# Session 4b

Grider

# Recent Developments in SiC Power Technology at Cree

## High Megawatt Converter Technology Workshop

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# SiC Power Devices

- SiC Material Advantages for Power
- 1200 V JBS Diodes
- 1200 V SiC DMOSFETs
- SiC Device Scaleup & Yield Improvement
- 10 kV SiC DMOSFETs
- SiC PiN Diodes, p-IGBTs, and Thyristors

# SiC Materials Advantages For Power Device Technology

## 10X Breakdown Field of Si

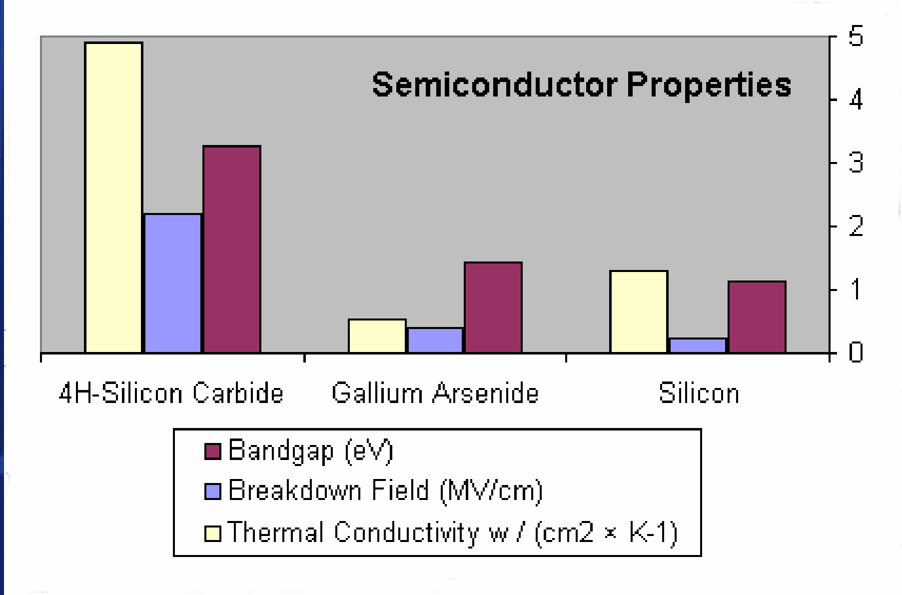
- Tradeoff higher breakdown voltage
- Lower specific on-resistance
- Faster switching

## 3X Thermal Conductivity of Si

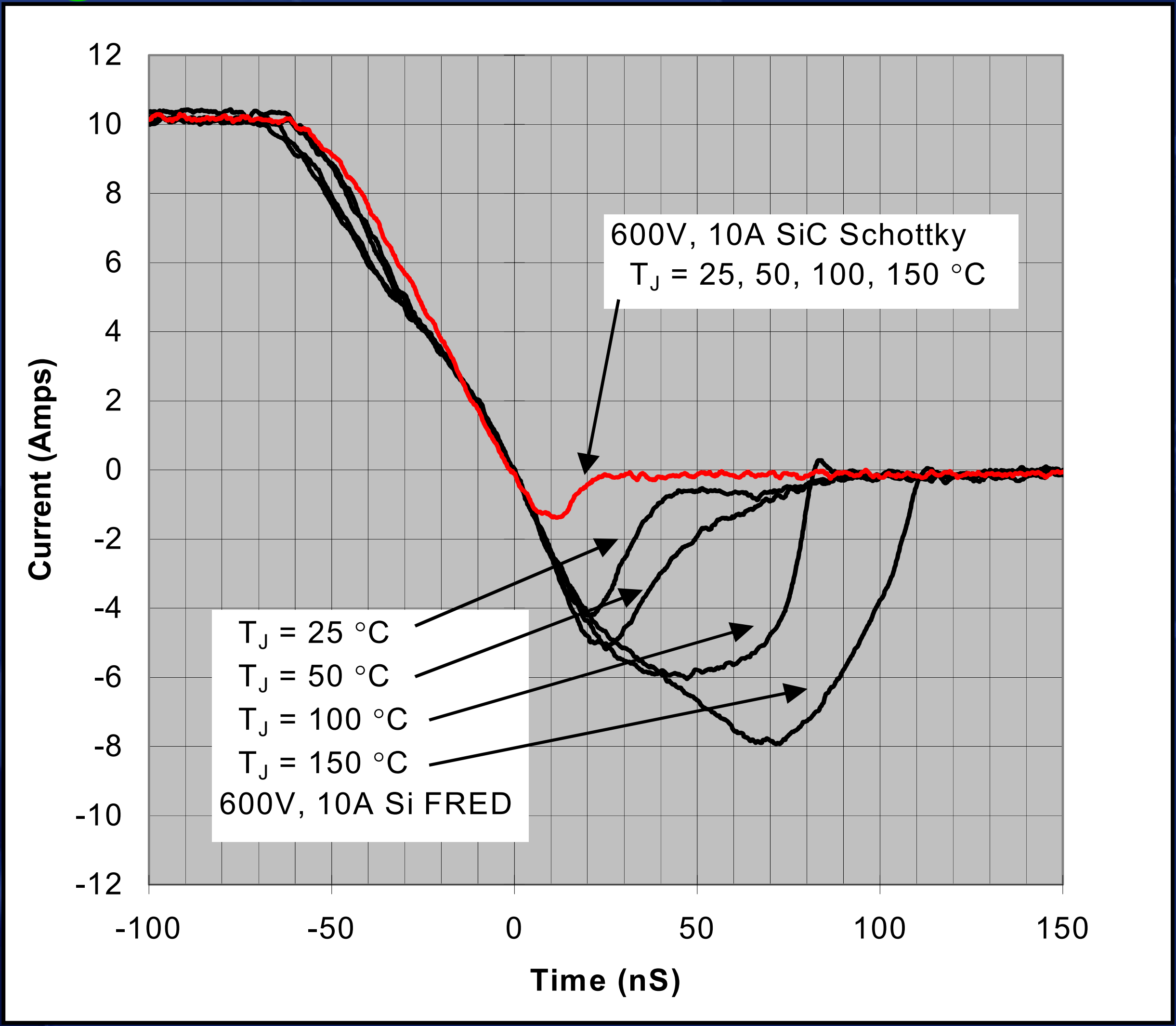
- Higher current densities

## 3X Bandgap of Si

- Higher temperature operation



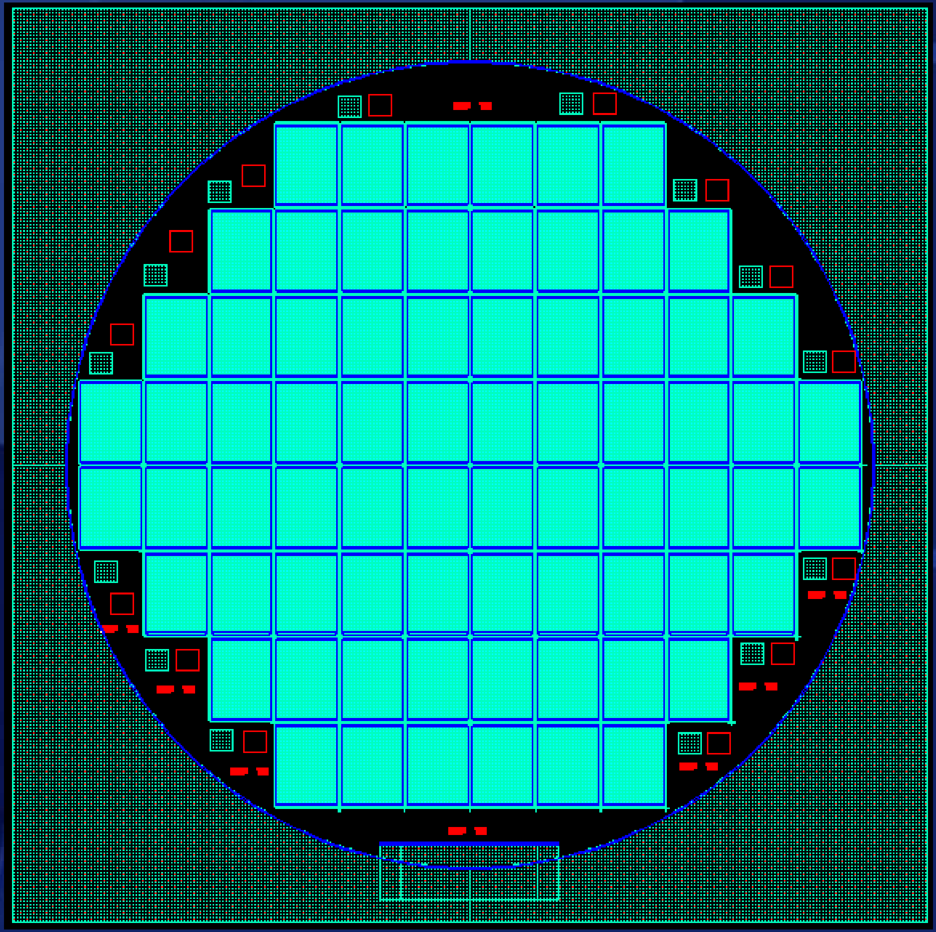
# 600 volt SiC Schottky and Si PiN Diode Reverse Recovery Comparison




- **Si PiN Diode**
  **Reverse recovery increases with temperature, slew rate and forward current**
- **SiC Schottky**
  **Virtually no reverse recovery, regardless of temperature, slew rate,**

# 1200 V 75 A JBS diodes

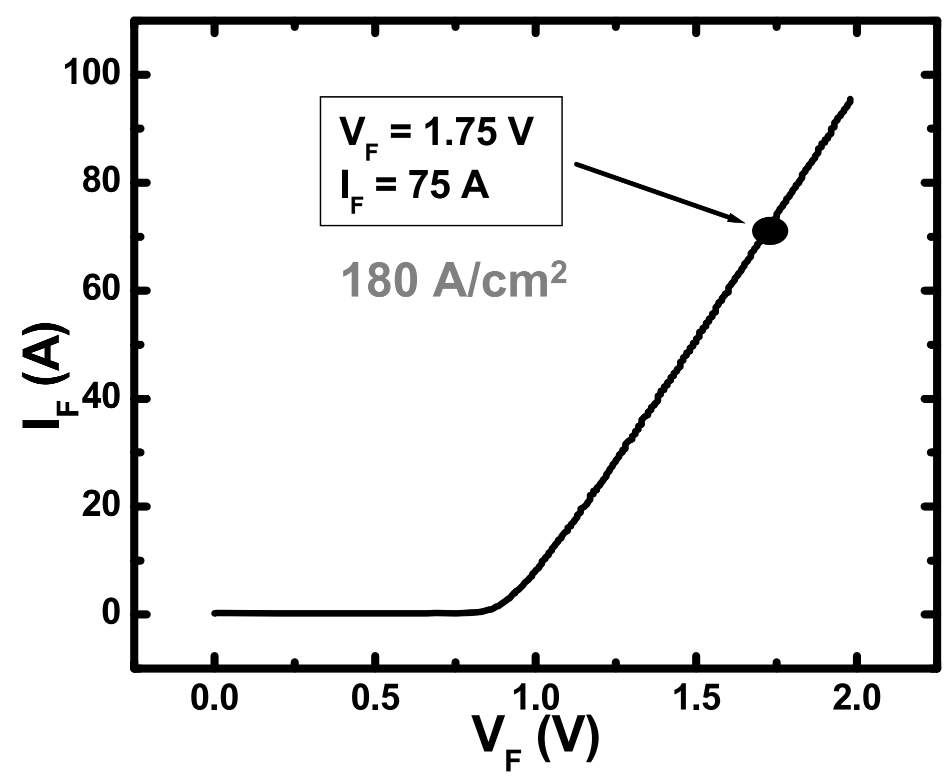
## 1200 V / 75 A

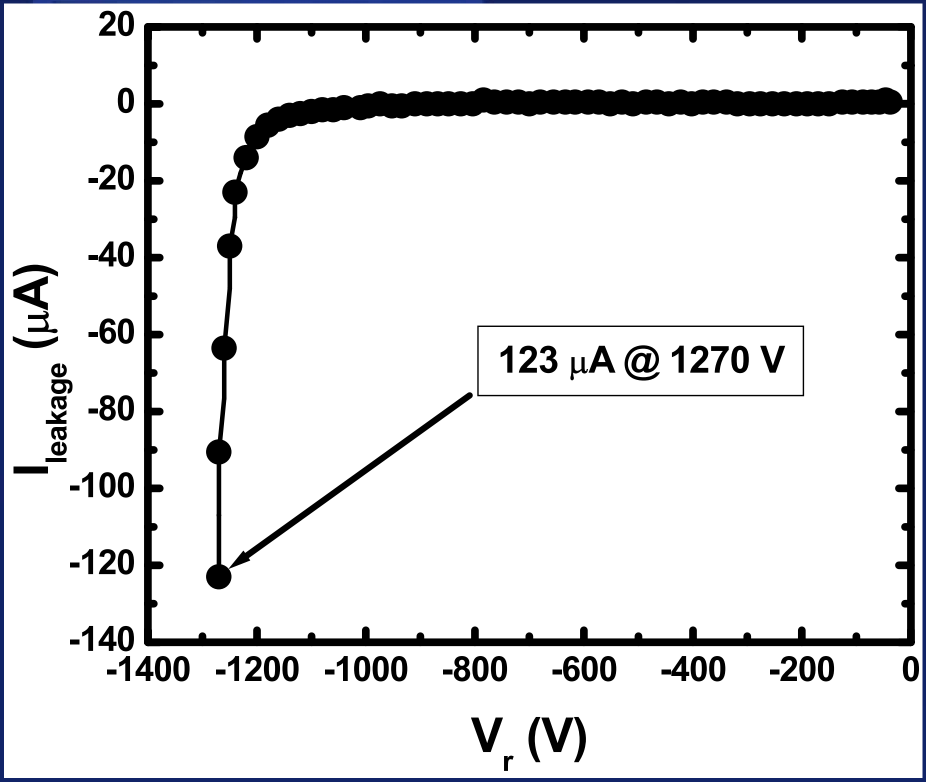


**Die size: 6 mm x 8 mm**

**Active area: 0.413 $cm^2$**

# 1200 V / 75A diode I-V Characteristics



# A SiC Switch Is Required For Even More Efficiency Improvement

## SiC Power Switches Currently Being pursued:

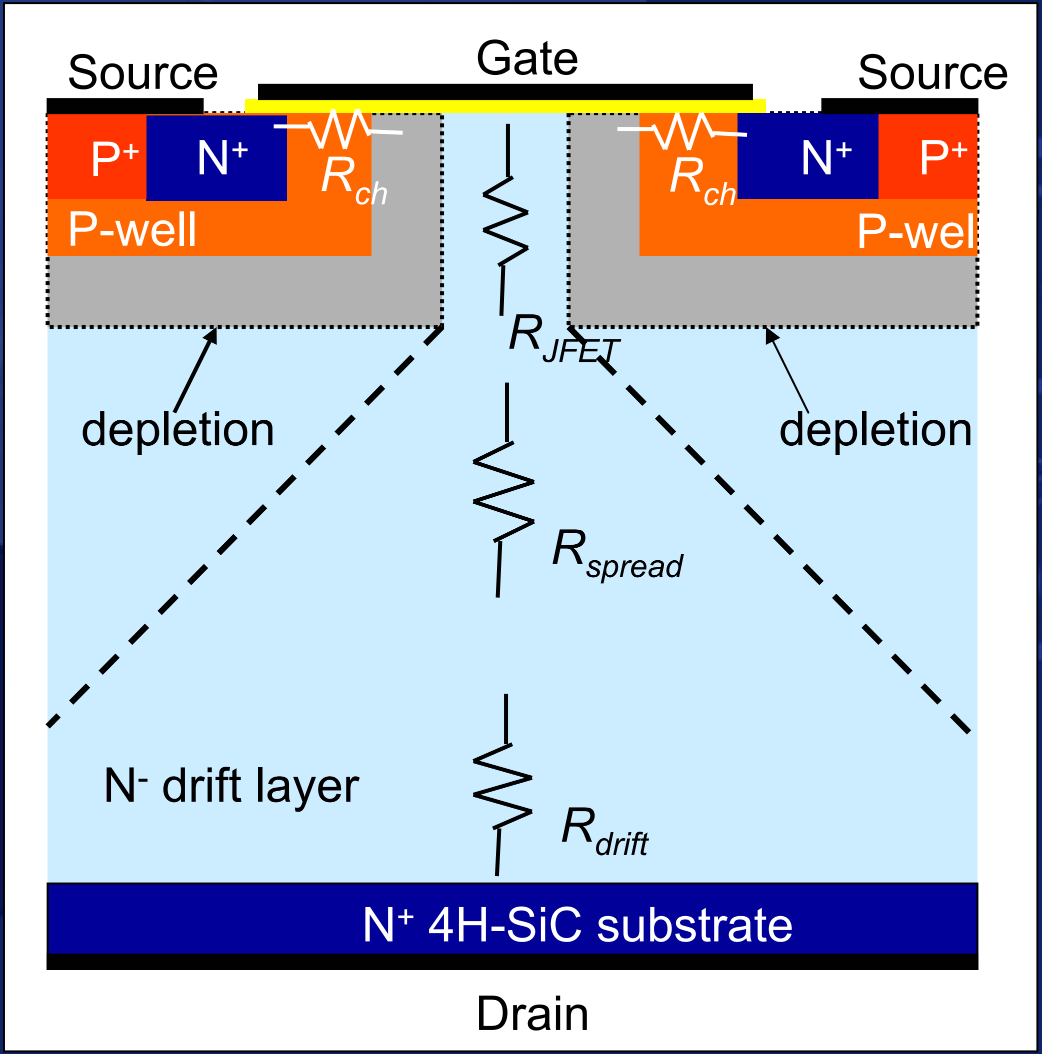
- DIMOSFETs
- UMOSFETs
- Vertical JFETs
- IGBTs
- BJTs
- Thyristors/GTOs

Increasing Voltage

Decreasing Speed

Increasing Operating Temp

# Double Implanted MOSFET (DMOSFET)



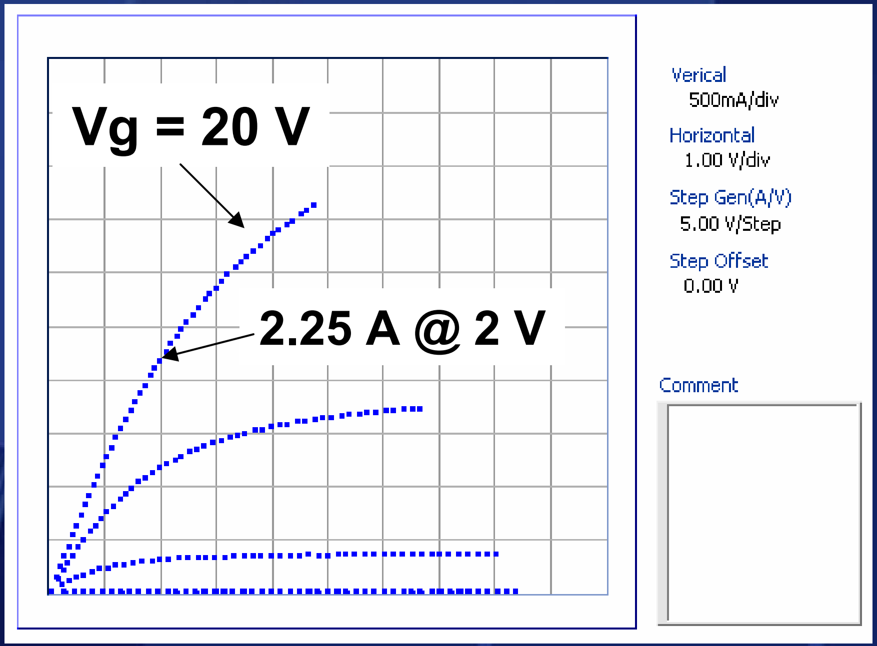

**Pursuing DMOSFET As Switch From 600V Up To 10kV**

## *DMOSFET Requirements*

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

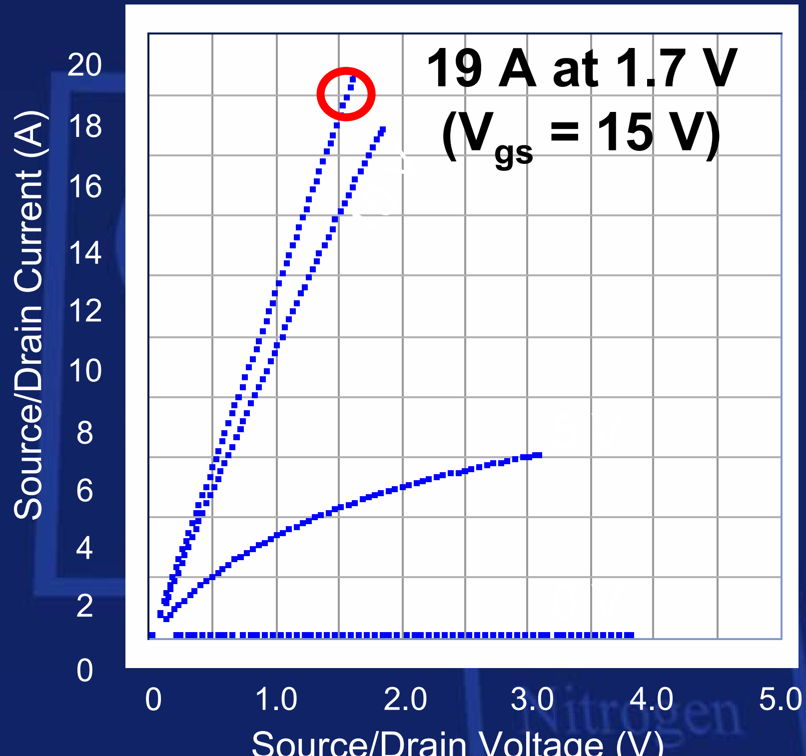
# Dramatic Reduction in 25 ºC 1.2 kV DMOSFET On-Resistance

## January 2004



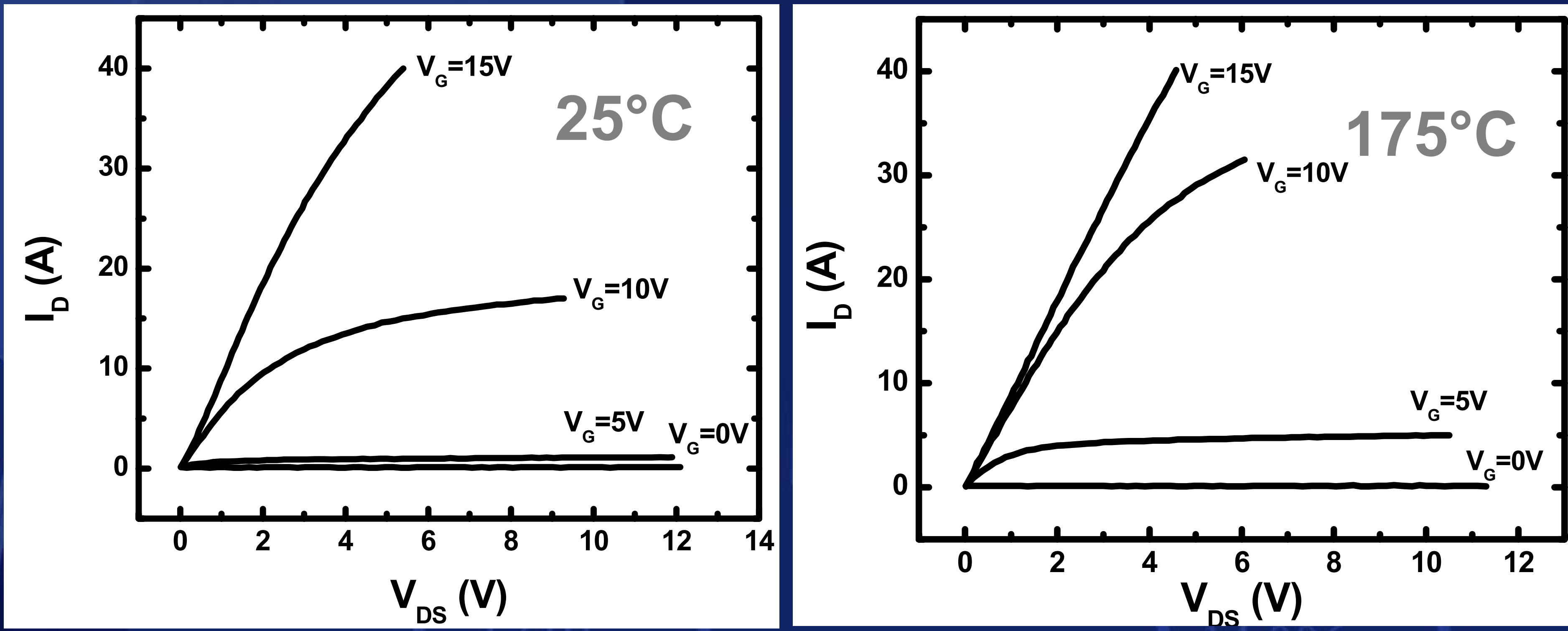

**21.8 mΩ-cm²**

## March 2006

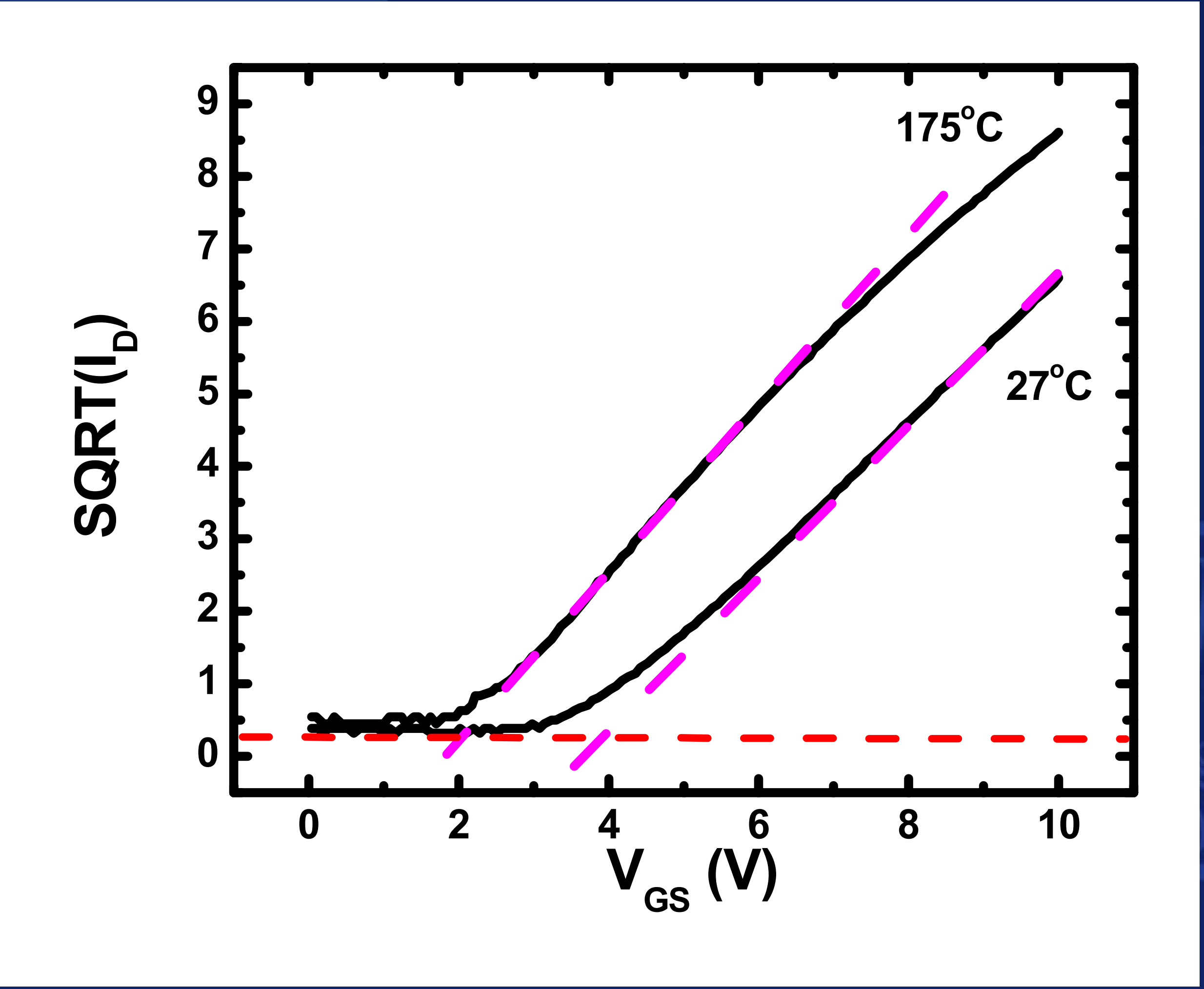



**8.1 mΩ-cm²**

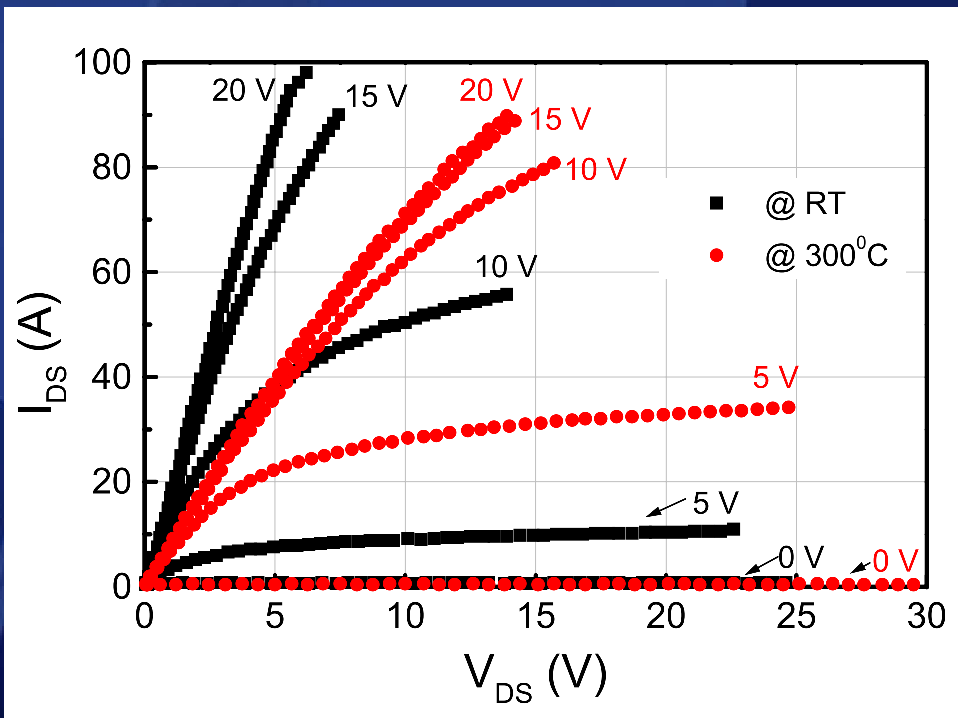
# 1200 V/15 A SiC Power MOSFET – DC Data

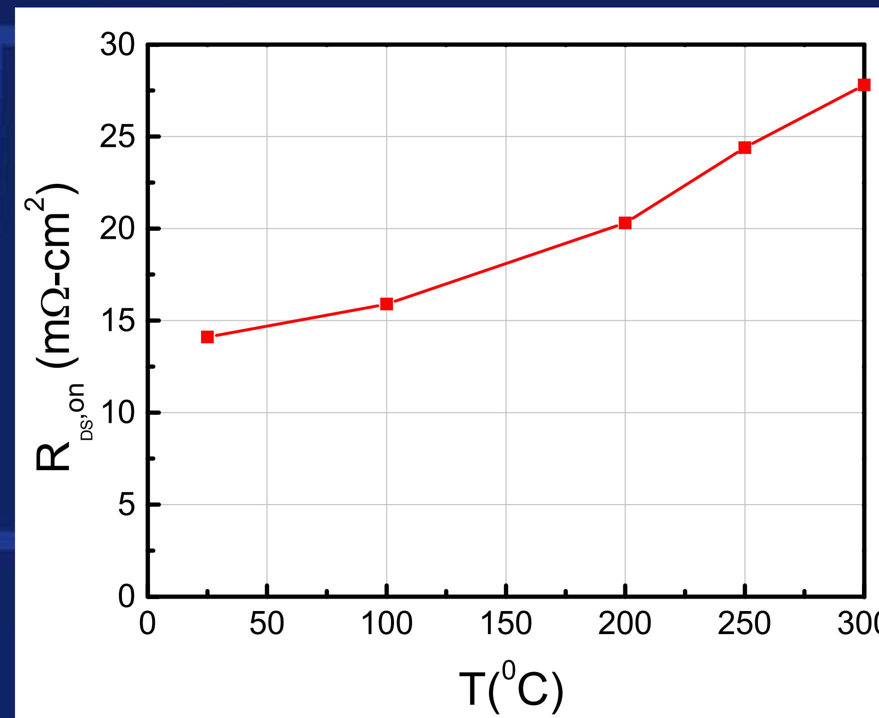


# $V_{TH}$ Reduces from 4 V to 2 V at 175°C



# High Temp DC Data – $R_{ON}$ doubles at 300°C



# Comparison of Switching Energy of 1200V SiC DMOSFET and Si IGBT

| | Turn-on 25 ºC | Turn-on 150 ºC | Turn-off 25 ºC | Turn-off 150 ºC |
|---|---|---|---|---|
| SiC MOSFET | 201 µJ | 173.5 µJ | 57.8 µJ | 60.2 µJ |
| Si IGBT | 239 µJ | 315 µJ | 565.9 µJ | 1200 µJ |

- SiC MOSFET total switching loss:
  - 258.8 µJ @ 25 ºC
  - 233.7 µJ @ 150 ºC
- Si IGBT total switching loss:
  - 804.9 µJ @ 25 ºC
  - 1515 µJ @ 150 ºC

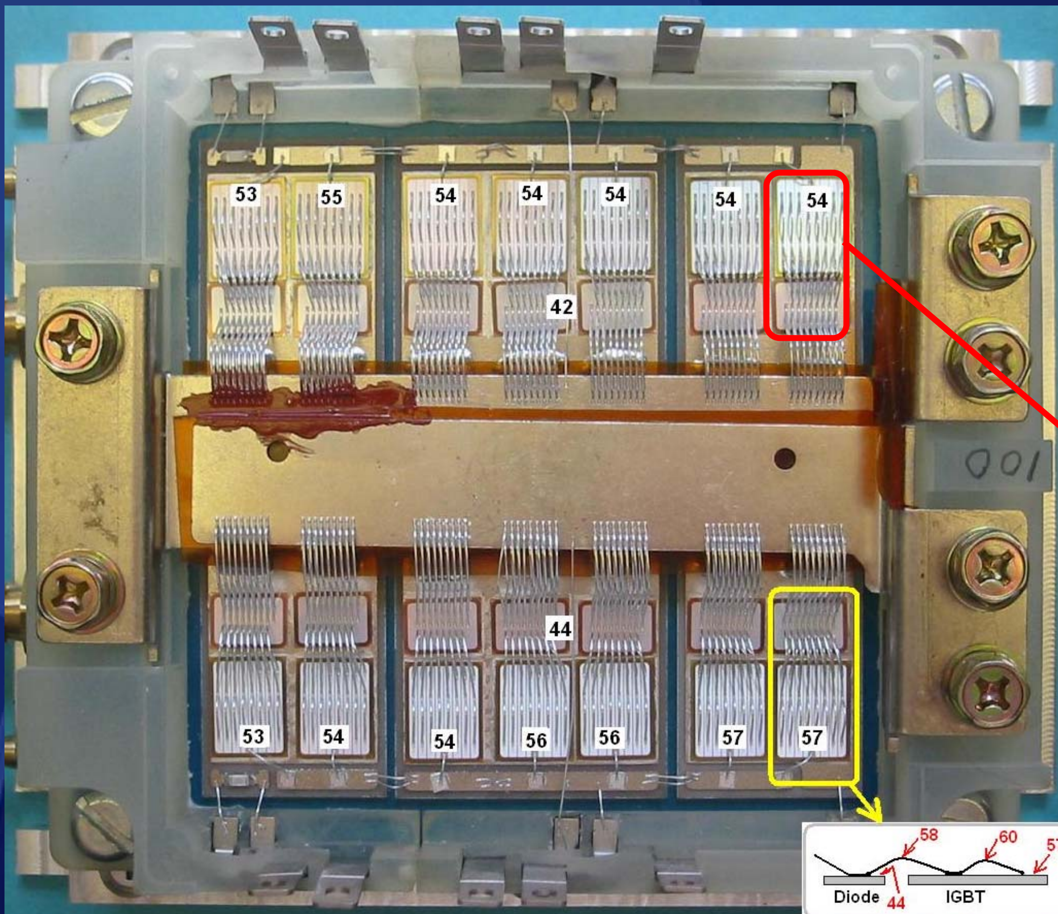
**Cree C2D10120 1.2 kV / 10 A SiC Schottky used in both cases as inductor diode**

# Comparison of Switching Losses of 1200V SiC DMOSFET and Si IGBT

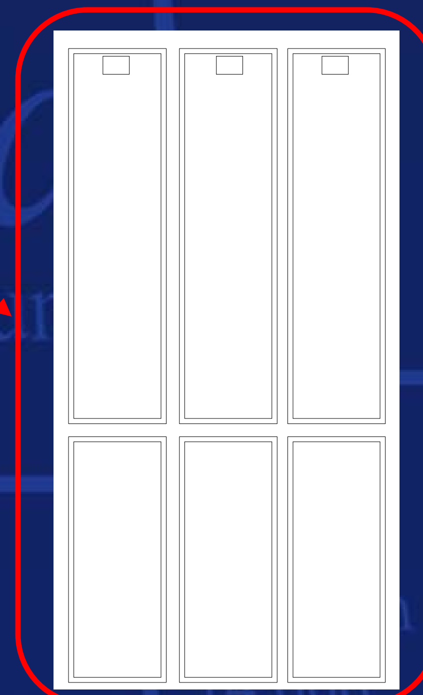
- SiC MOSFET has substantially lower inductive switching losses than competitive Si IGBT especially at high temperature,
  - At 25 ºC, total inductive switching loss of SiC DMOSFET is less than 1/3 of Si IGBT
    - Turn-on losses are similar and turn-off losses are about 1/10 of Si IGBT
  - At 150 ºC, total inductive switching loss of SiC DMOSFET is less than 1/6 that of a Si IGBT
    - Turn-on losses are about 1/2 and turn-off losses are about 1/20 of Si IGBT

- Next Steps ⇒
  - Scale Up & Cost Reduction
  - Insertion Into SiC Power Modules
- Primary Concern ⇒ Yield

# All SiC Dual 1200V/1400A Module w/ 67A MOSFET Die




- Replace each 12x15.6 mm Si IGBT with 3.7mm x 14.5mm SiC MOSFET
- Replace each 12x8.5mm Si FWD with 3.7x 9.5mm SiC JBS Diode

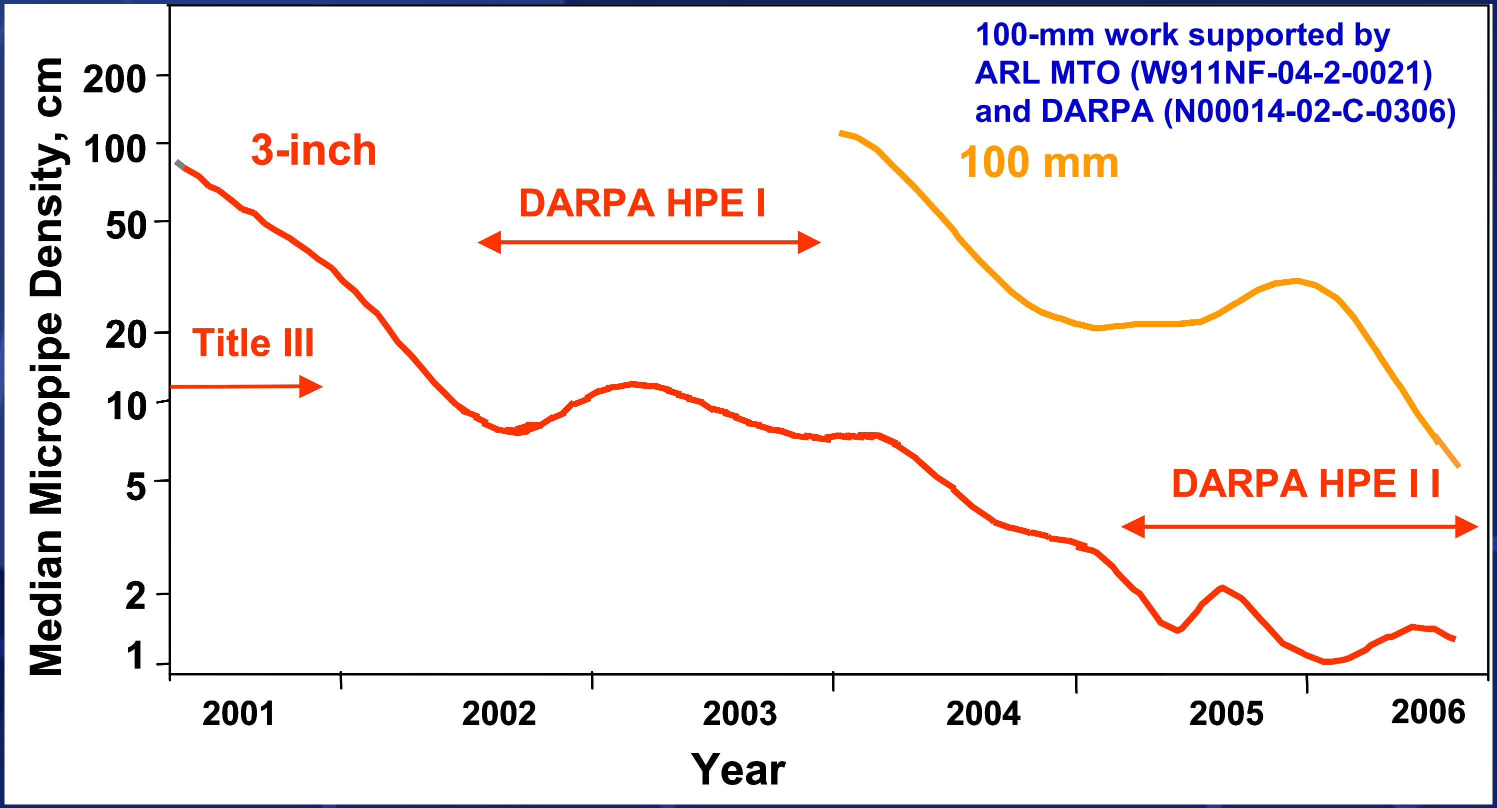


- 67A SiC MOSFET – 53mm$^2$, 150A/cm$^2$, $V_f$ = 1.5 V @ 25°C, $V_f$ = 2.0 V @ 175°C
- 53A SiC JBS Diode – 35mm$^2$, 150A/cm$^2$, $V_f$ = 1.8 V @ 25°C, $V_f$ = 2.2 V @ 175°C

# Producibility of 1200V SiC Power Devices

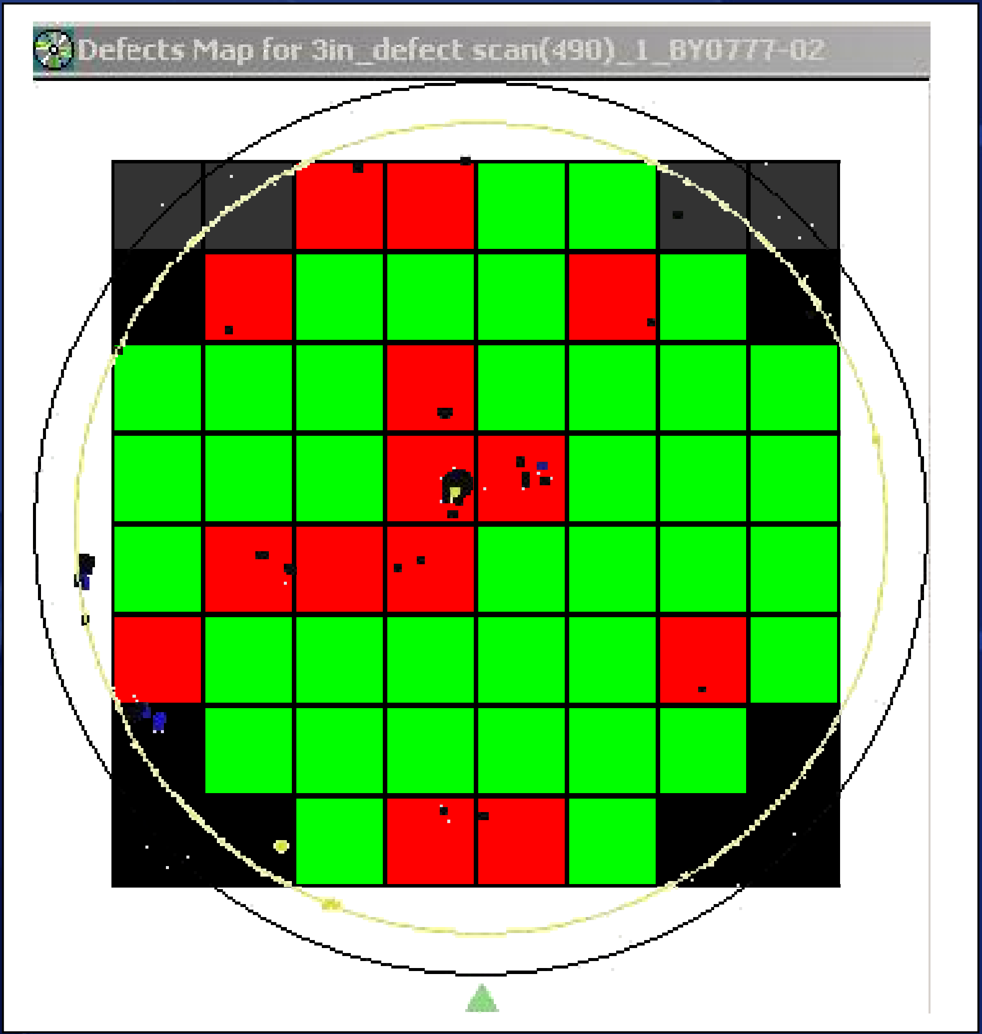
- High Quality SiC Material for SiC Power Devices
  - Reduced 4HN-SiC Micropipe Density for Increased SiC Power Device Yield
  - Pre-Screening of SiC Substrate and Epi Material for Enhanced SiC Power Device Yield
- Improved SiC Power Device Fabrication
- Large Area SiC DMOSFET Devices
  - 10A/9kV SiC DMOSFETs
- SiC DMOSFET Stability and Reliability

# Cree SiC Micropipe Density Dramatically Reduced For Enhanced SiC Device Yield



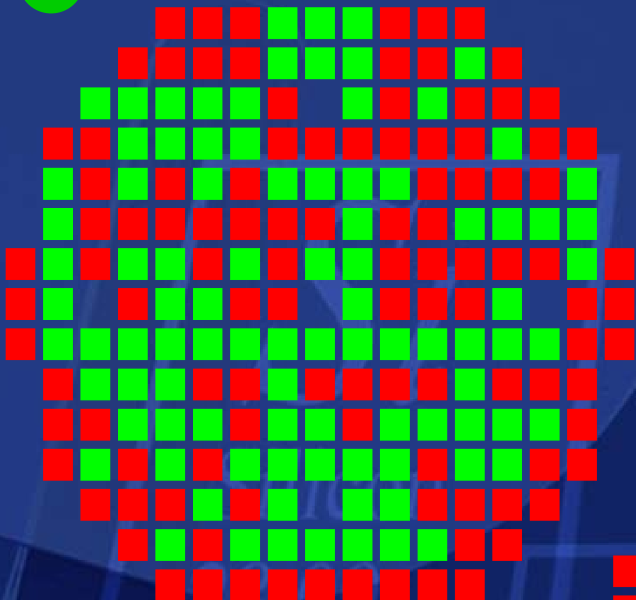

- Cree Monthly Median Production SiC Substrate Micropipe Density (MPD)
- Zero Micropipe Density 3-inch 4HN SiC Wafer Demonstrated!

# Pre-Screening of SiC Material To Maximize SiC Device Yield




- Distribution of Catastrophic SiC Material Defects Determined by Candella Tool
  - SiC substrate & epi defects
  - 2.31 defects $cm^{-2}$ on this wafer
- Project 8x8 mm SiC Devices on Candella Material Defect Map
- Provides Estimate of SiC Device Yield From Material Defect Distribution
  - 73% material yield on this wafer

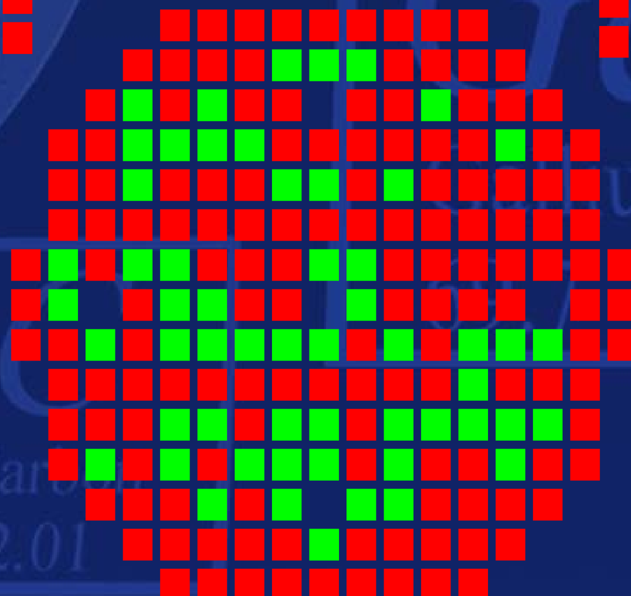
# 15A/1200V SiC DMOSFET Device Yield Maps



**1200V Blocking Yield**

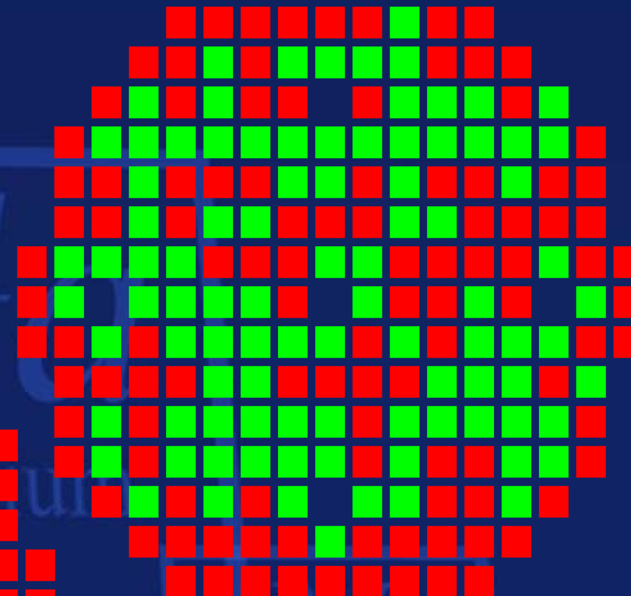
$I_{DS}$ < 100 μA

**46.5%**



**Combined Yield**

**27.7%**

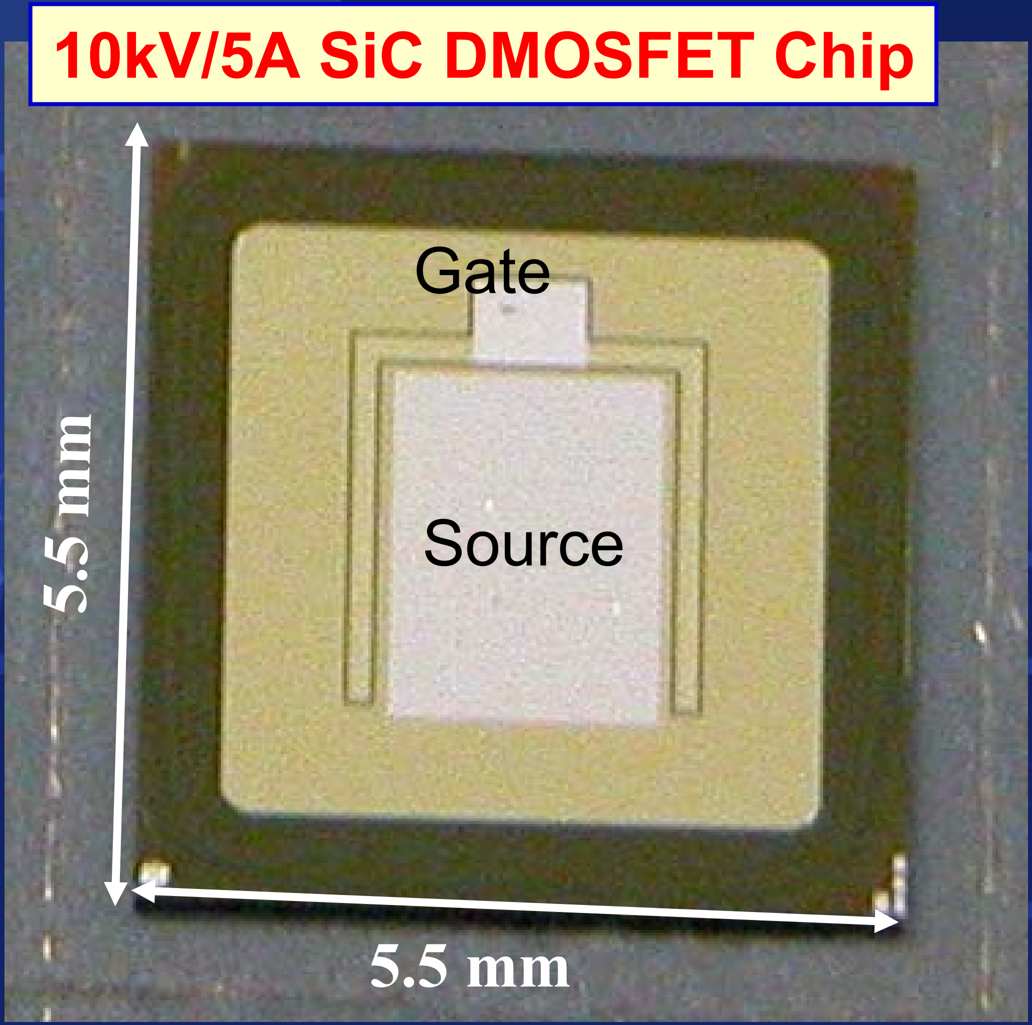


**On-State Yield**

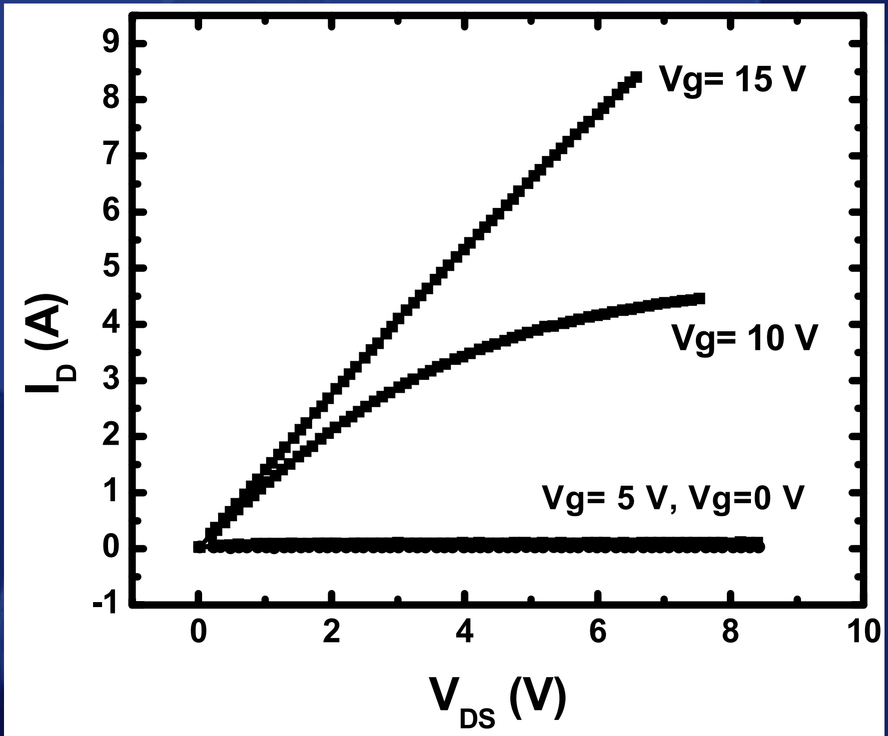
$I_{DS}$ > 3 A at $V_G$ = 15 V and $V_{DS}$ = 0.5 V

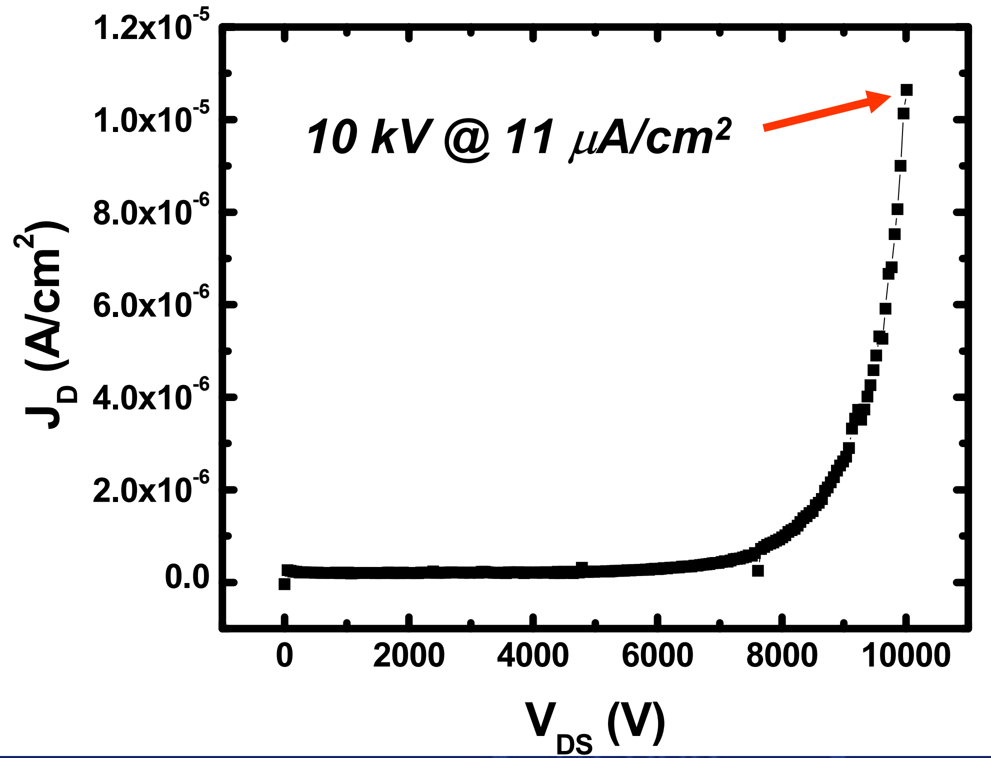
**46.0%**

# 10kV SiC DMOSFET Area Scaled Up By Factor of 36x During HPE-II



# 10kV/5A 4H-SiC DMOSFET
# Forward & Reverse Characteristics

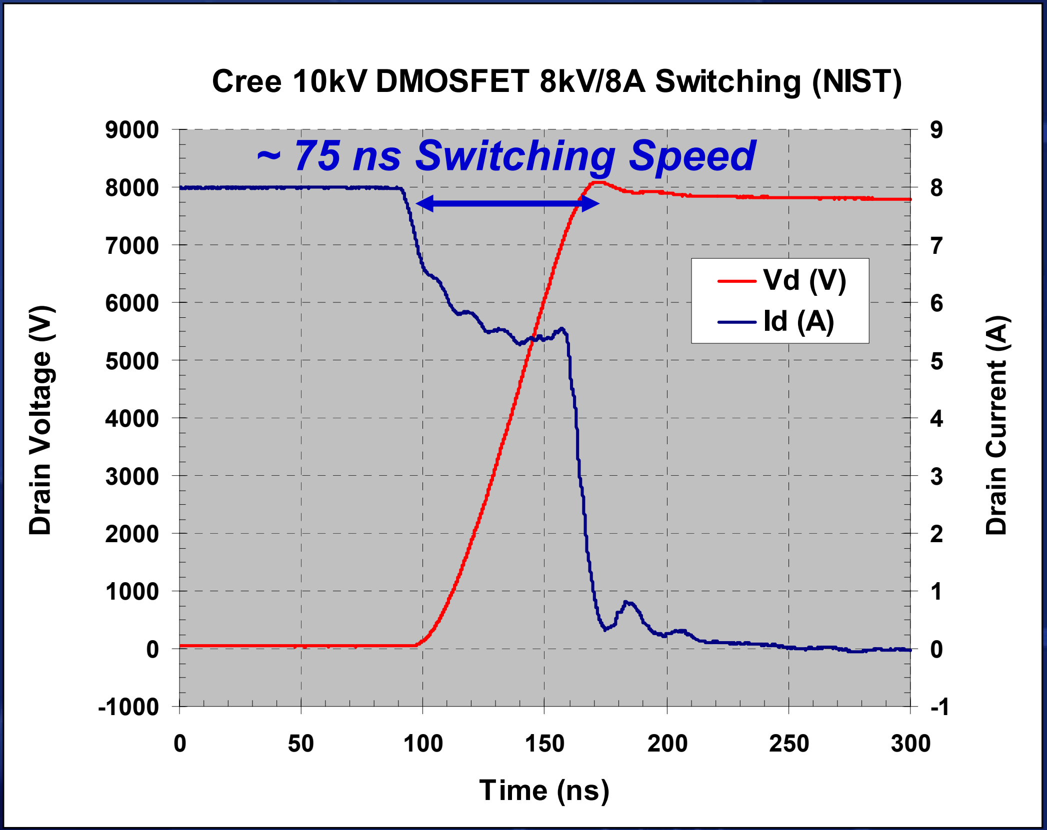



$R_{on,sp}$ = 111 mΩ-cm²
$V_F$ @ 5A = 3.9 V

BV > 10 kV

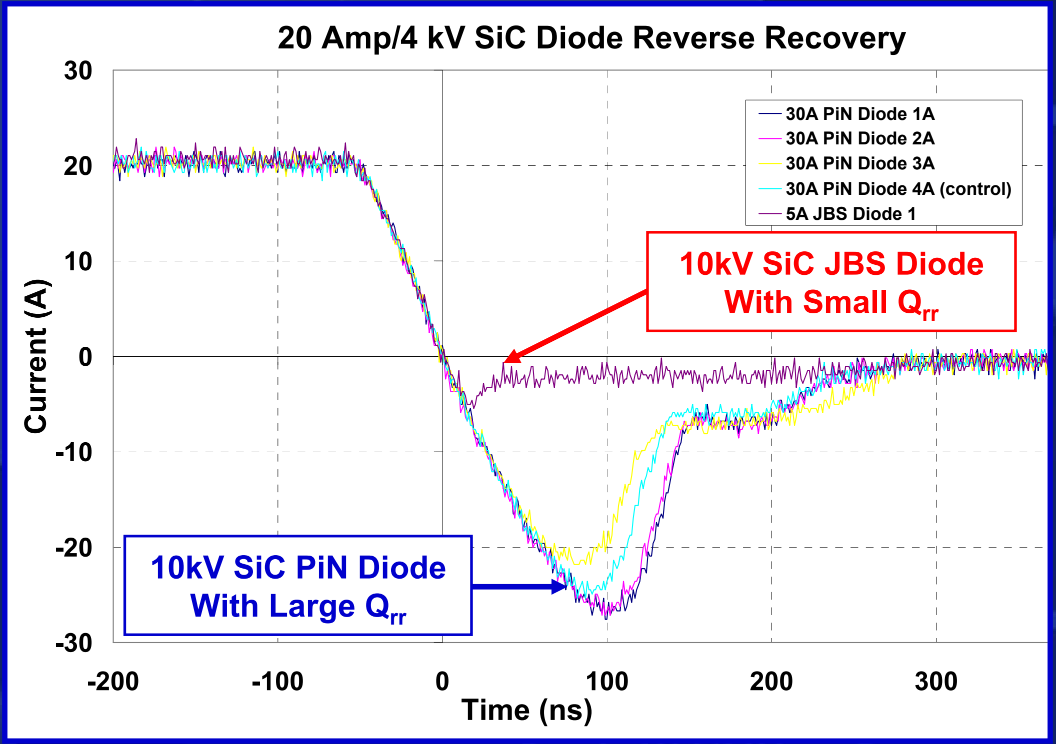
# 10kV SiC DMOSFET Demonstrated For 20 kHz Switching of SiC Module




**Measured Switching Speed of ~ 75 ns for 10kV SiC DMOSFET at 25°C**

- **10kV/10A SiC DMOSFETs Have Been Demonstrated**
- **10kV SiC DMOSFETs Capable of $T_j$ = 200°C Operation**
- **10kV SiC DMOSFETs Have Switching Speed ~ 75 ns**
- **Enables 20kHz Switching of 10kV SiC Half H-Bridge Module**
- **Remaining Issue – 10kV SiC DMOSFET Needs to Be Scaled Up to 20A with 30% Yield**

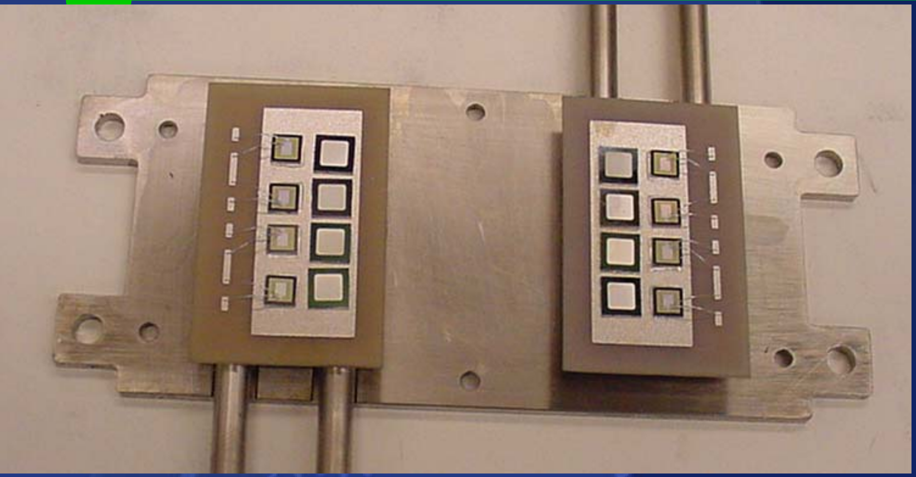
# 10kV SiC JBS Diode Demonstrated For 20 kHz Switching of SiC Module

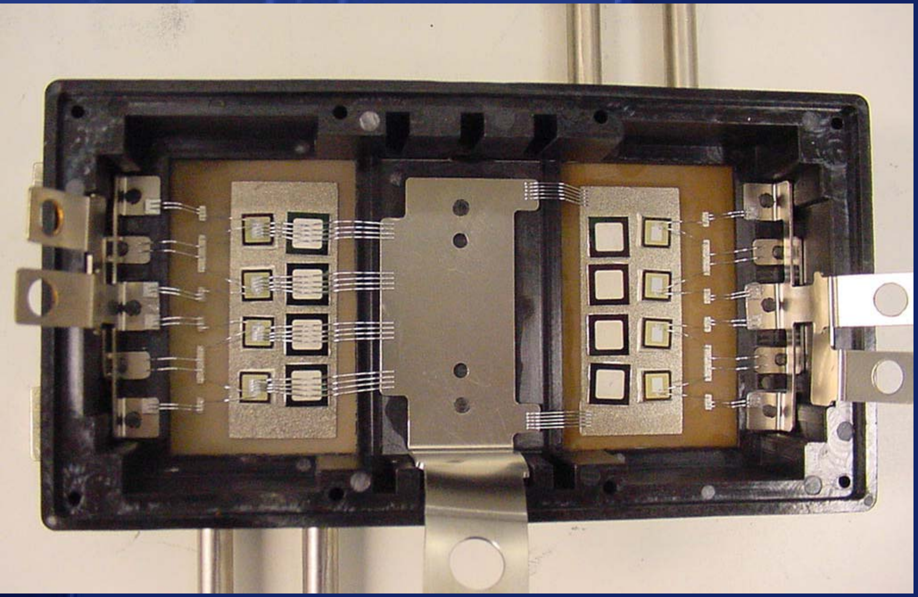


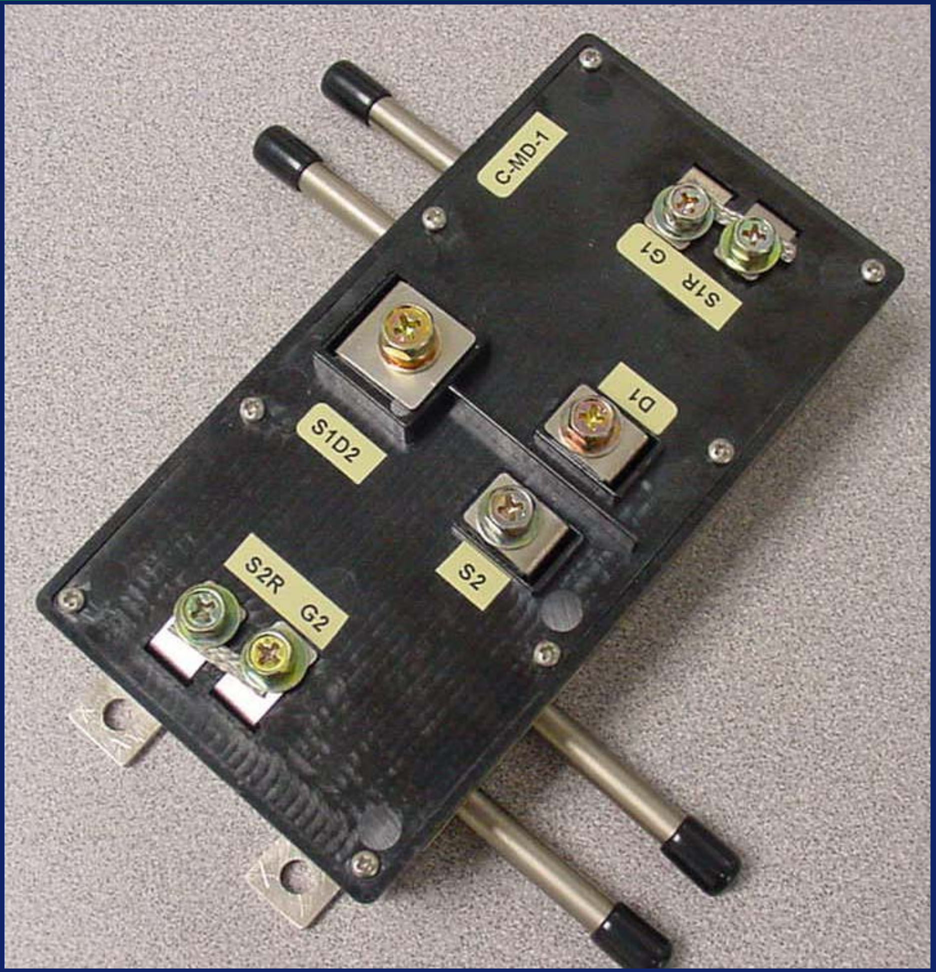

**10kV/20A SiC JBS Diode Has Much Smaller Reverse Recovery and Higher Switching Speed Compared to PiN**

- SiC PiN Reverse Recovery Energy Dissipated On SiC DMOSFET
- Solution - Use SiC Junction Barrier Schottky (JBS) Diodes With Much Smaller Reverse Recovery ($Q_{rr}$) and Higher Switching Speed
- HPE-II Refocused on 10kV/20A SiC JBS Diodes
- 10kV/5A SiC JBS Diodes Have Been Demonstrated with Single Wafer Blocking Yield > 40%
- Remaining Issue – 10kV SiC JBS Diode Needs to Be Scaled Up to 20A with 30%Yield

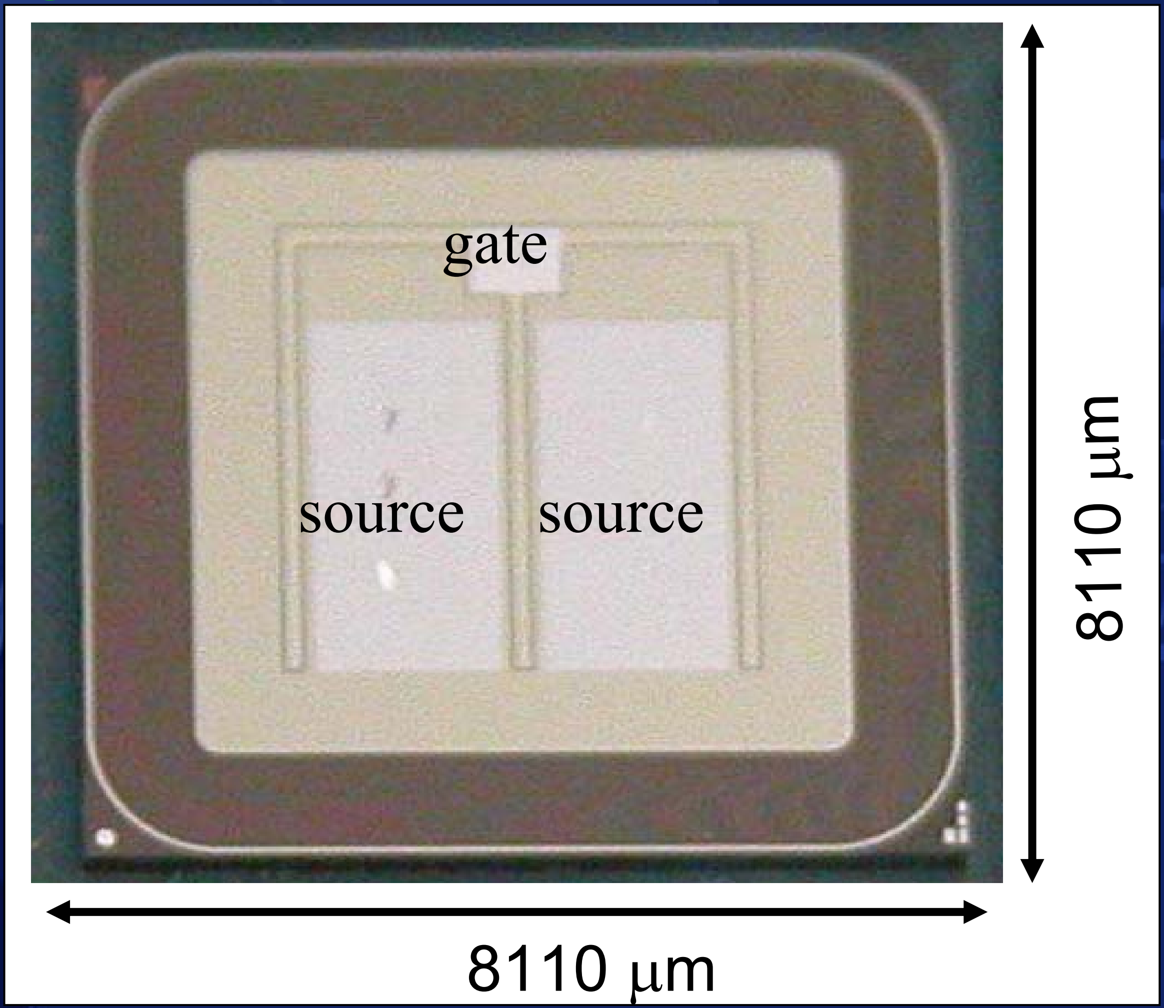
# 10kV 20A Dual SiC MOSFET Module





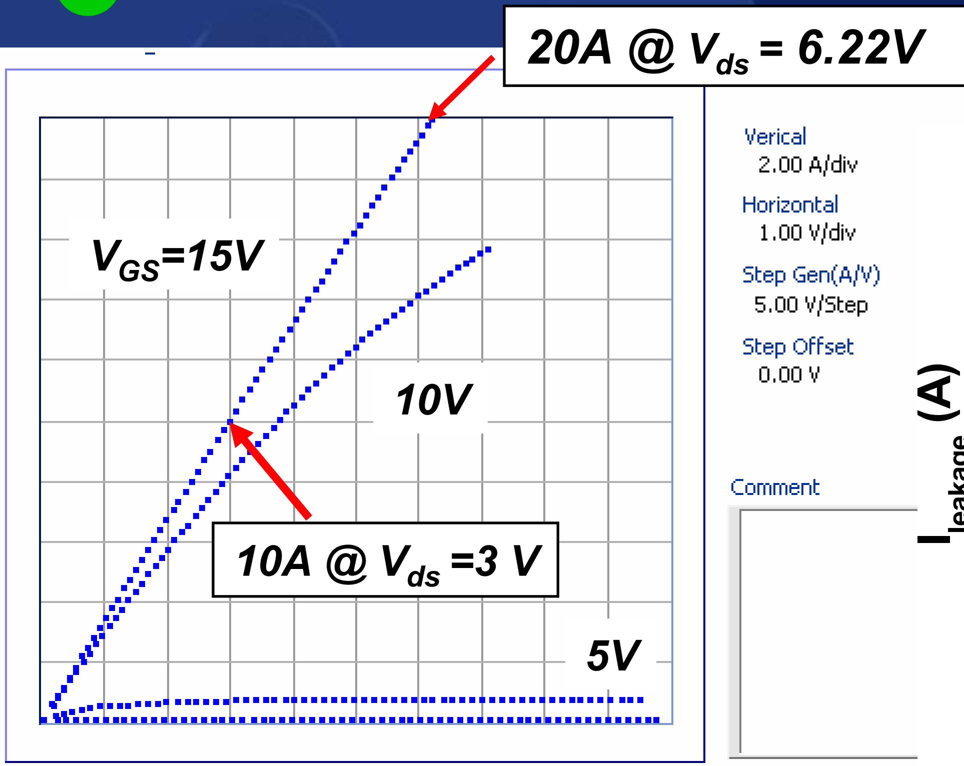


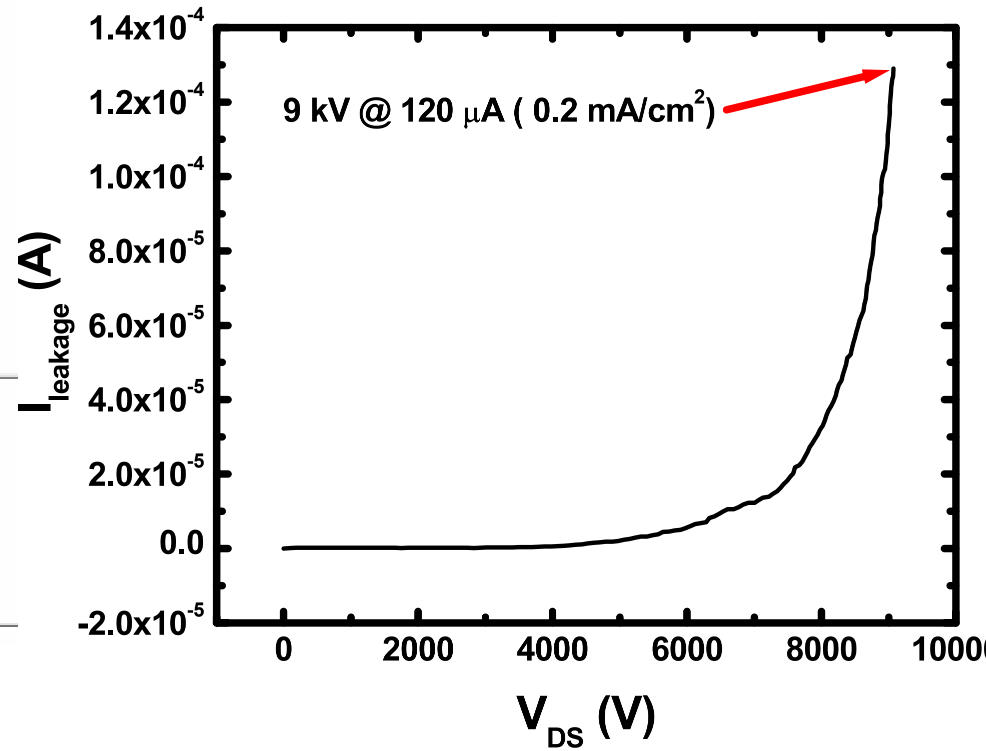
# Demonstrated Capability of Fabricating Large 9kV SiC DMOSFET Devices




- 9 kV / 20 A SiC DMOSFET
- 8.1 x 8.1 $mm^2$ Chip Area
- 0.31 $cm^{-2}$ Active Area

# 9kV/20A 4H-SiC DMOSFET Demonstrated

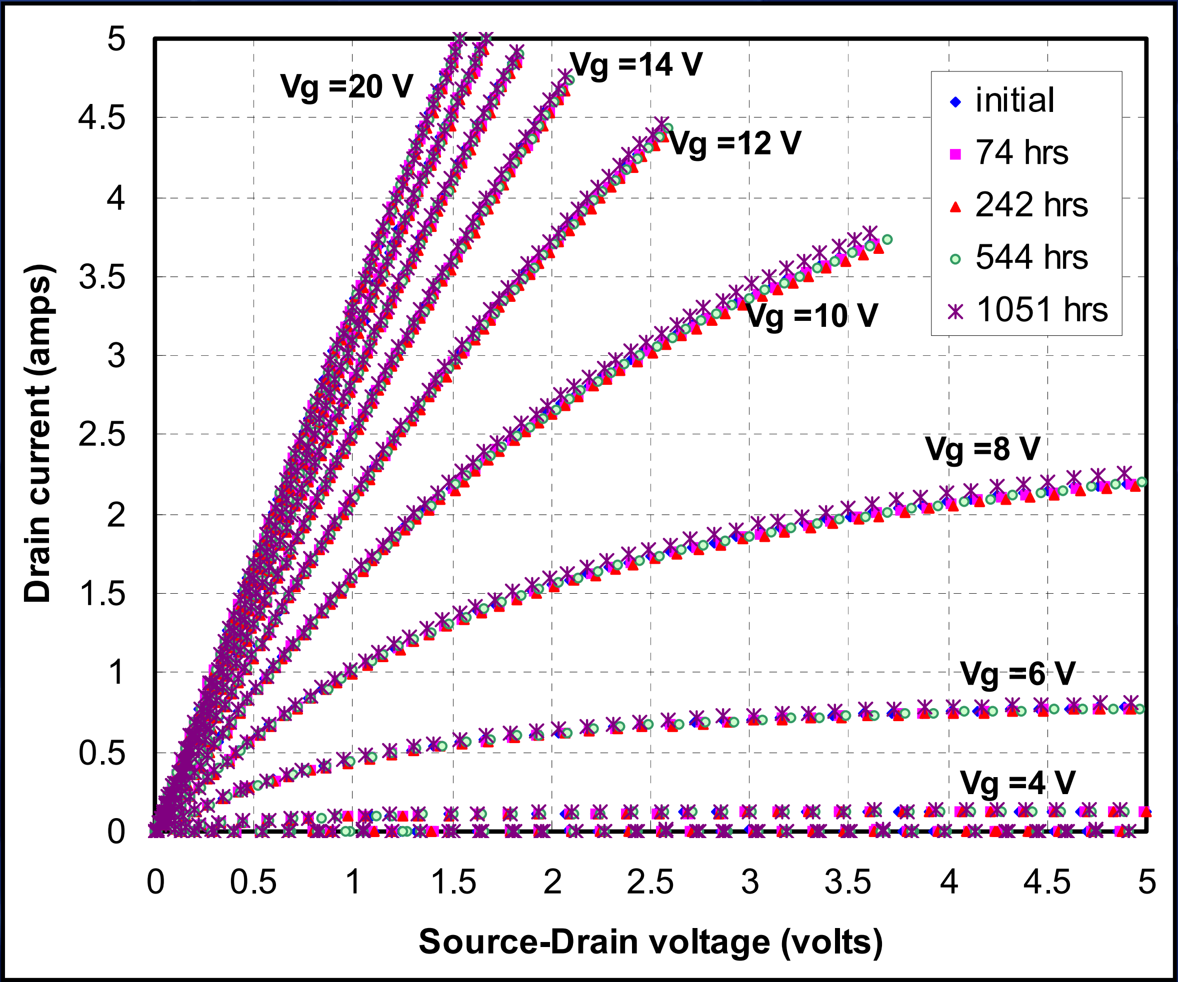



**91 mΩ-cm$^2$**
**20 A @ 189 W/cm$^2$**

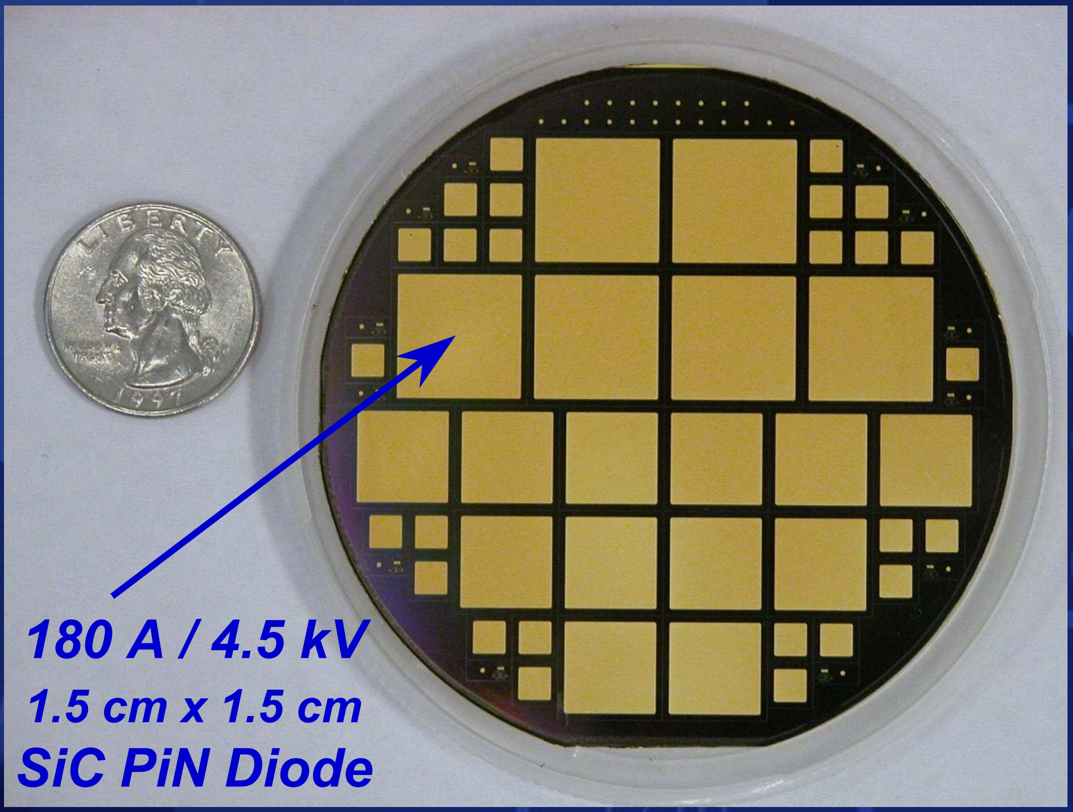
**BV > 9 kV**

# Stability of 1200V/5A SiC DMOSFETs Under High Temp Forward Gate Bias Stress




- Forward Gate Bias Stress of Packaged 1200V/5A SiC DMOSFETs (0.0753 $cm^2$)
  - Stressed at 175°C - $V_g$ = 15 V
  - Source/Drain Grounded
  - Similar to Si MOSFET Stress Test Adjusted for Oxide Field
- SiC DMOSFETs Cooled to RT and Remeasured
- 1200V SiC DMOSFET I-V Curve Remains Virtually Unchanged Up To ~ 1050 Hrs High Temp Forward Gate Stress

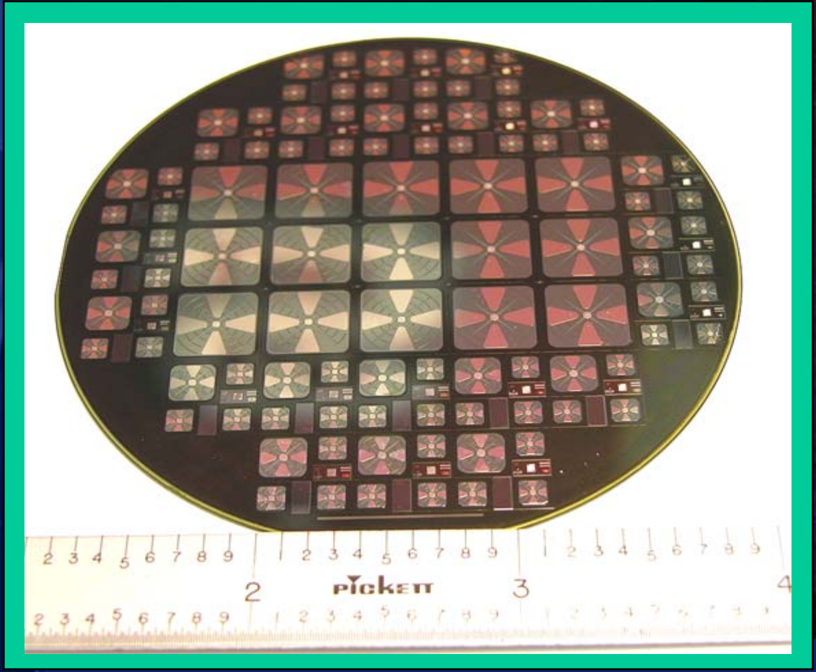
# 180 A / 4.5 kV SiC PiN Diode

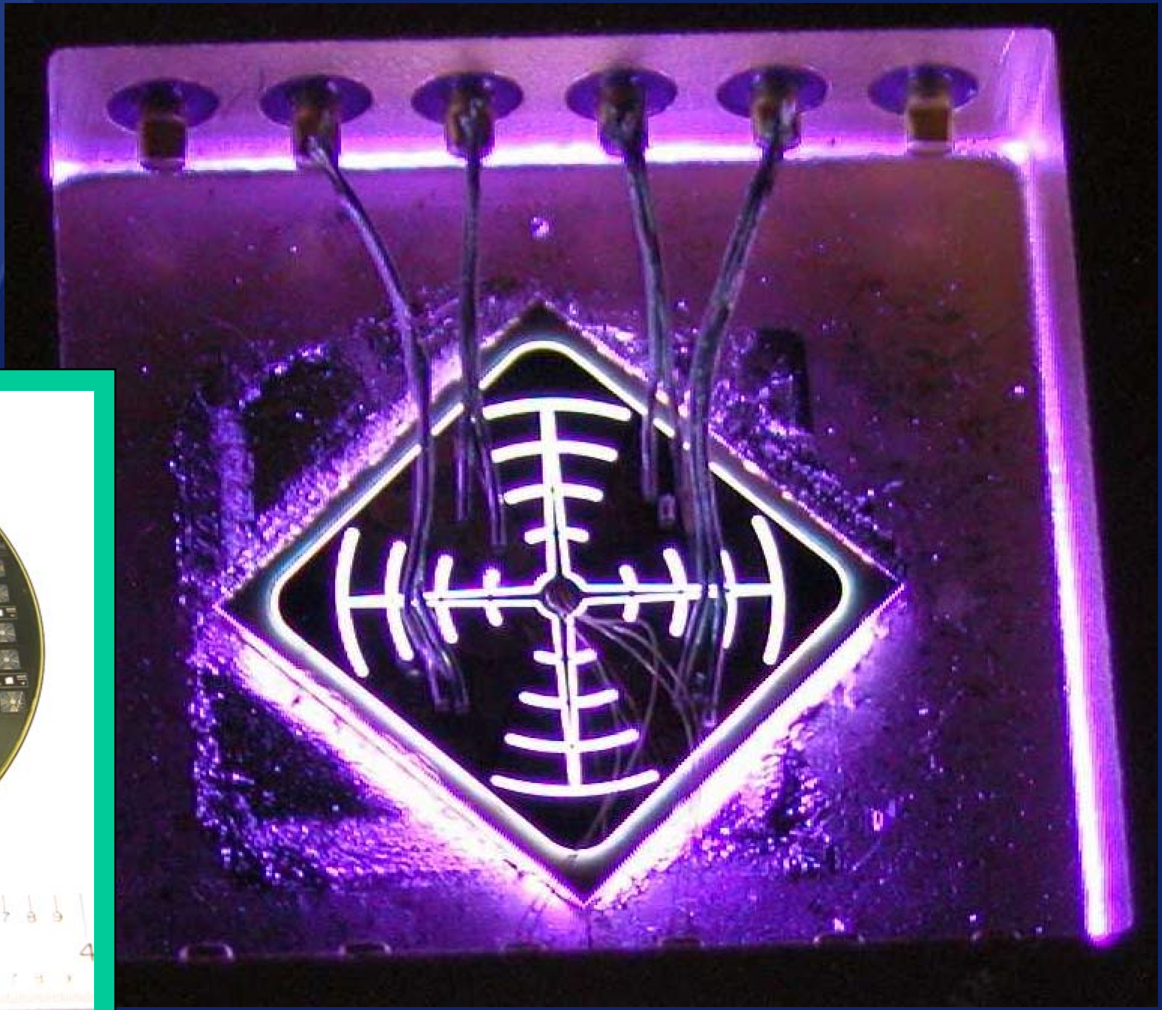



- **Largest SiC Device Demonstrated**
- **Over 65% Device Yield On 3-inch 4HN-SiC Wafer**
- **1.5 cm x 1.5 cm SiC PiN Diode Blocking Voltage Limited by Thinner Blocking Layer**
- **Result of High Quality Material Growth and Device Fabrication**
- **Demonstrates That Large Area SiC Power Devices Can Be Fabricated With Good Yield**

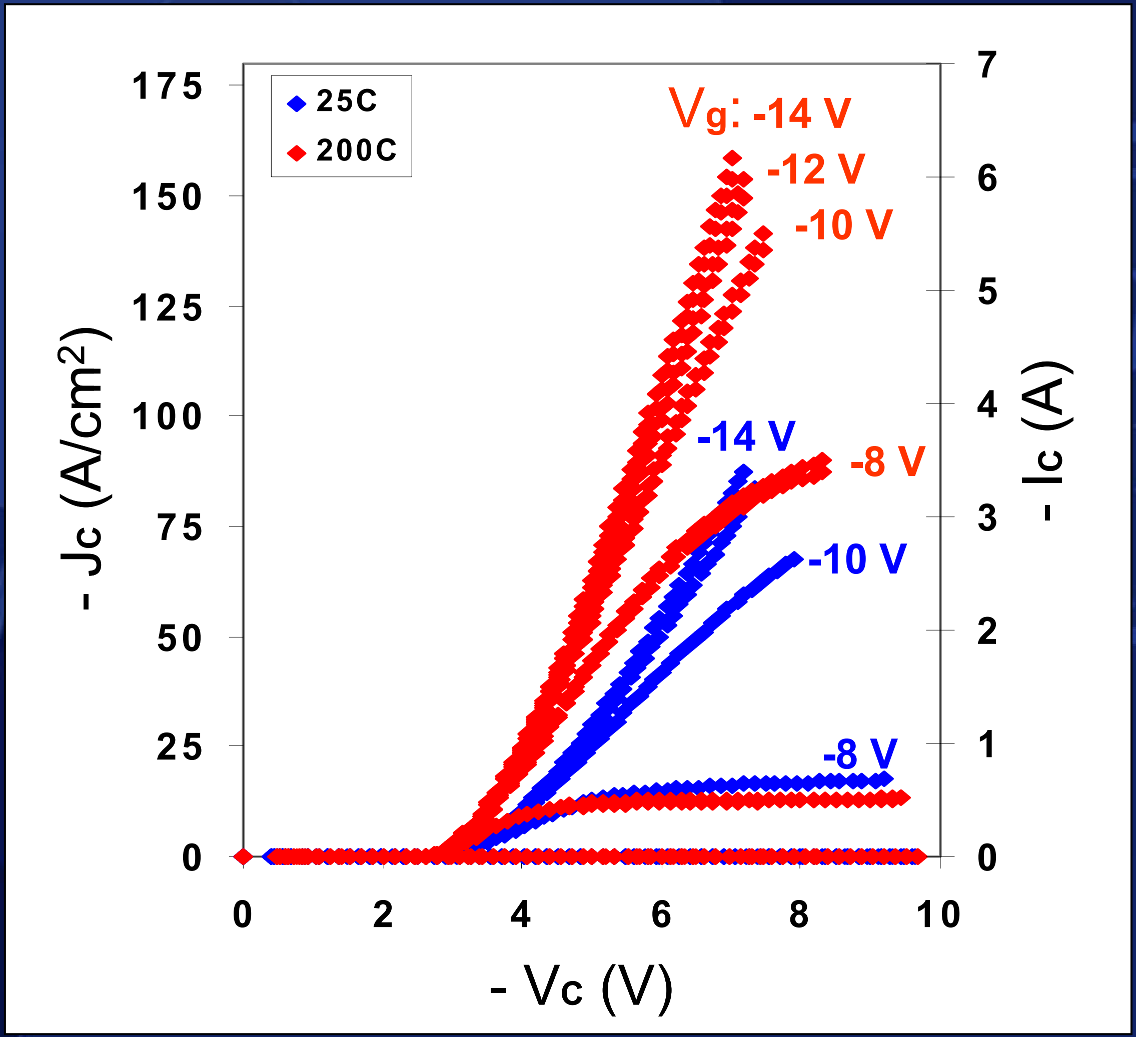
# 1 cm x 1 cm SiC Thyristor

**5 kV / 300 Amp**
**4H-SiC**
**Thyristor**



# 2mm x 2mm 7.5 kV 4H-SiC p-IGBT Forward Characteristics




- **Active area:**

  2mm x 2mm

- **At 25°C**
  - R diff, on: 38.8 mΩ·cm²
  - $V_F$ @ 50A/cm²: 5.8 V
- **At 200°C**
  - R diff, on: 22.6 mΩ·cm²
  - $V_F$ @ 50A/cm²: 4.7 V

$\mu_{ch}$ ~ 10 cm²/V-s

$V_{TH}$ = -7.6 V

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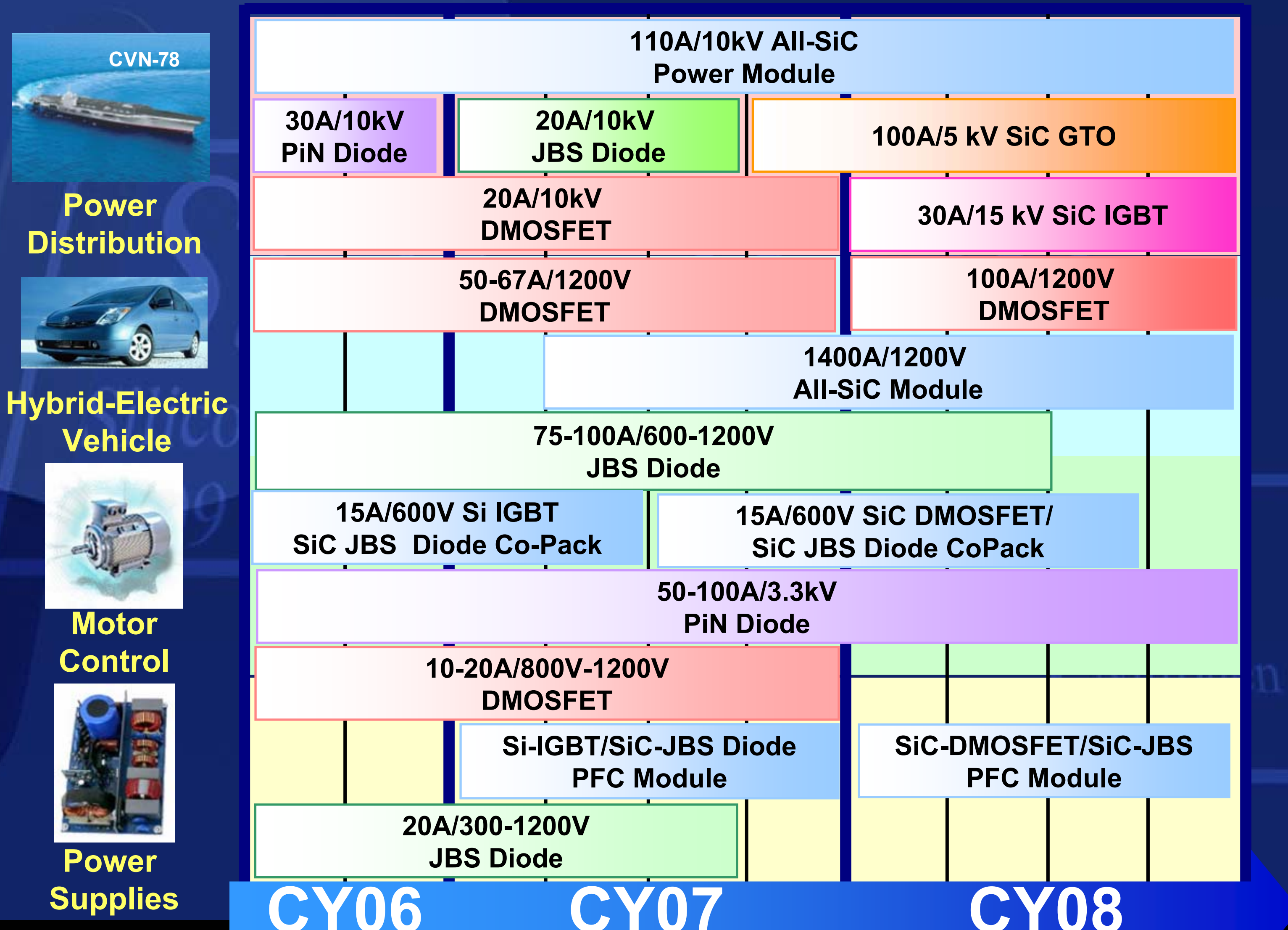
# SiC Power Technology Roadmap



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