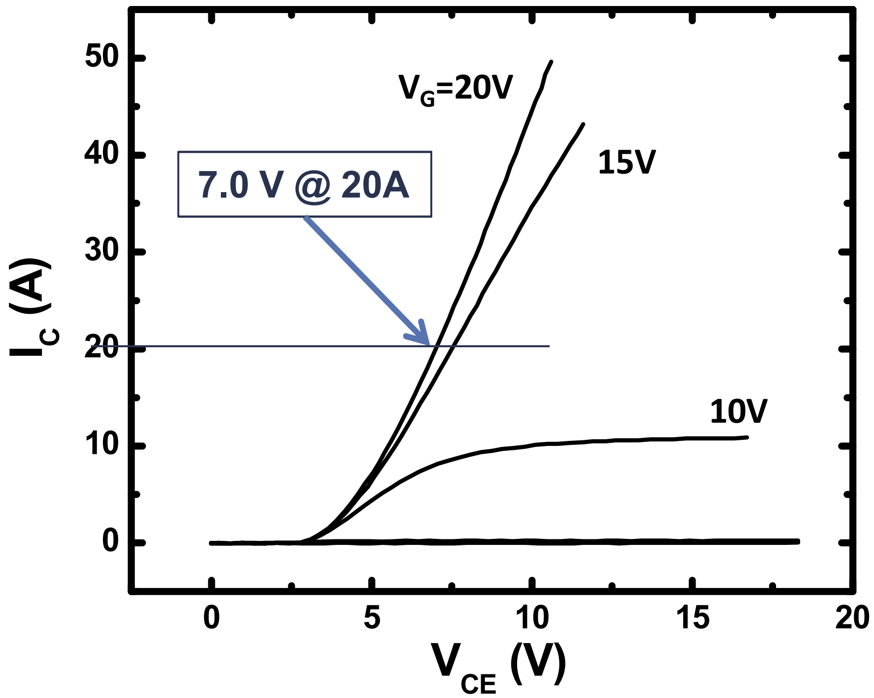


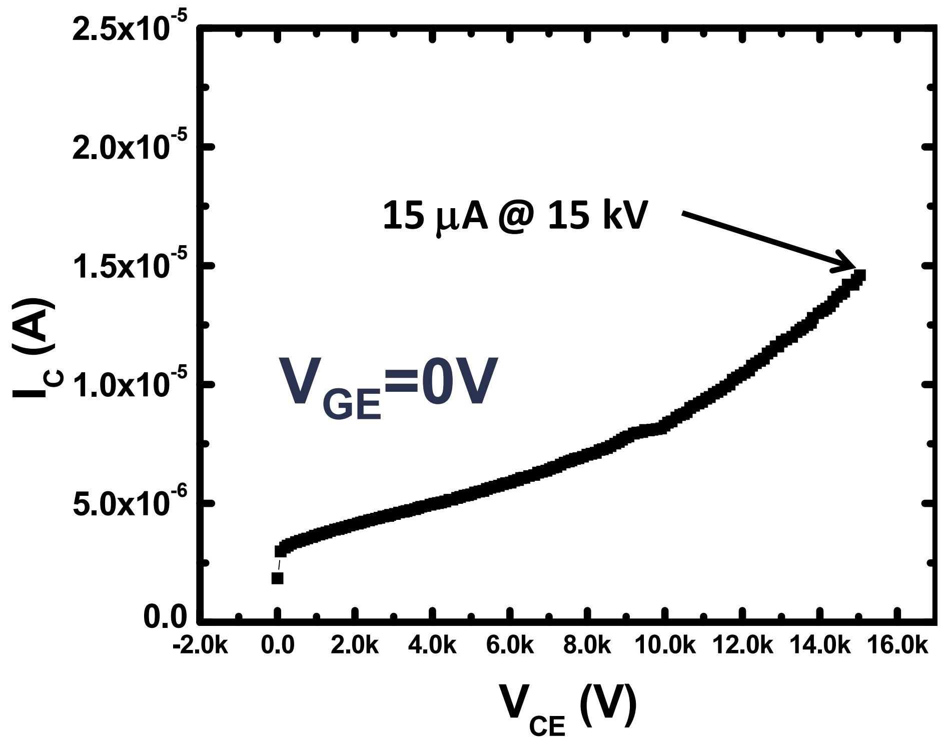


Measurements by Al Hefner at NIST

15 kV/20A SiC n-IGBT (Lot #4A) Successfully Demonstrated

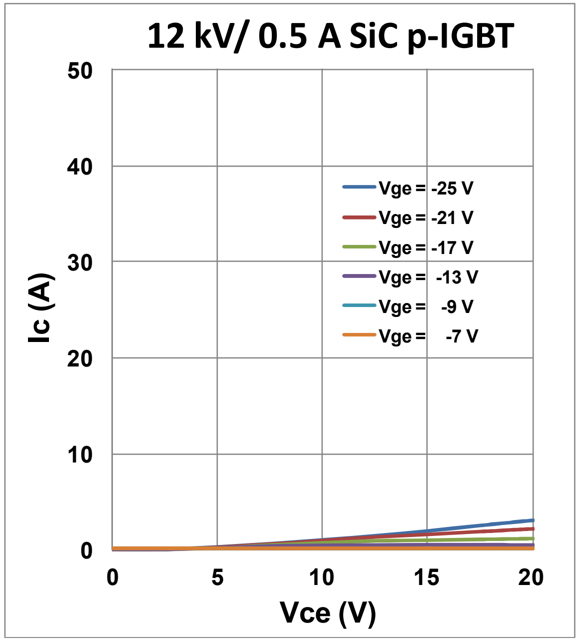
15 kV/20 A SiC n-IGBT Lot #4A
Die Size: 8.4 mm x 8.4 mm / Active Area: 0.32 cm^2



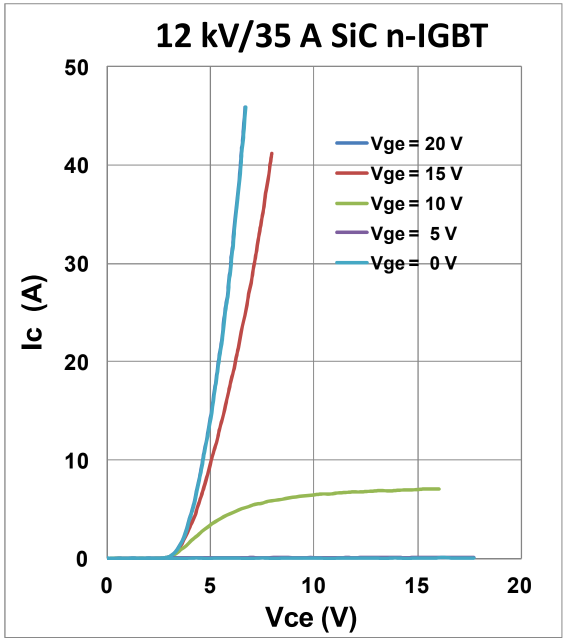


Room temperature, on-wafer measurements

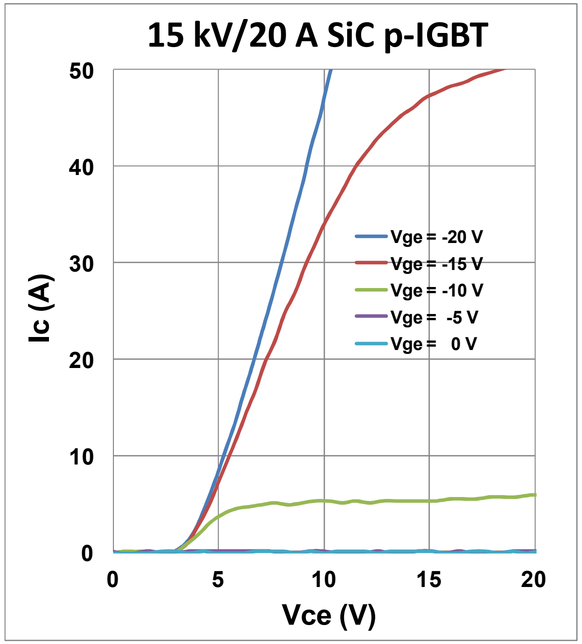
Dramatic Improvement in SiC IGBTs Under the ARPA-E ADEPT Program



- 12 kV/0.5 A SiC p-IGBT & n-IGBT
- V_F = 6.5 V @ 0.5 A, V_{GE} = 20V
- Previously Developed Under DARPA/ONR HPE Program



- 12.5 kV/35 A SiC n-IGBT
- V_F = 6.5 V @ 35 A, V_{GE} = 20V
- State-of-the-Art SiC n-IGBT Developed Under ARPA-E ADEPT Program



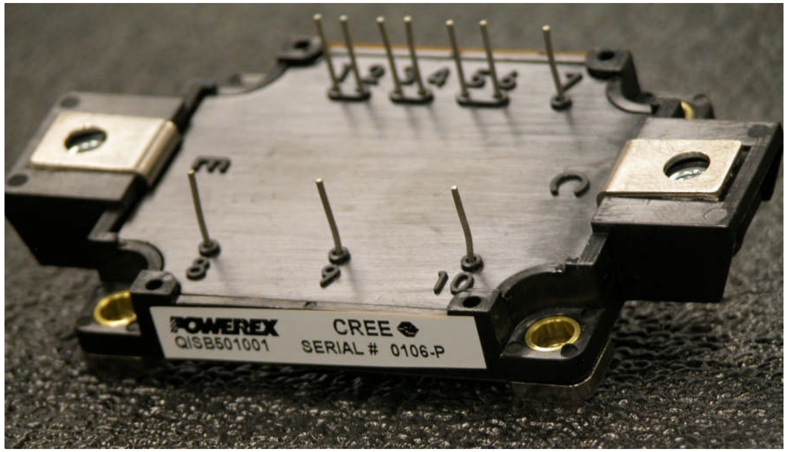
- 15 kV/20 A SiC p-IGBT
- V_F = 6.5 V @ 20 A, V_{GE} = 20V
- State-of-the-Art SiC p-IGBT Developed Under ARPA-E ADEPT Program

SiC IGBT - Room Temperature Forward I-V Characteristics

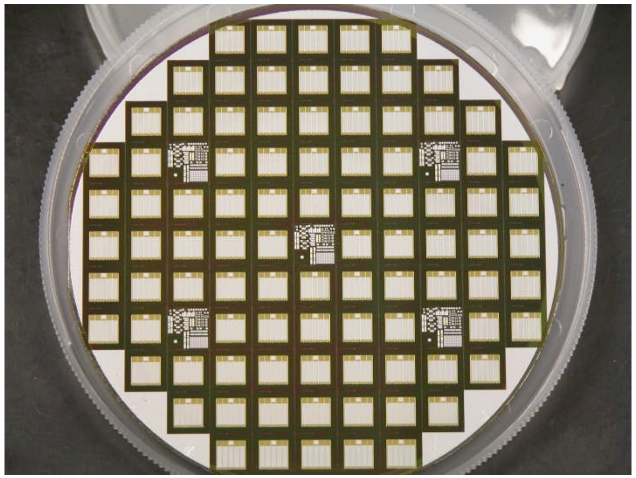
- **Dramatic Improvement in SiC IGBTs Under ARPA-E ADEPT Program**
- **Over 40x Increase in Current Rating of SiC n-IGBTs and SiC p-IGBTs**
- **15 kV SiC p-IGBT – Highest Voltage Semiconductor Switch Ever Developed**

Highlights of SiC IGBT Development Under the ARPA-E ADEPT Program

arpa·e



- 15 kV SiC IGBT Switch Module – World's Highest Voltage Semiconductor Switch

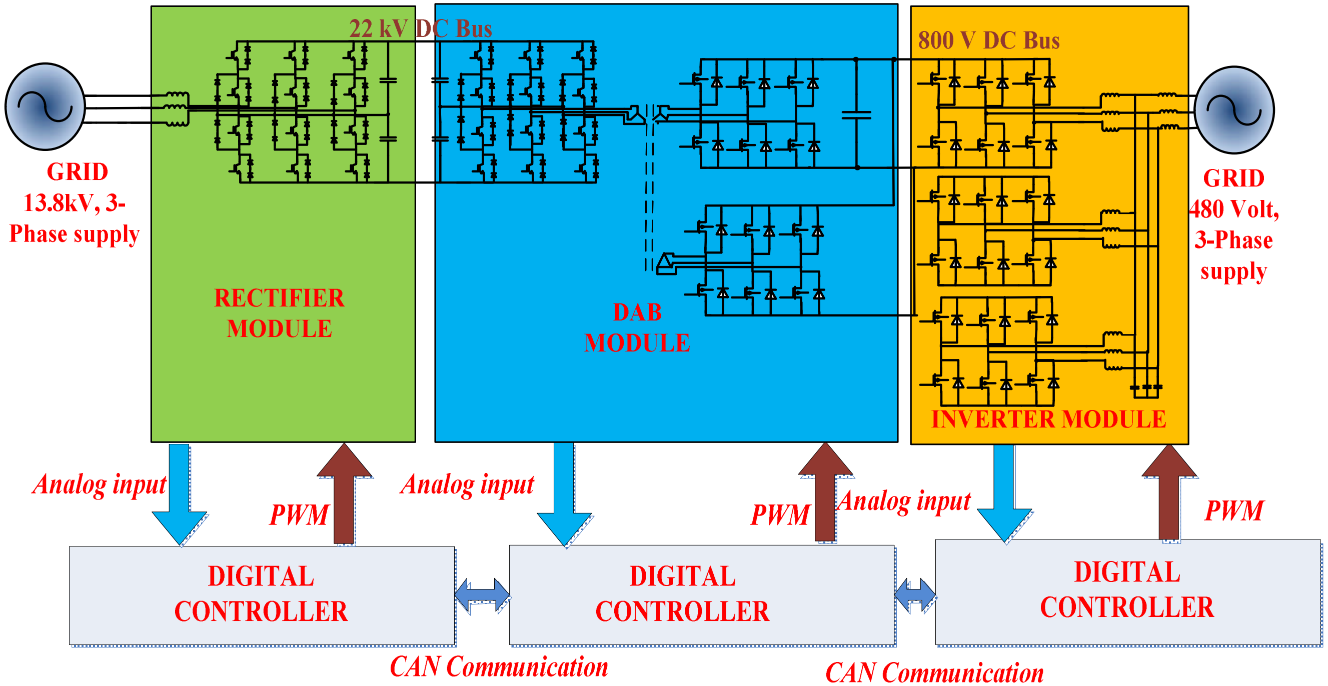


- 15 kV/10 A SiC p-IGBTs Fabricated On 100 mm 4HN-SiC Wafer

- Developed 15 kV SiC IGBT – World's Highest Voltage Semiconductor Switch
  - Over 2x Higher Than 6.5 kV SiC IGBT
- SiC IGBTs Capable of Switching Over 20x Faster Than Si IGBT
- Higher Voltage and Switching Speed of SiC IGBTs Enables a 3x to 5x Reduction in Size and Weight of Solid State Transformer (TIPS)
- SiC IGBTs Result in a 3x to 4x Reduction in Losses for Solid State Transformer (TIPS)

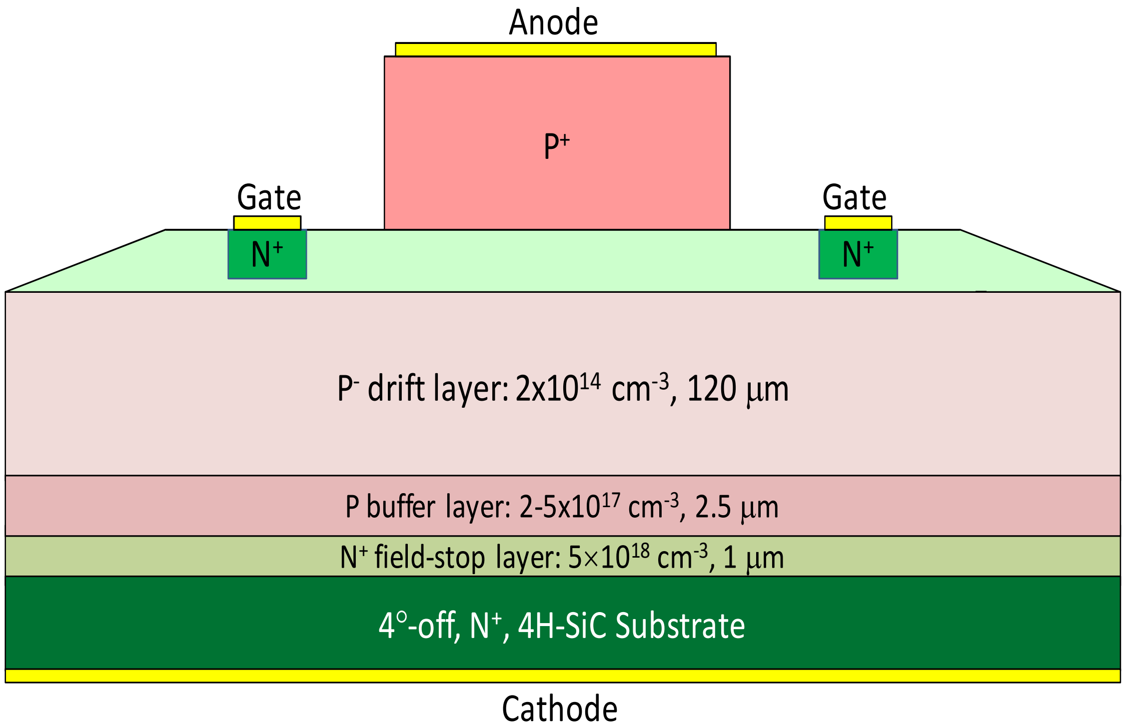
CREE

NCSU Developing TIPS Based Upon 15 kV SiC IGBTs

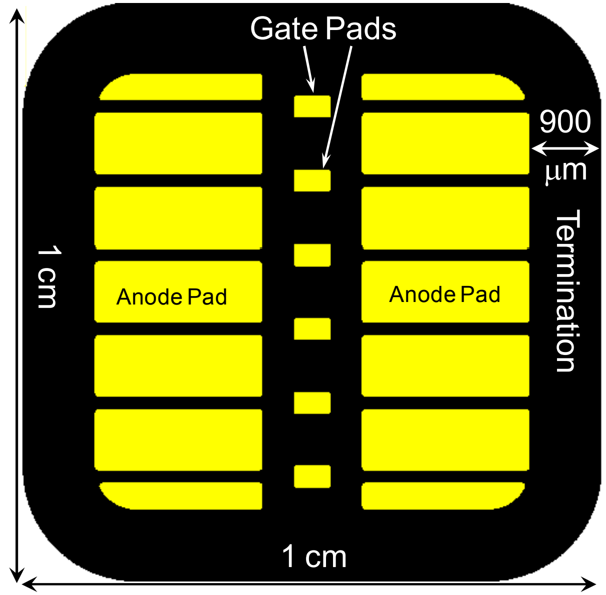


- **Develop 13.8 kV to 480 V Solid State Distribution Transformer With Dramatically Reduced Weight and Size**
- **TIPS Functions as VAR Compensator On Both HV and LV Side.**
- **15 kV SiC IGBT Power Switches on HV Side and 1.2 kV SiC MOSFET Power Switches on LV Side**
- **High Frequency Link Nanocrystalline Transformer Provides Magnetic Isolation**

11526DCC1: 15 kV, 1 cm², SiC p-SGTO

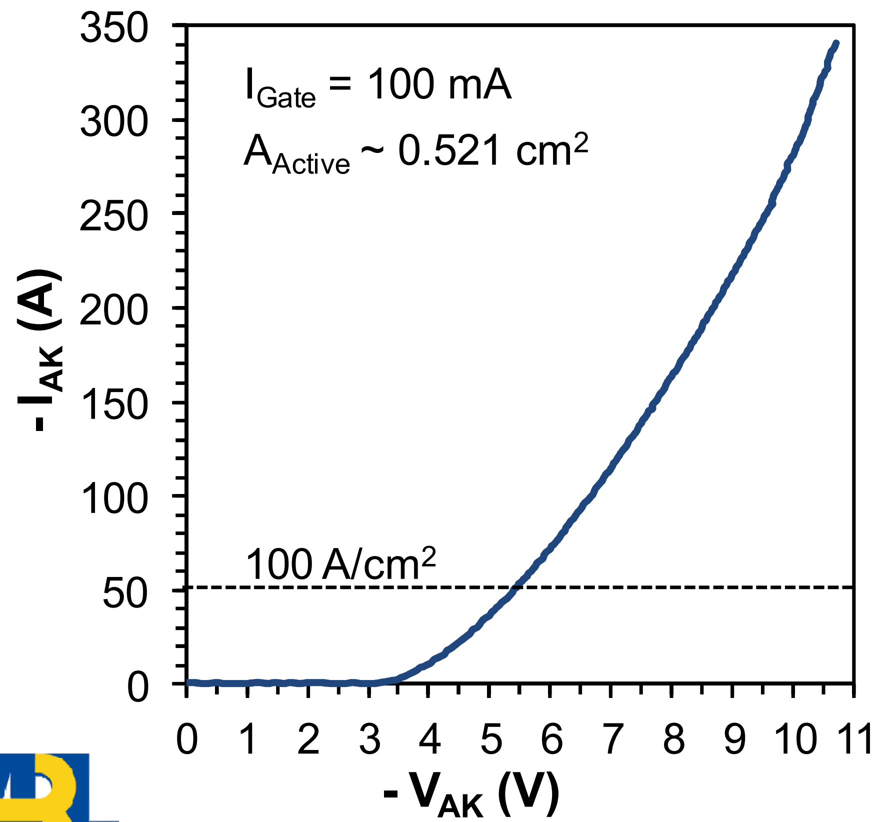


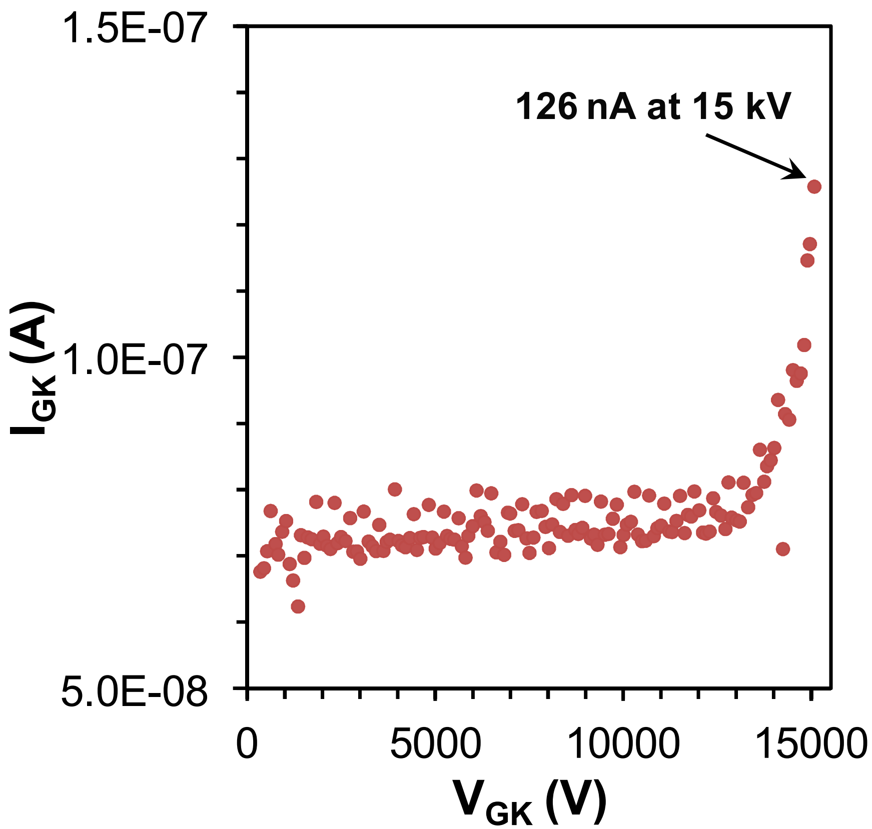
A_{active} = 0.5214 cm²



11526DCC1: DC Characteristics of SiC p-SGTO

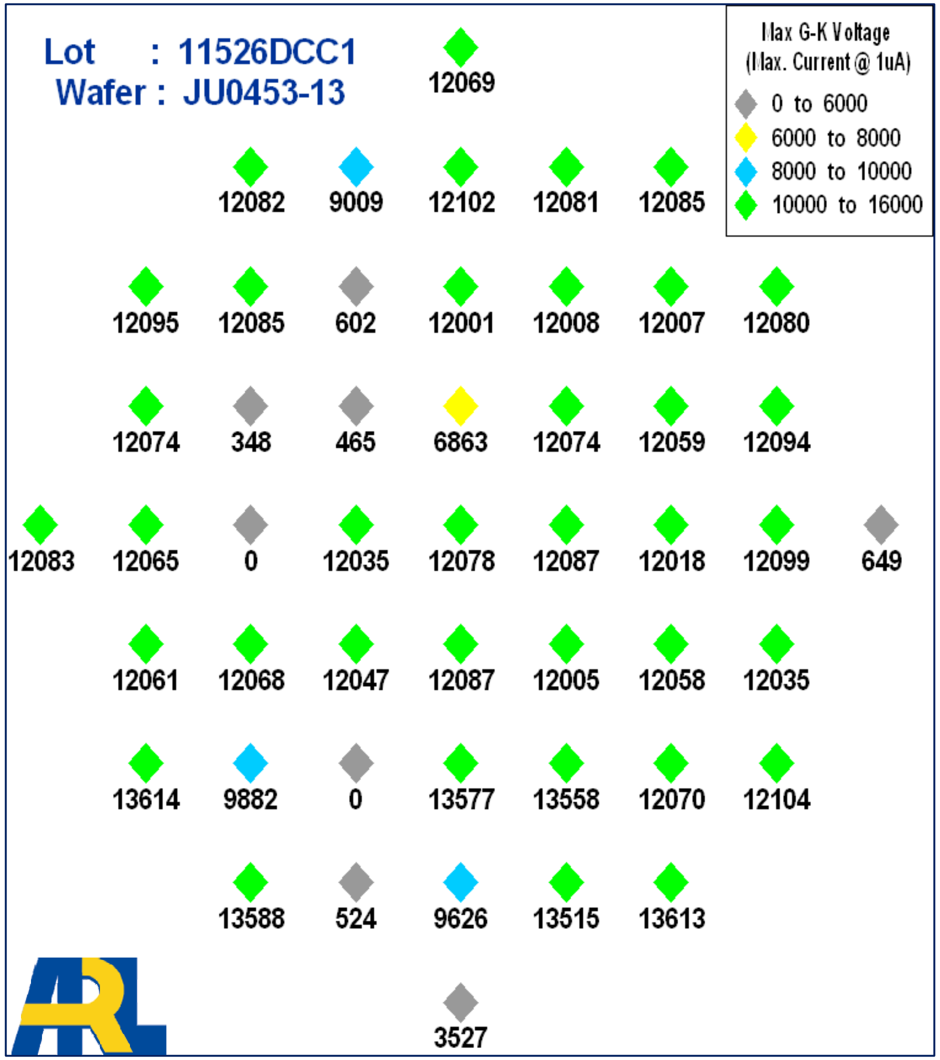
- **V_f (100 A/cm²) = 5.47 V, V_f (650 A/cm²) = 10.68 V**
- **Avg. $R_{ON,diff}$ = 9.5 mΩ·cm² at 100~650 A/cm²**
- **Avg. $R_{ON,diff}$ = 5.99 mΩ·cm² at 600~650 A/cm²**



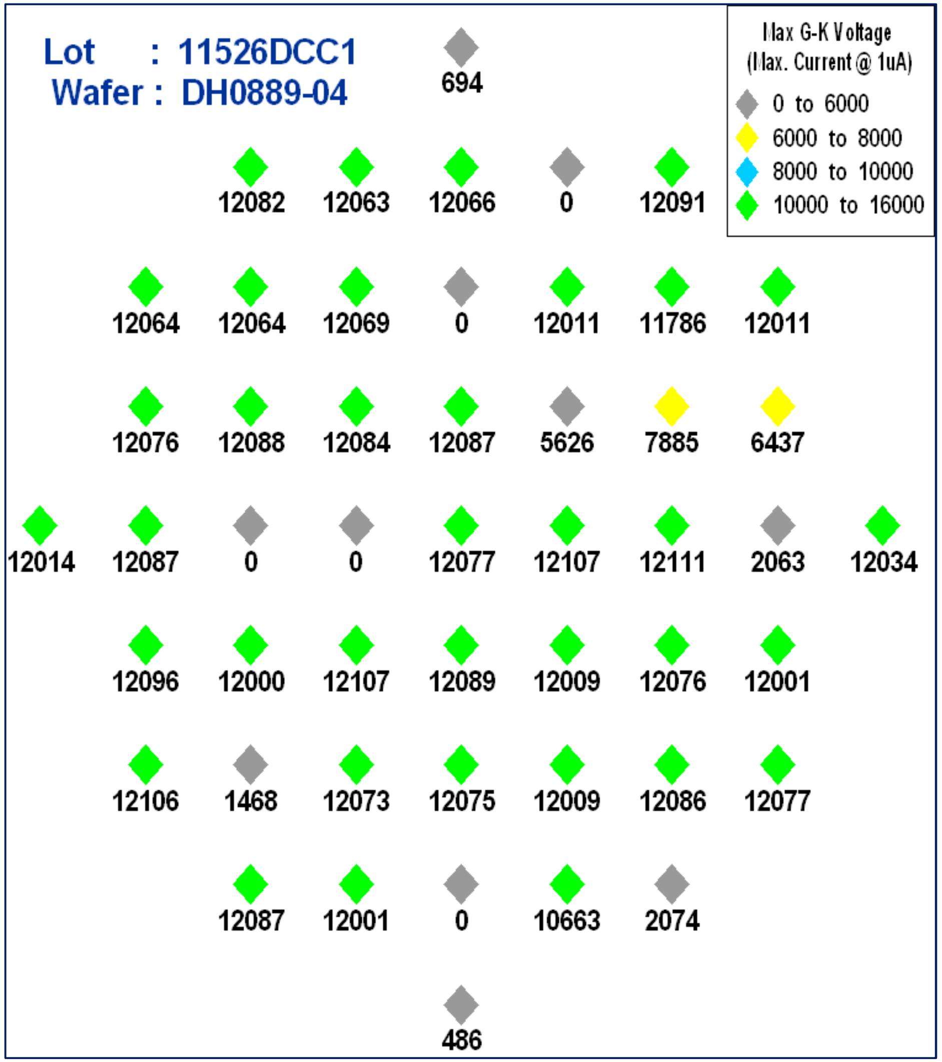


11526DCC1: 1 cm^2, SiC p-SGTO: on-wafer BV maps

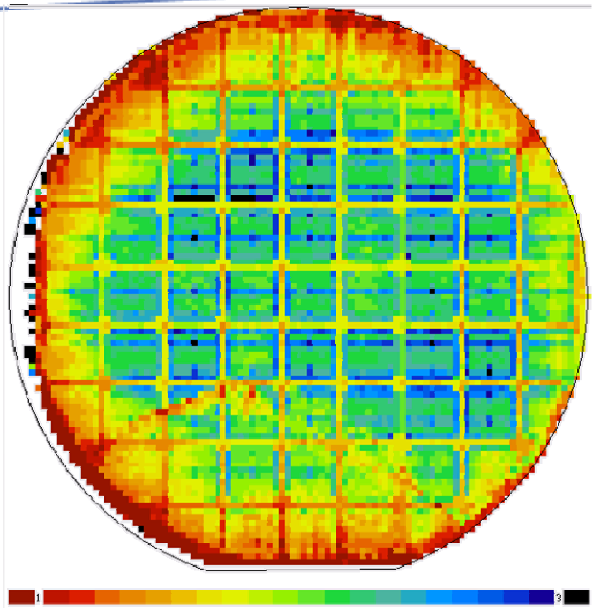
12 kV @ ≤ 1 μA yield: 77.6% (38/49)



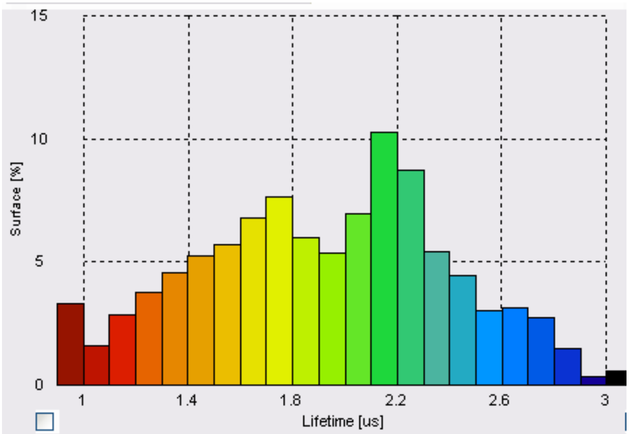
12 kV @ ≤ 1 μA yield: 73.5% (36/49)



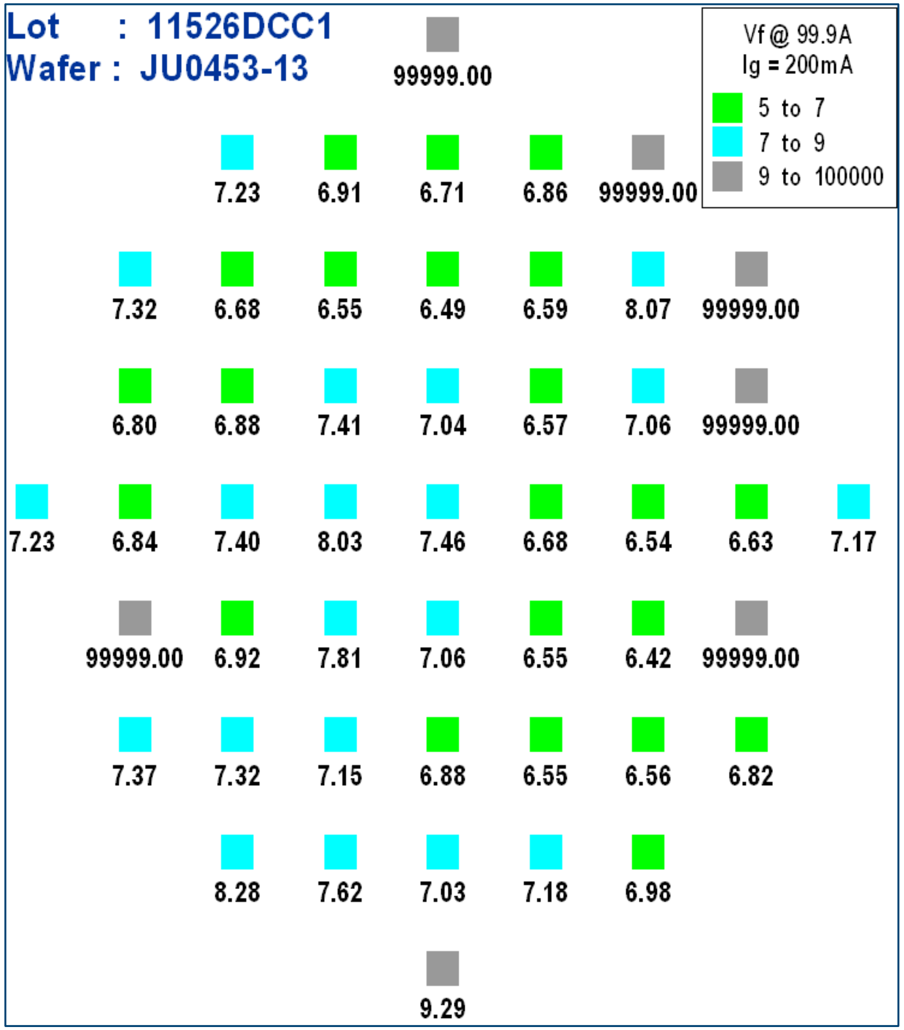
11526DCC1: 1 cm^2, SiC p-SGTO: on-wafer V_f map



Average:	1.93	Minimum:	0.36
Median:	1.95	Maximum:	17.677
Deviation:	33.109		



Avg. V_f = 6.98 V, Median V_f = 7.09 V



Acknowledgements

Dr. Allen Hefner

Dr. Scott Leslie

Mr. Rick Worth

Prof. Joe Flemish
Mr. Mike Horgan

Ravi Raju
Michael Schutten
Bob Steigerwald

Dr. Subhashish Bhattacharya

With Generous Support From:

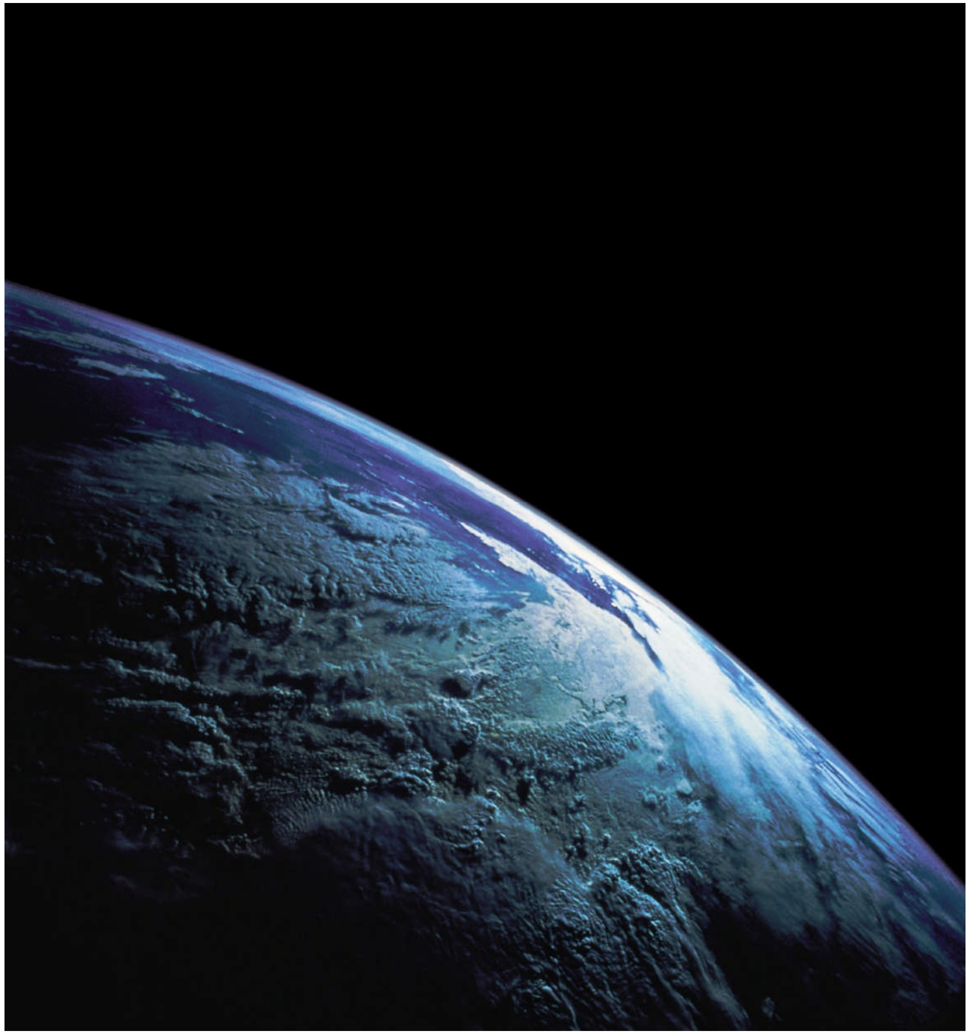
Skip Scozzie
Wes Tipton

Jim Scofield
Joe Weimar

Fritz Kub
Karl Hobart
Bob Stahlbush

Sharon Beerman-Curtin
Terry Ericsen

Rajeev Ram



Cree SiC Power

- ***The material difference.***