Advances in SiC Power Technology

DARPA MTO Symposium

San Jose, CA
March 7, 2007

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Cree, Inc.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **07 MAR 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Advances in SiCPower Technology**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Cree, Inc.**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

DARPA Microsystems Technology Symposium held in San Jose, California on March 5-7, 2007. Presentations, The original document contains color images.

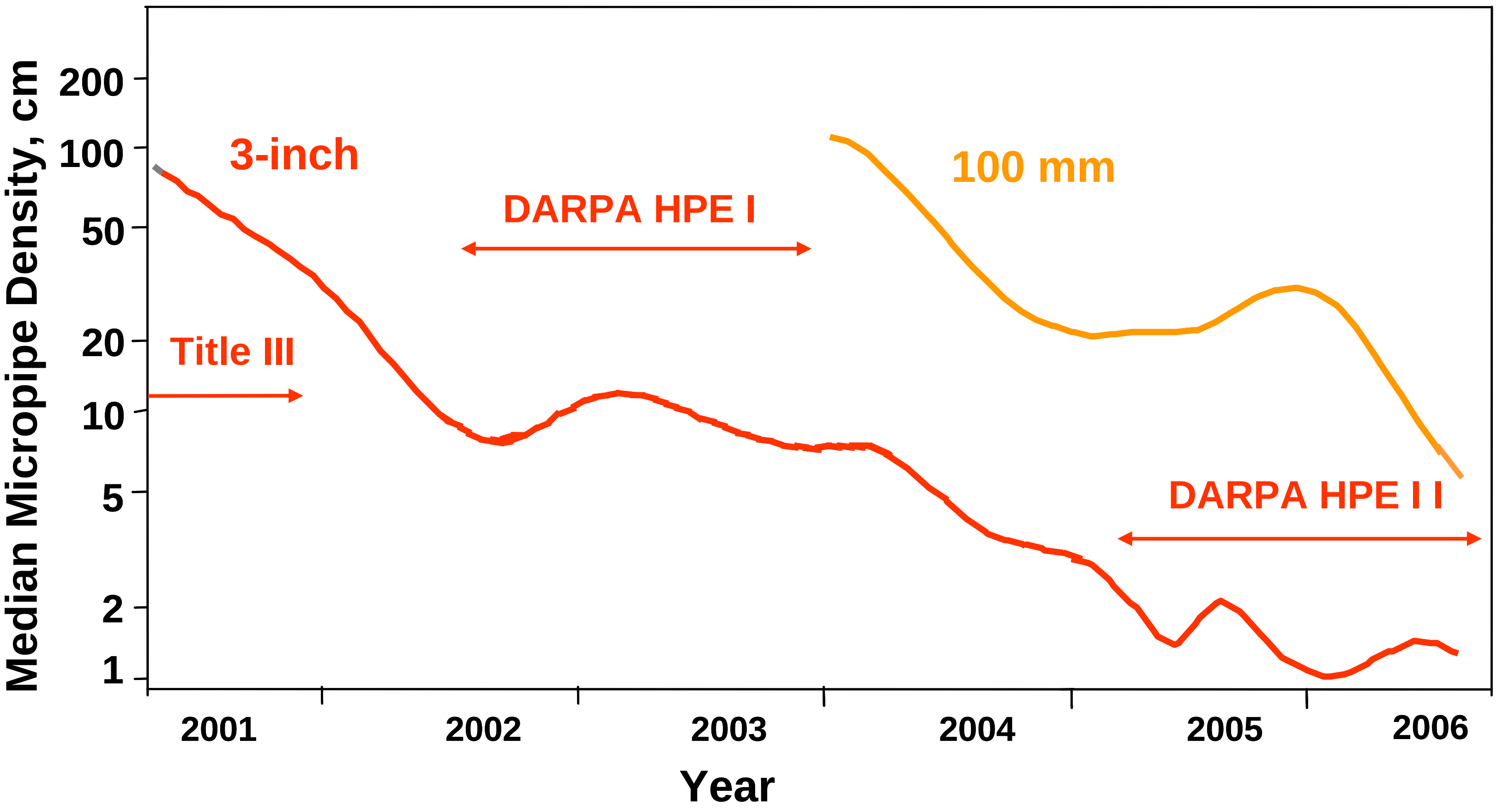
14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**21**	

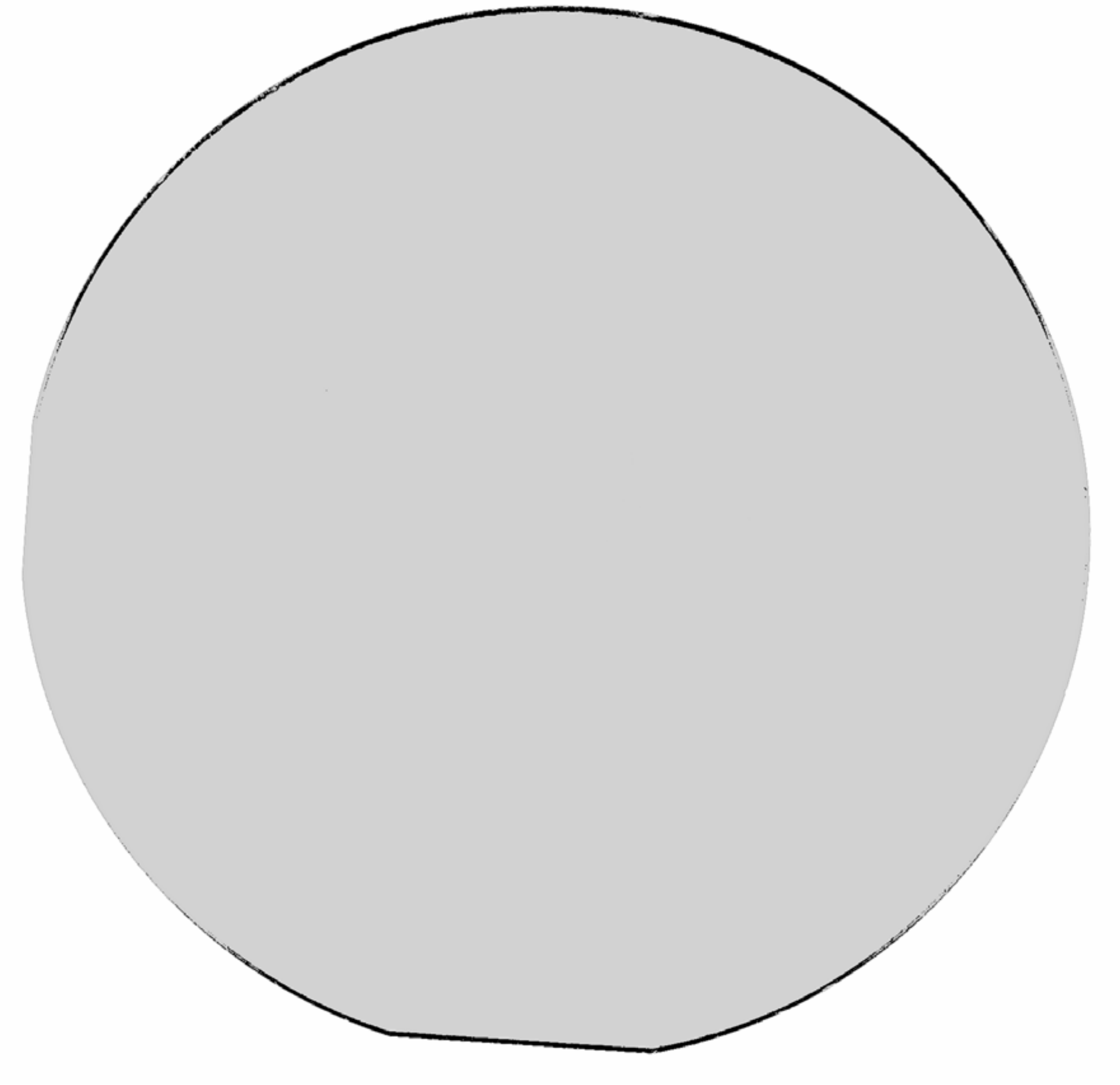
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Monthly Median Production MPD



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

3-inch 4HN SiC Wafer Production Process Quality

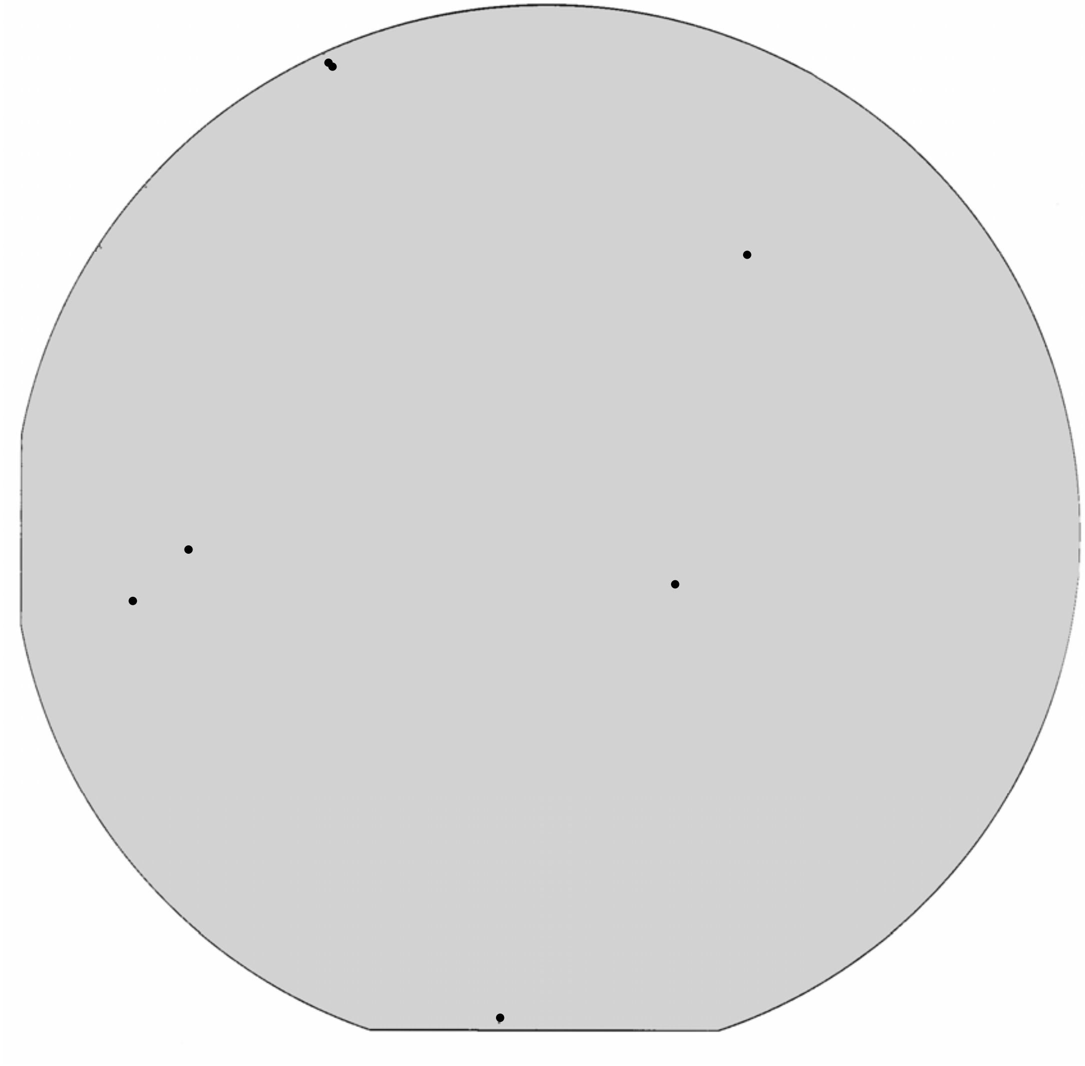


- **Best Production 3-inch 4HN SiC wafer MPD = 0.02 cm^{-2}**

- **Best R&D 3-inch 4HN SiC Wafer MPD = 0.00 cm^{-2}**

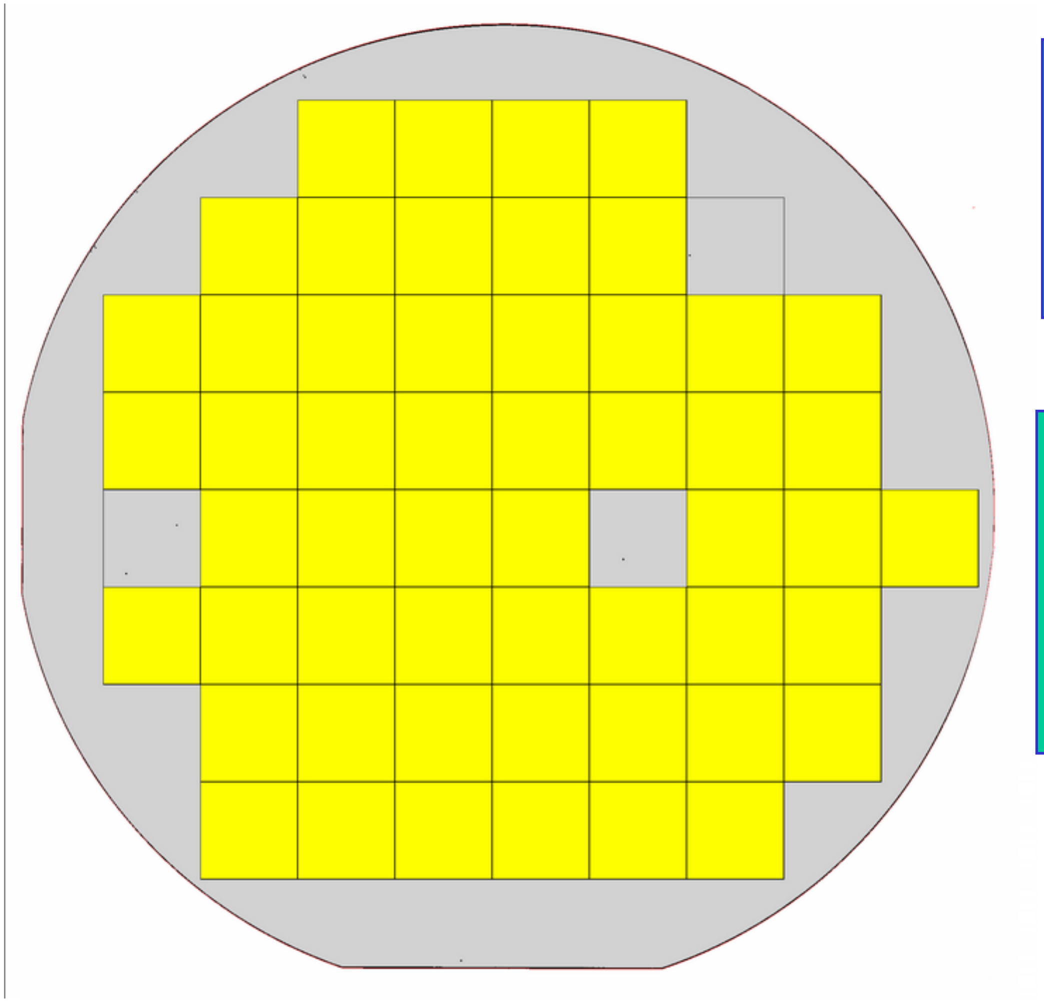
ZMP

100 mm 4HN-SiC Wafer Production Process Quality



- Almost Double the Area of a 3-inch 4HN-SiC Wafer
- Lowest MPD for 100 mm 4HN-SiC With MPD = 0.1 cm^{-2}
- Median MPD < 5 cm^{-2} in Production Process

Projected Device Yield From Lowest MPD 100 mm Wafer Thus Far

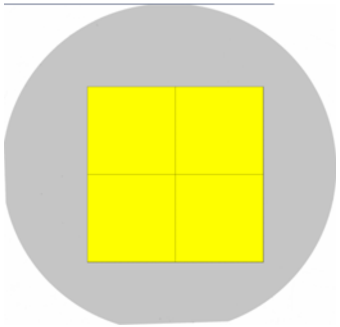


- Projected Yield for 1 cm^2 Devices
- Assume Device Failure Only From Micropipes

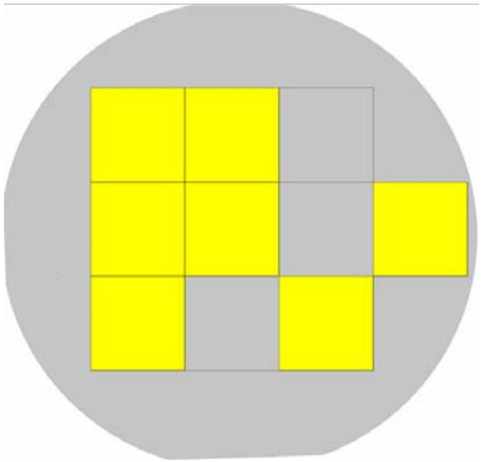
- Micropipe Density = 0.1 cm^{-2}
- Projected Device Yield > 94%
- Yielded Devices = 53
- 65% More Devices Than Ideal 3-inch 4HN SiC Wafer

Decreasing Cost of SiC Devices by Scaling Up 150mm Wafers

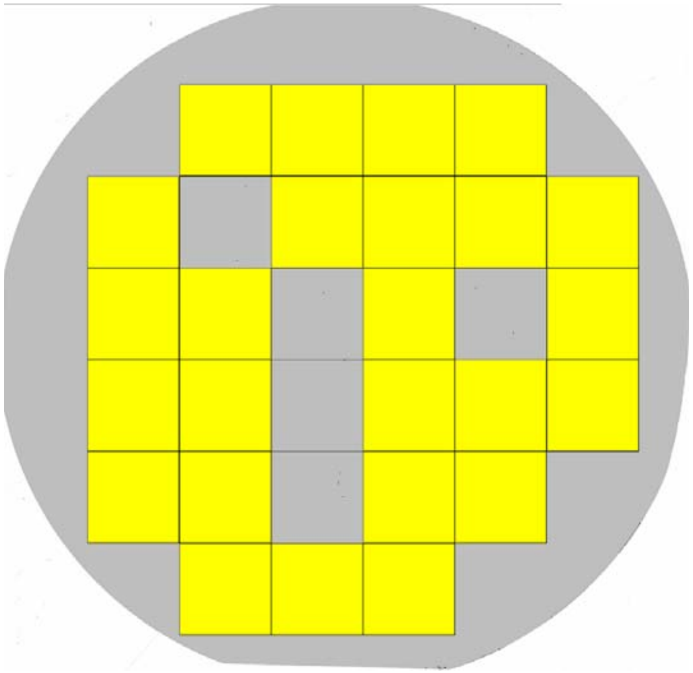
Projected Impact ⇒ > 6X More 4 cm^2 Devices on 150 mm 4HN SiC Wafer



3-inch 4HN-SiC Wafer
ZMP Wafer MPD = 0 cm^{-2}
4 cm^2 device yield = 100%
Yielded 4 cm^2 devices = 4

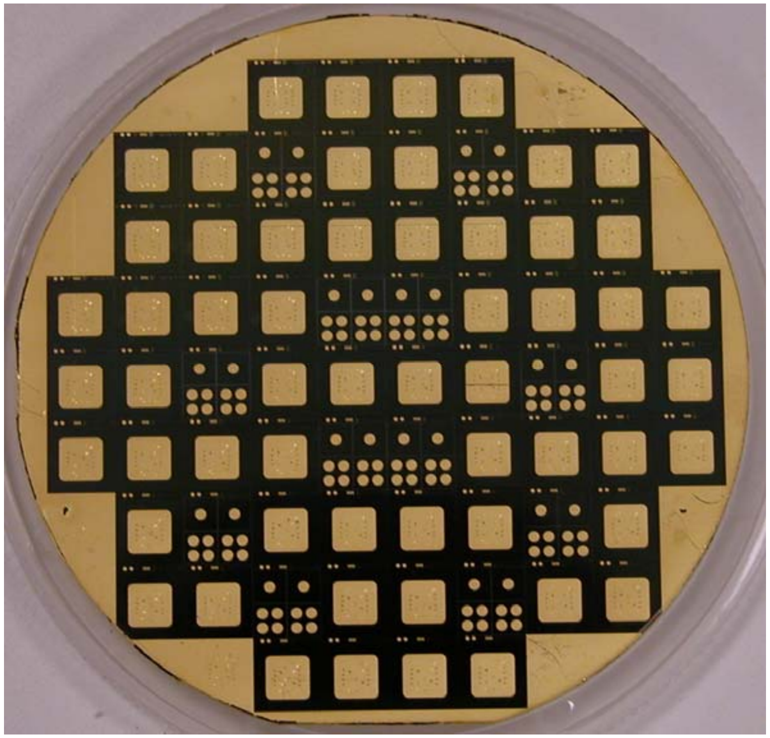


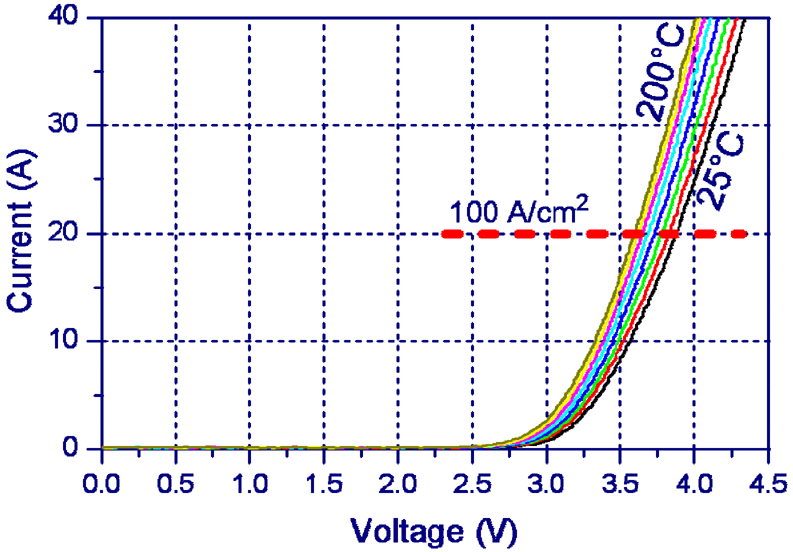
100 mm 4HN-SiC Wafer
Wafer MPD = 0.20 cm^{-2}
4 cm^2 device yield = 70%
Yielding 4 cm^2 devices = 7

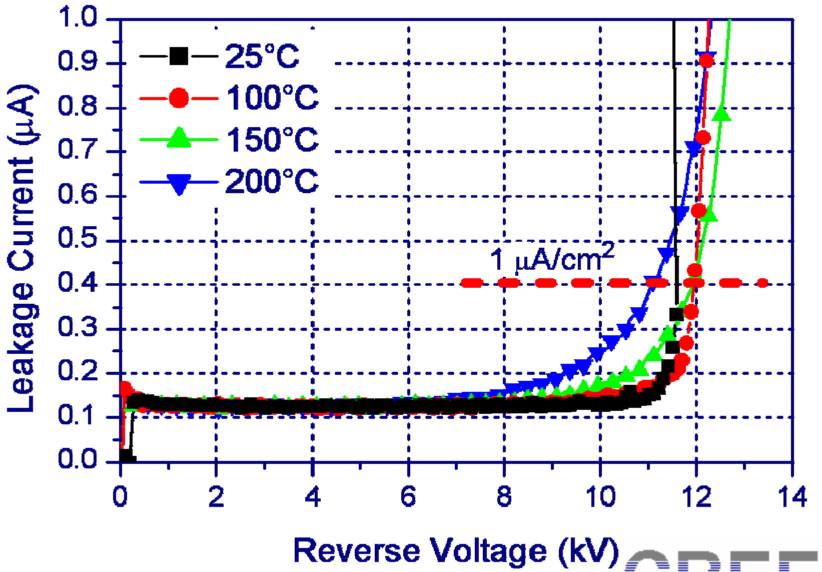


Projected 150 mm 4HN-SiC Wafer
Estimated MPD = 0.20 cm^{-2}
4 cm^2 device yield = 83%
Yielding 4 cm^2 devices = 25

10kV/20A SiC PiN Diode Characteristics Up to 200ºC

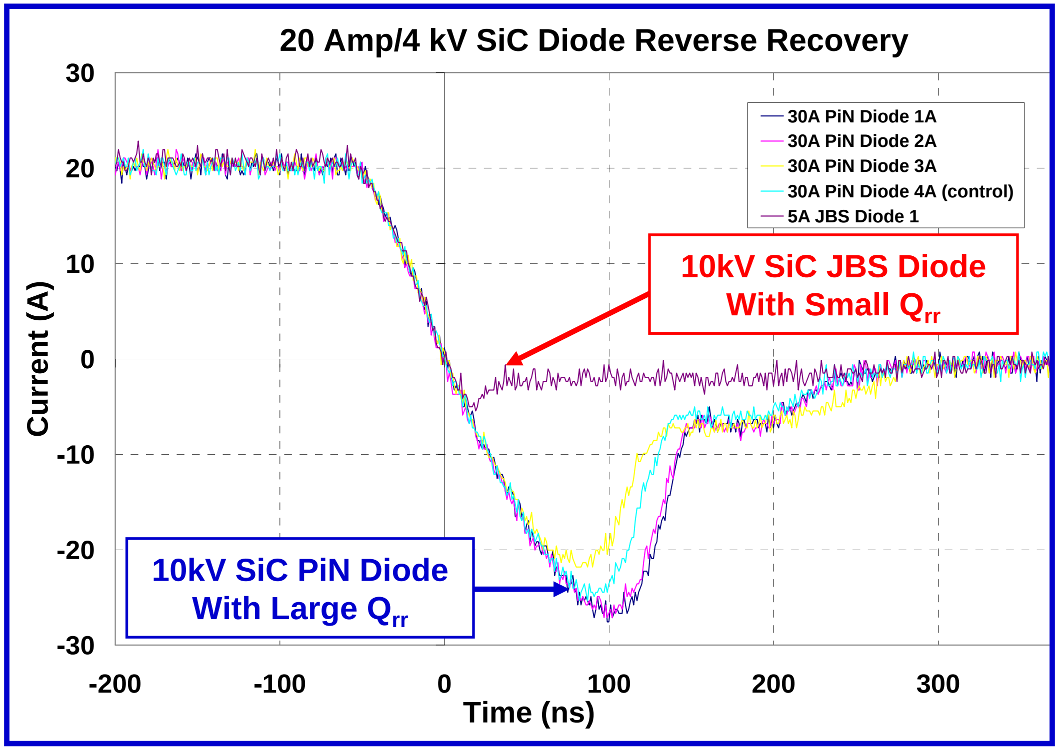






- **10kV/20A SiC PiN Diode**
  - V_F = 3.87 at 25°C
  - V_F = 3.60 at 200°C
  - V_{BR} > 11.5 kV
  - I_R < 300 nA at 10 kV & Tj = 200°C
- **Total SiC PiN Diode Yield ~ 40%**

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


20 Amp/4 kV SiC Diode Reverse Recovery

10kV SiC JBS Diode With Small Q_{rr}

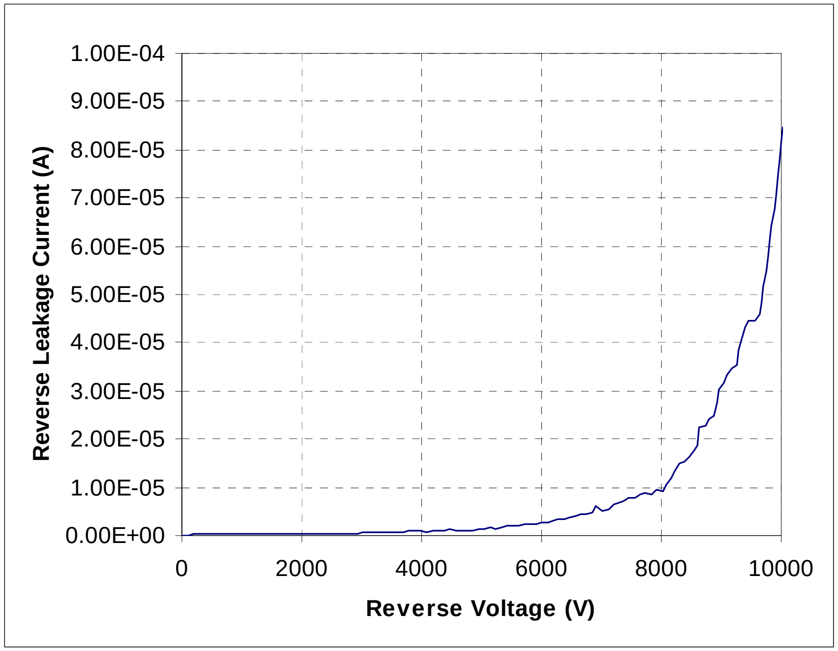
10kV SiC PiN Diode With Large Q_{rr}

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

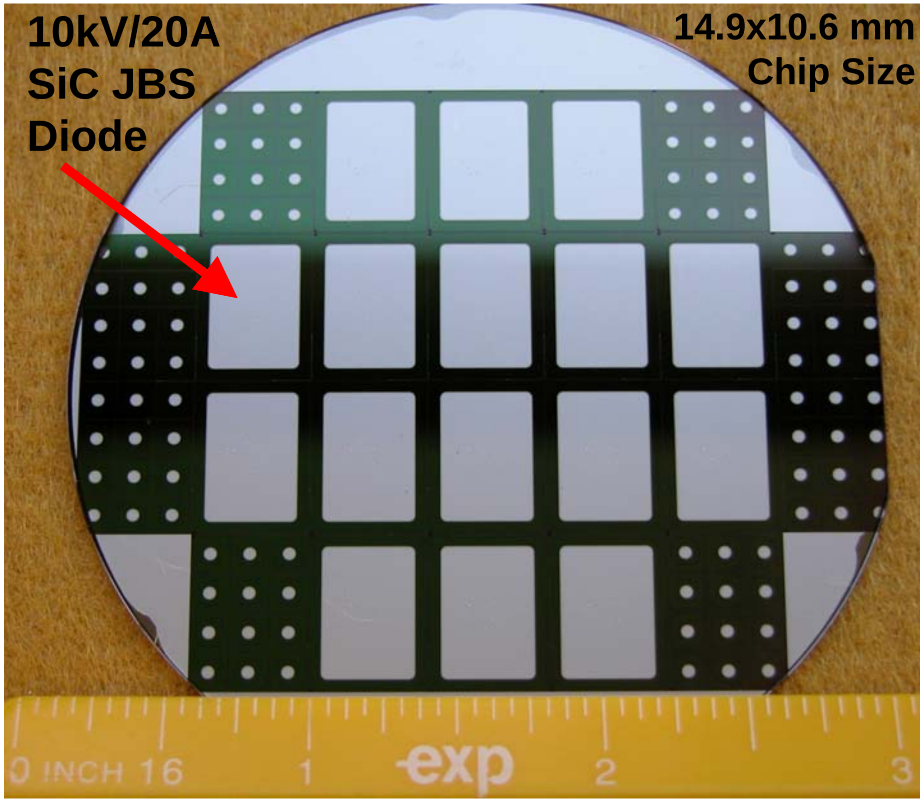
- **SiC PiN Reverse Recovery Energy Dissipation still too high for 20 kHz**
- **Solution - Use SiC Junction Barrier Schottky (JBS) Diodes**
- **Much Smaller Reverse Recovery (Q_{rr}) and Higher Switching Speed**
- **HPE-II Refocused on 10kV/20A SiC JBS Diodes**
- **10kV/5A SiC JBS Diodes Demonstrated with Single Wafer Blocking Yield > 40%**
- **Remaining Issue – 10kV SiC JBS Diode Needs to Be Scaled Up to 20A with 30%Yield**

10kV/20A SiC JBS Diode Device Characteristics

10kV/20A SiC JBS Diode Yield Up to 37%

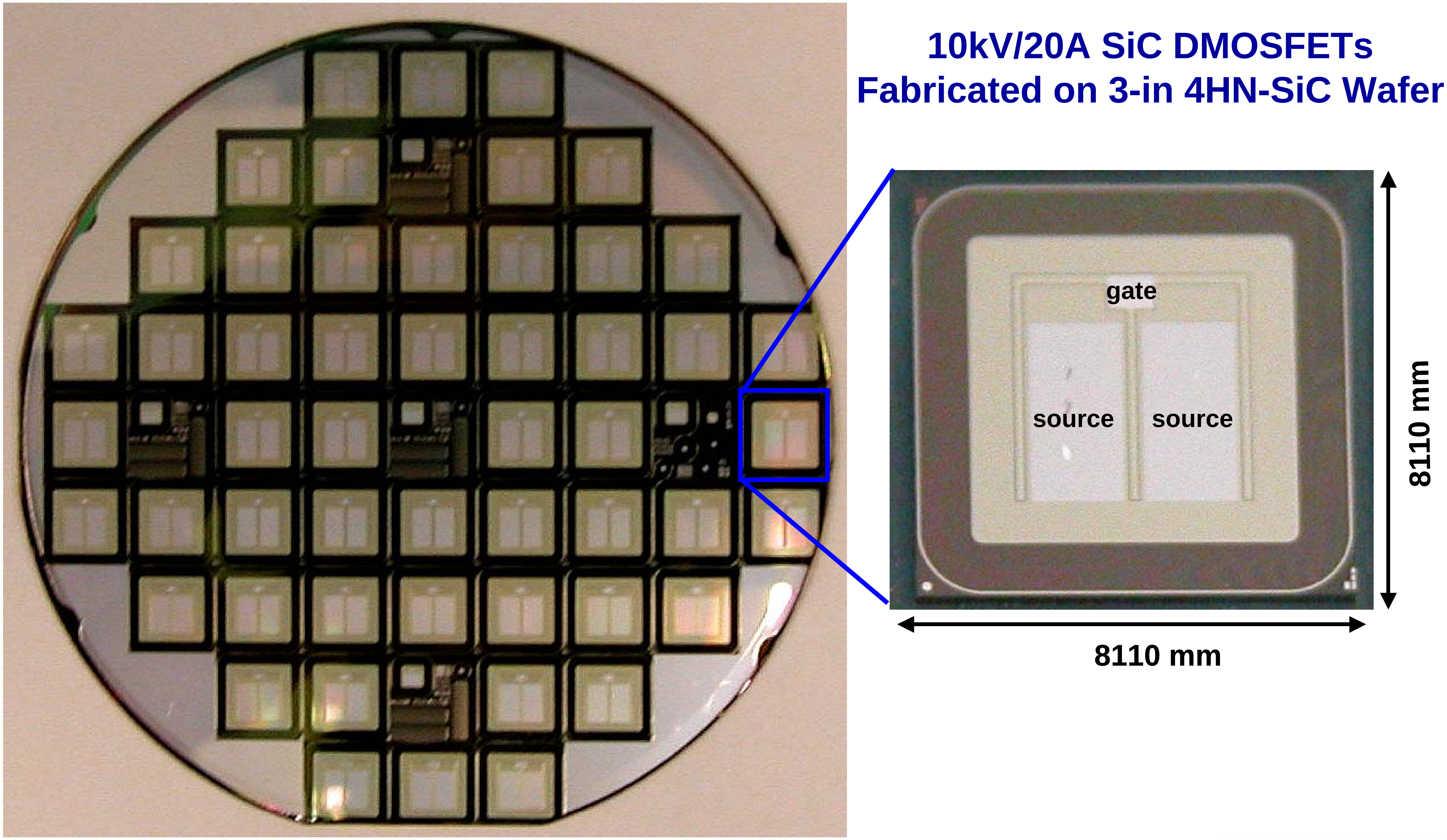


Reverse Blocking of
10kV/20A SiC JBS Diodes



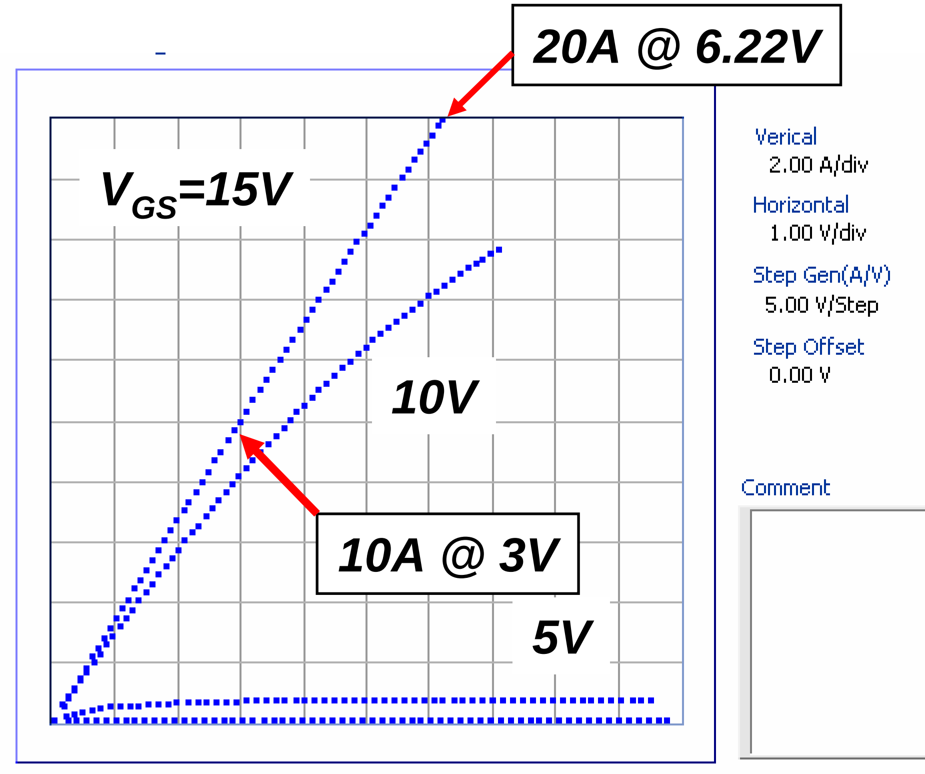
10kV/20A SiC JBS Diodes
Fabricated on 3-in 4HN-SiC Wafer

10kV/20A SiC DMOSFET



10kV/20A SiC DMOSFETs Fabricated on 3-in 4HN-SiC Wafer

9kV/20A SiC DMOSFET
Device Characteristics

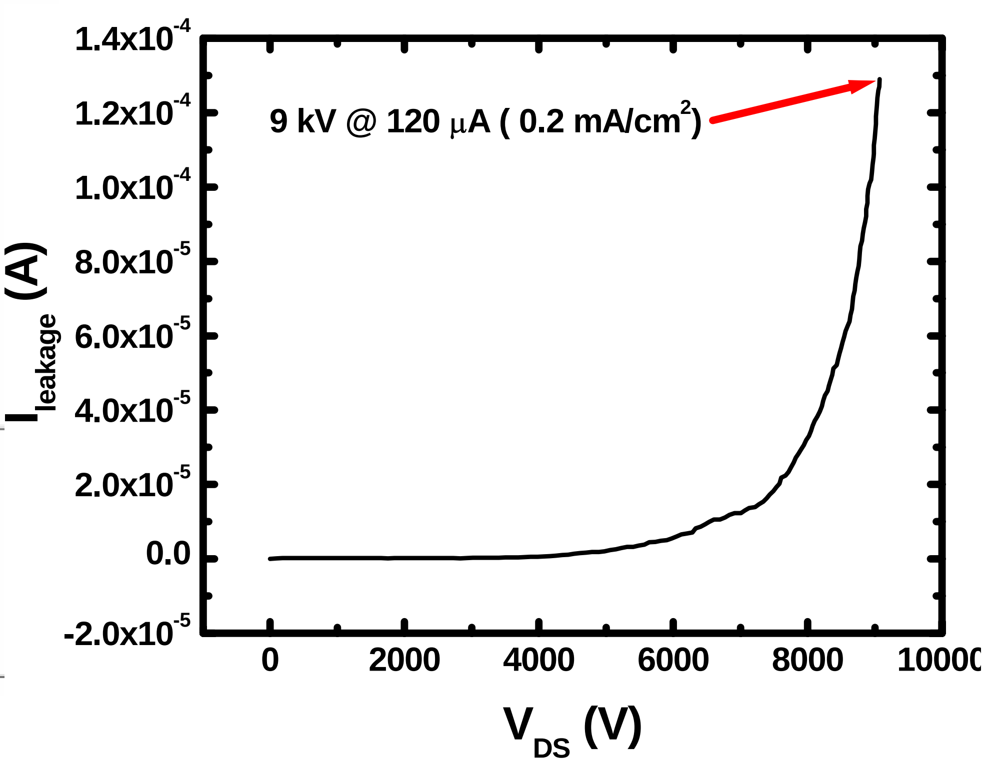


20A @ 6.22V

10A @ 3V

Verical
2.00 A/div
Horizontal
1.00 V/div
Step Gen(A/V)
5.00 V/Step
Step Offset
0.00 V

Comment

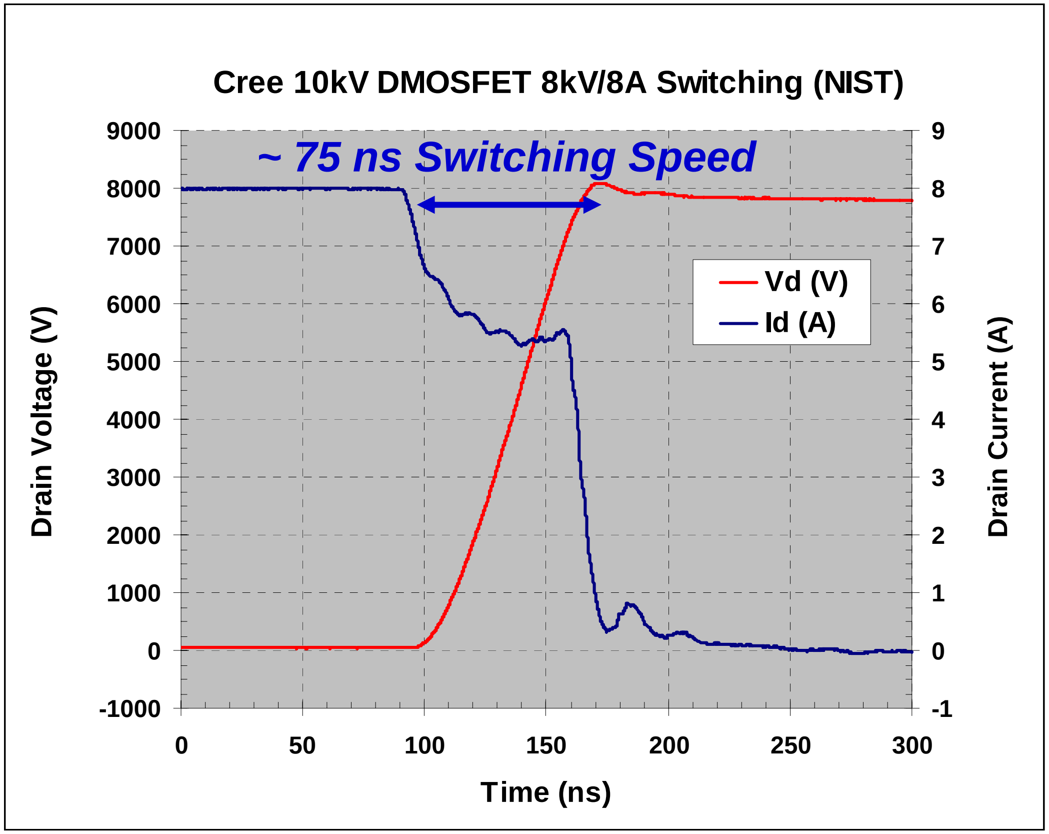


9 kV @ 120 μA (0.2 mA/cm^2)

$R_{on,sp}$ = 91 mΩ-cm^2
20 A @ 189 W/cm^2

BV > 9 kV

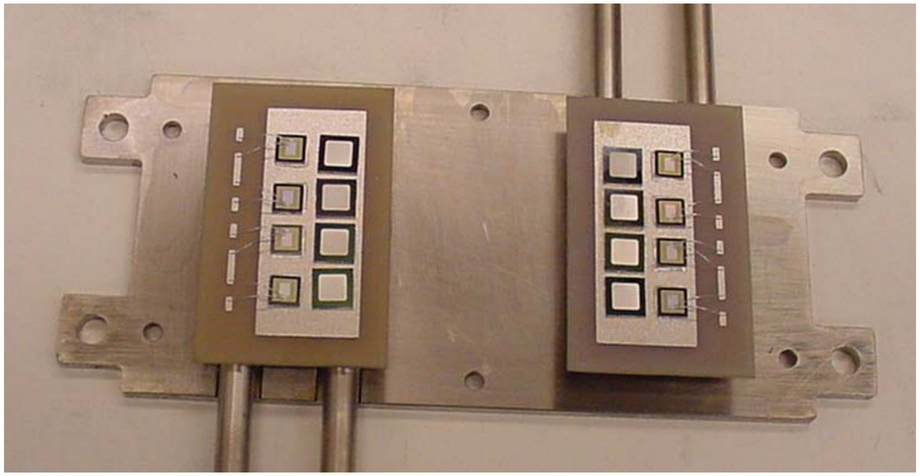
10kV SiC DMOSFET Demonstrated For 20 kHz Switching of SiC Module

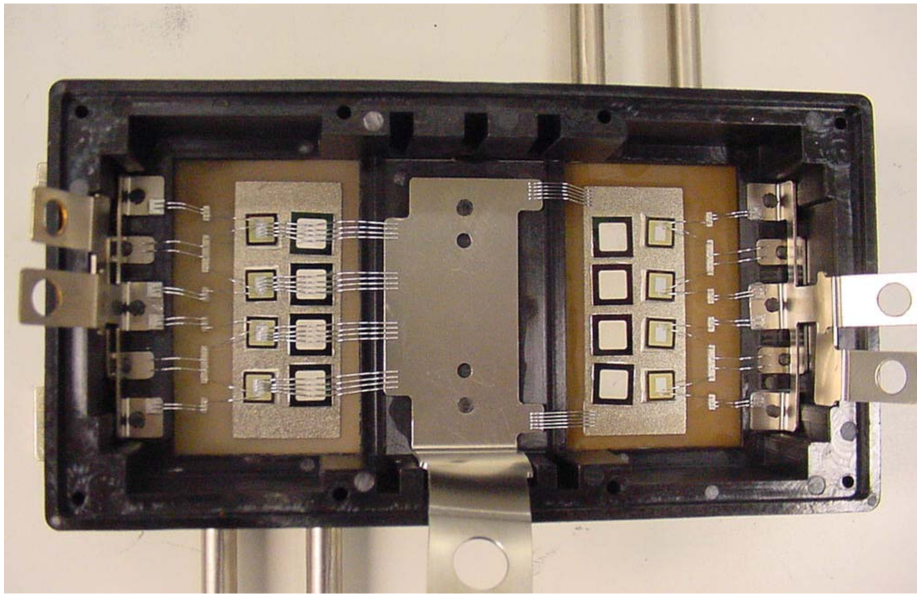


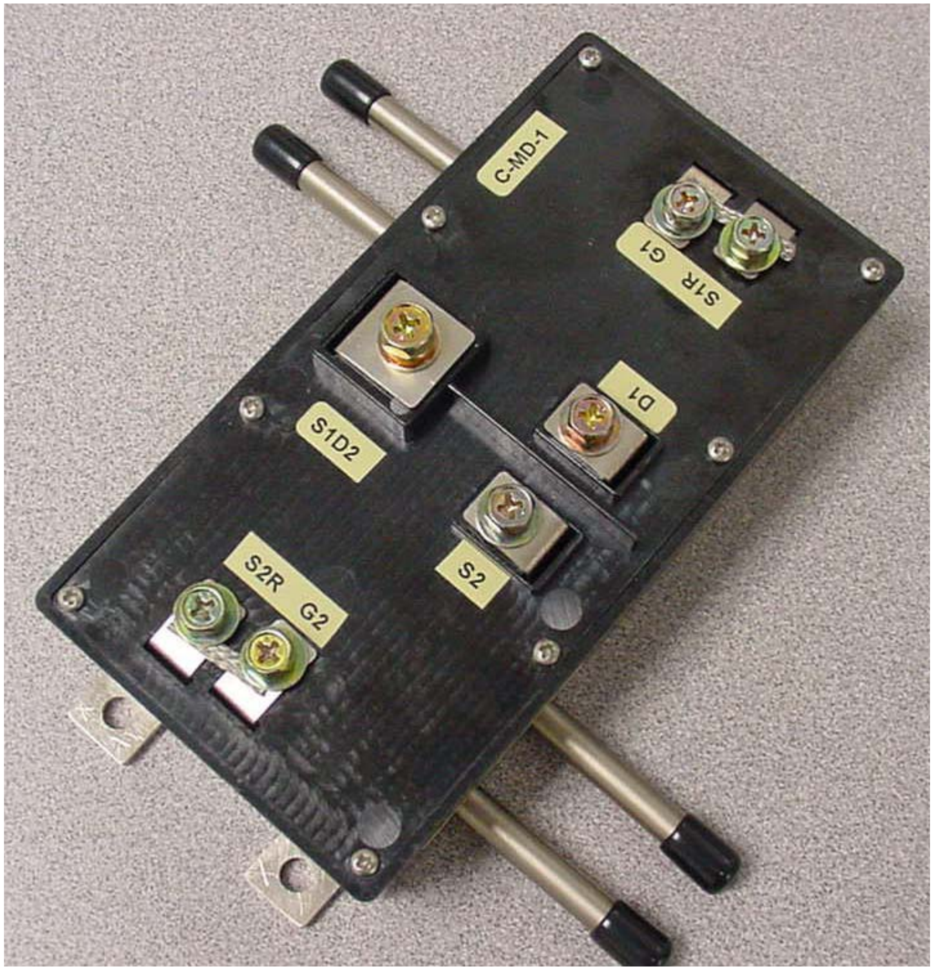
Measured Switching Speed of ~ 75 ns for 10kV SiC DMOSFET at 25°C

- 10kV/10A SiC DMOSFETs 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/20A SiC DMOSFET
Half H-Bridge Module



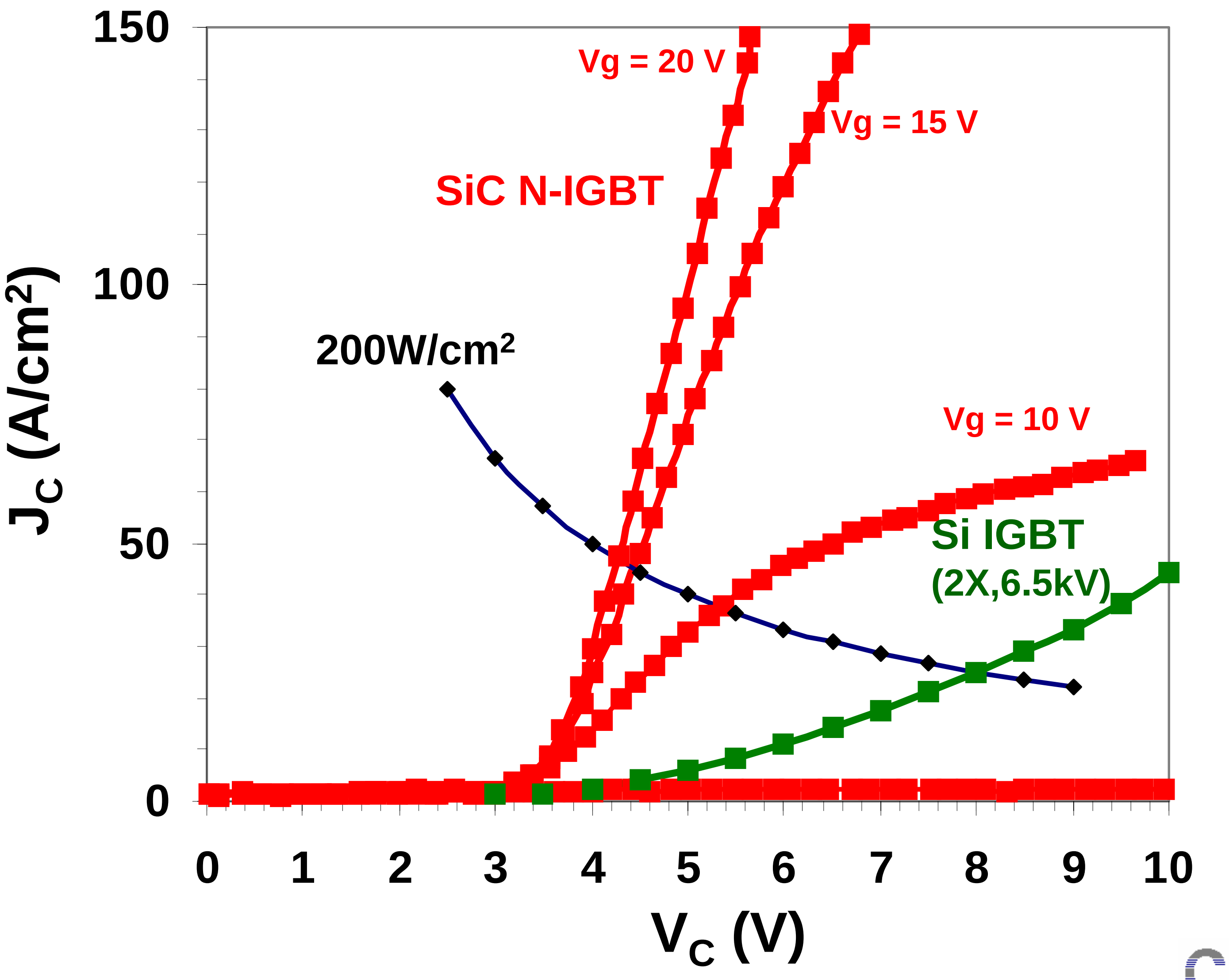




What is next for SiC Power Devices?

- 10 kV pushing upper limit of SiC unipolar devices such as MOSFETs and Schottky diodes
- Higher voltage operation will require minority carrier devices (bipolar)
- The IGBT is the device used in Si for high speed bipolar switching above 1kV
- For SiC, this holds true for >10 kV
  (10 x the electric breakdown field of silicon)

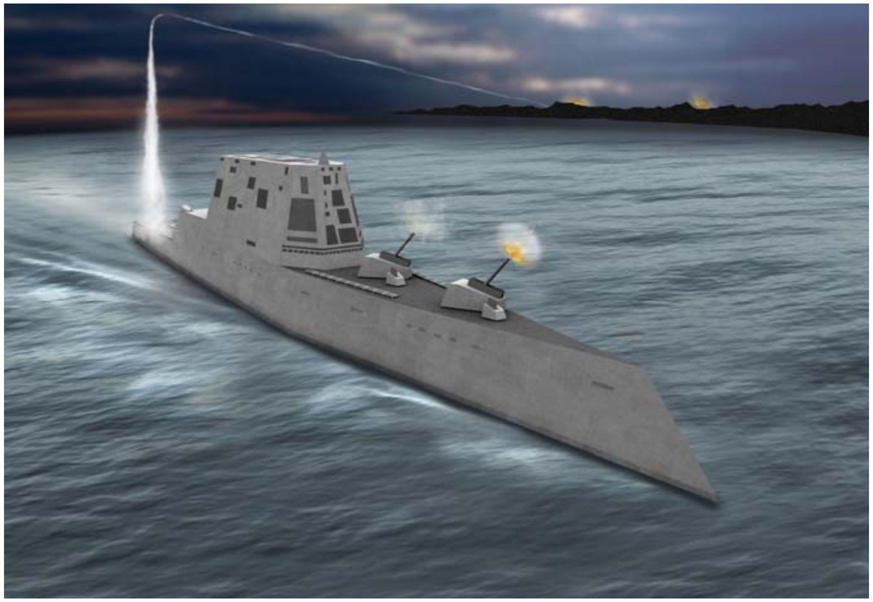
Experimental Results of 12kV SiC N-IGBT and Si IGBT



Applications for SiC IGBTs

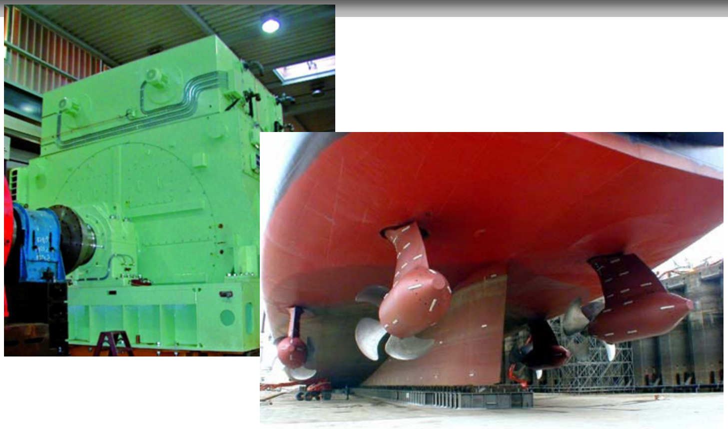
15 - 20 kV SiC IGBTs Offer Significant Advantages for Future Combat Vessels Using Electrical Power for Propulsion, Aircraft Launch/Recovery & Weapons Systems

CVN-21



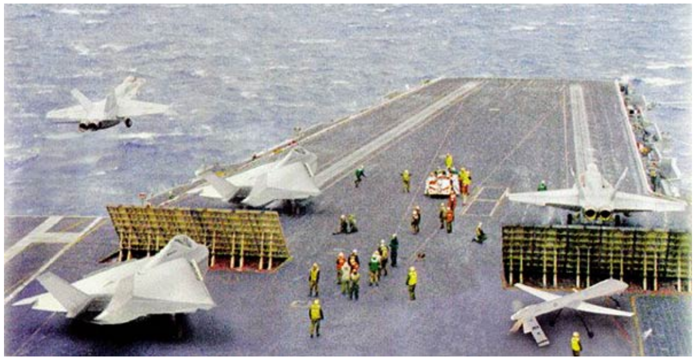
DD (X)

Navy Applications For SiC IGBTs



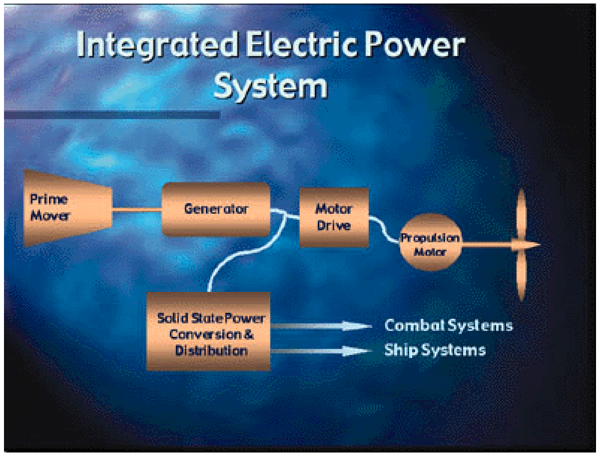
Propulsion

- 4160 V + Motor Drives



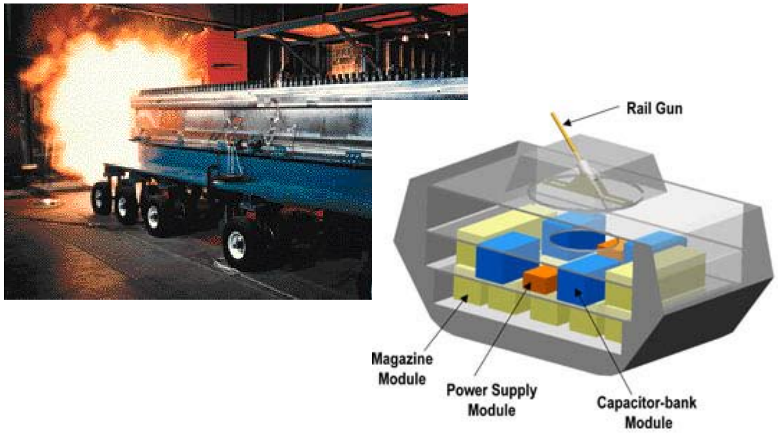
Aircraft Launch and Recovery (EMALS)

- 4 kV Motors



DC Power Distribution

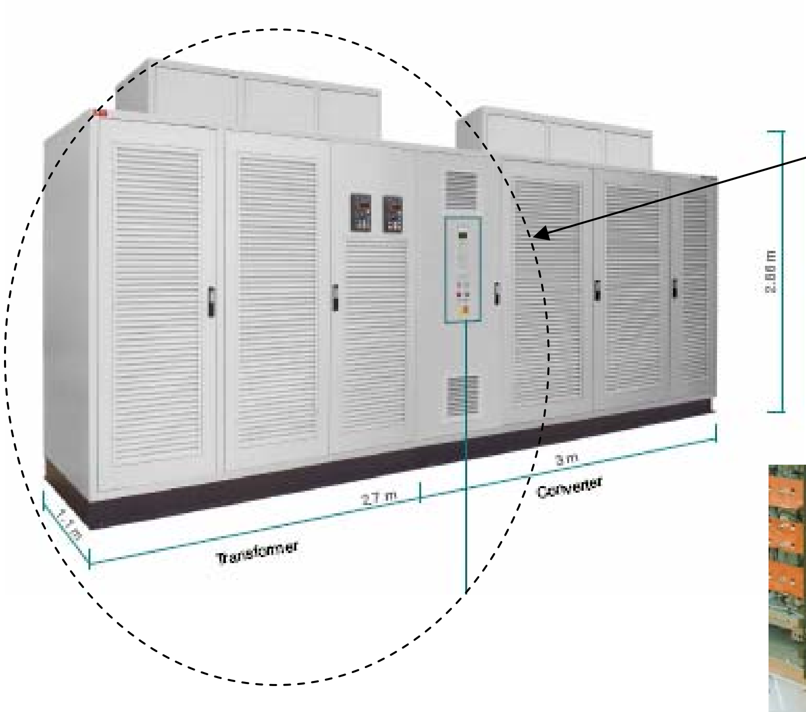
- 6 kV Switchgear



Electromagnetic Gun

Silicon Switch Issues

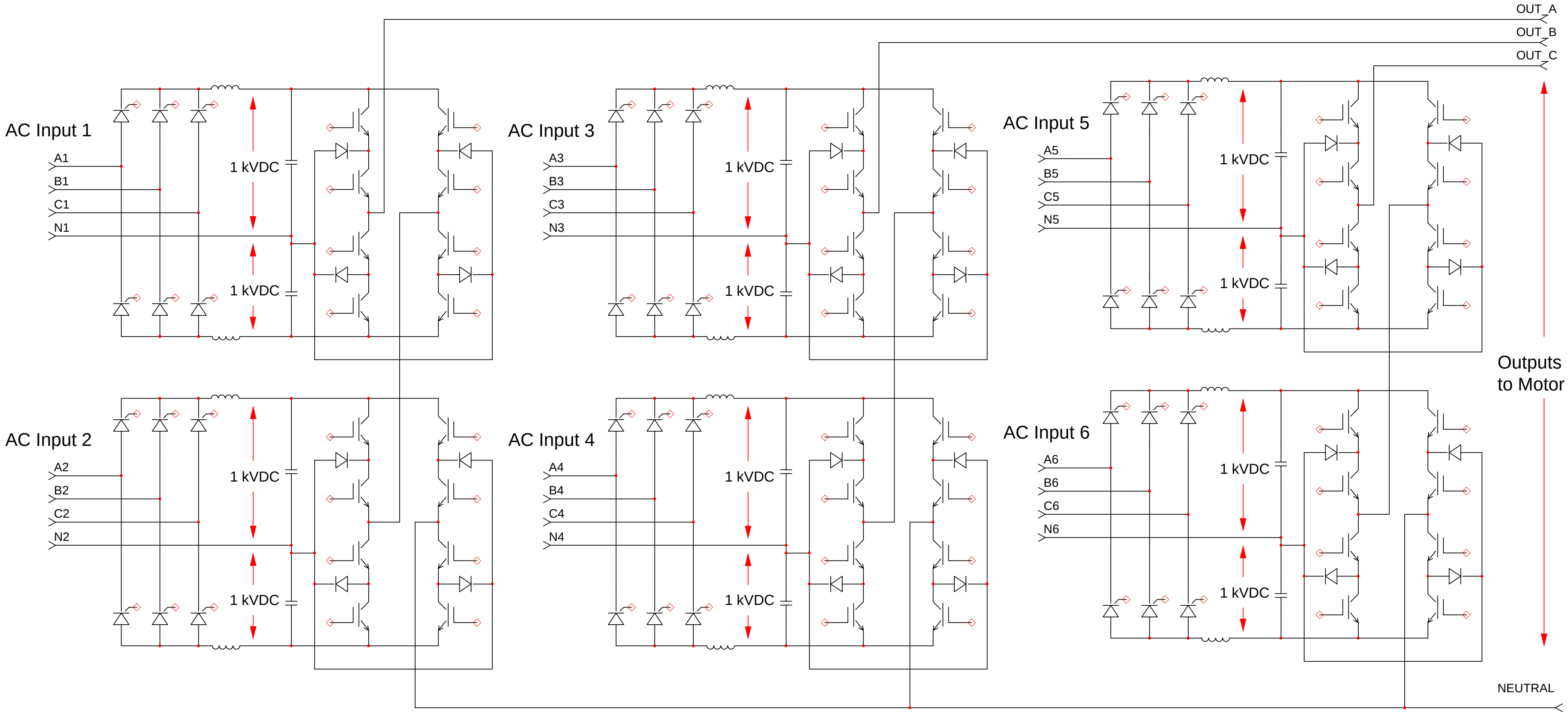
Low Voltage Rating of Silicon Switches Addressed Using Complicated Multi-Level Converters



Multi-level converter requires isolated voltages – large line frequency transformer needed that is almost as big as the converter

Several Si switching devices are required

Cascaded Multilevel Converter Suitable for EMALS Based on Si-IGBTs

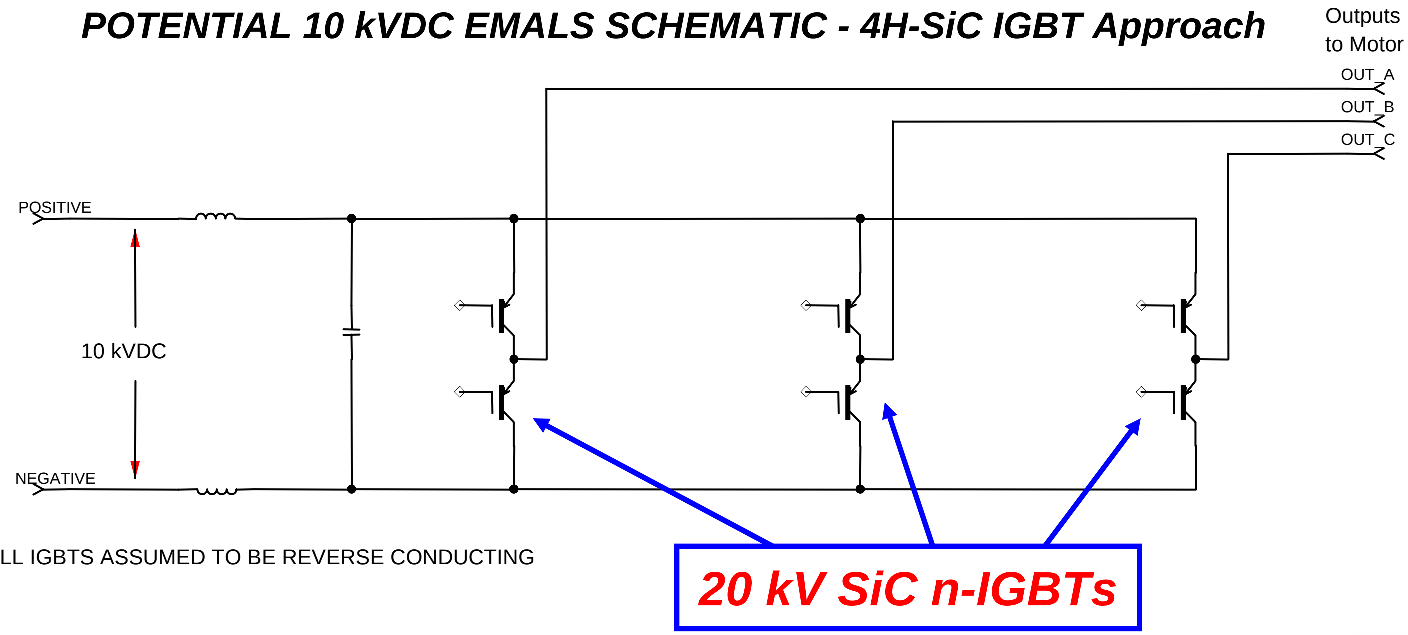


NOTE: ALL IGBTS ASSUMED TO BE REVERSE CONDUCTING

Simplified 2-Level Converter for EMALS Based On 20 kV SiC n-IGBTs

- 20 kV SiC n-IGBTs Used to Implement EMALS Converter Operating from Single Floating 10 kVDC Bus
- Results In Significant Reduction in System Complexity
- Utilize Simple 3-Phase PWM VSI Topology
  - – Pulse Width Modulated Voltage Source Inverter Topology

POTENTIAL 10 kVDC EMALS SCHEMATIC - 4H-SiC IGBT Approach



NOTE: ALL IGBTS ASSUMED TO BE REVERSE CONDUCTING

Summary

- SiC material and device technology has advanced very rapidly under DARPA programs
- MOSFETs and Diodes of unprecedented size and voltage demonstrated
- 150 mm SiC substrates will make large area power devices much more affordable
- 12 kV SiC IGBTs demonstrated with characteristics far superior to silicon
- 15-20 kV SiC IGBTs would offer tremendous benefits for electric propulsion, EMALS, and EM Gun applications in form of size, weight, and efficiency