PowerAmerica

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PowerAmerica
BP2: June 2016 – June 2017

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U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
June 13-14, 2016

PowerAmerica is a U.S. Department of Energy WBG Semiconductor Manufacturing Institute

- The U.S Department of Energy launched the PowerAmerica Institute under the initiative of “National Network of Manufacturing Institutes (NNMI)” to commercialize Wide Band Gap (WBG) power devices.
- PowerAmerica started operations in 2015 with $140M funds over 5 years, and is managed by North Carolina State University in Raleigh, NC USA.

PowerAmerica Supports MRL 4-7 Projects to Stimulate High-tech WBG Manufacturing

TRL 1:	Basic principles observed and reported	MRL 1:	Manufacturing feasibility assessed
TRL 2:	Technology concept and/or application formulated	MRL 2:	Manufacturing concepts defined
TRL 3:	Analytical and experimental critical function and/or characteristic proof of concept	MRL 3:	Manufacturing concepts developed
TRL 4:	Component and/or breadboard validation in a laboratory environment	MRL 4:	Capability to produce the technology in a laboratory environment
TRL 5:	Component or breadboard validation in a relevant environment	MRL 5:	Capability to produce prototype components in a production relevant environment
TRL 6:	System/subsystem model or prototype demonstration in a relevant environment	MRL 6:	Capability to produce prototype system or subsystem in a production relevant environment
TRL 7:	System prototype demonstration in an operational environment	MRL 7:	Capability to produce systems, subsystems or components in a production relevant environment
TRL 8:	Actual system completed and qualified through test and demonstrated	MRL 8:	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production
TRL 9:	Actual system proven through successful mission operations	MRL 9:	Low rate production demonstrated; Capability in place to begin Full Rate Production

NNMI Target

TRL: Technology Readiness Level, MRL: Manufacturing Readiness Level

PowerAmerica Strategy for Accelerating Large-scale Adoption of WBG Semiconductor Devices

PowerAmerica

Mission

US Manufacturing Jobs Creation and Energy Savings through Accelerated Large scale Adoption of WBG Semiconductor Devices in Power Electronics Systems

Strategy

- **Fabricate, Train, and Highlight Performance Advantages of WBG Devices**
  - Stress high-voltage at low resistance, and high temperature/frequency WBG device operational advantages over those of *Si* devices
  - Train Workforce in WBG devices/modules/systems (short courses, University programs)
- **Develop Modules/Circuits and Establish Reliability**
  - Leverage *Si* Reliability best practices in developing WBG reliability standards
  - Develop module/circuit technology that allows for full WBG performance potential
- **Demonstrate WBG Power Electronic System Advantages**

  Establish WBG PE system smaller weight/volume and higher efficiency value proposition through low additional overall system cost and life of system energy savings
- **Reduce Cost of WBG Devices (TRL 4-7)**
  - Leverage mature *Si* fabrication practices and qualify WBG specific processes to enable multiple source high-yield volume manufacturing

Benefits of PA success

Job Creation, Accelerated Technology Innovation, Energy Savings, Smaller Environmental footprint

Strategic DOE/PowerAmerica Funding Allocation Accelerates Commercialization of WBG Power Electronics

PowerAmerica

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Funding Focus Areas

1 Management and Operations

1.1 Program and Financial Management
1.2 Technology Roadmap
1.3 Sustainability
1.4 Establish a Device Bank
1.5. Subawards Management
1.6 Open Innovation Fund
1.7 Membership and Industry Relations
1.8 Compliance Program
1.9 External Communications
1.10 Placeholder for Faculty Hiring for Sustainability
1.11 Metrics Reporting
1.12 Management of Foundry Process

2 Foundry and Device Development

2.1 Ion Implanter and PDK **X-Fab Texas**
2.2 1.2 kV Diode and MOSFET Foundry Qualification of SiC 150mm line **USCi**
2.3A Qualification an testing of of Gen 3 3.3kV/40mOhm SiC MOSFETS **Wolfspeed/Cree**
2.3B Qualification and testing of Gen3 10kV/350mOhm SiC MOSFETS **Wolfspeed/Cree**
2.4 Diode Commercialization and Production **Monolith**
2.5 Manufacture Vertical GaN devices on bulk GaN wafers **Qorvo/Triquint**
2.6 N/A
2.7 N-Polar GaN Power Devices **UCSB**
2.8 High frequency 12kV SiC Planar gate Power MOSFETS **NCSU (Baliga and Misra)**
2.9 N/A
2.10 Examine Material Defects in SiC Epilayers by UV Photoluminescence **NRL**
2.11 GaN Power Device R&D **UC Davis**
2.12 & 2.13 N/A
2.14 Low Cost 1200V SiC JBS Rectifiers and SJT Dev. **GeneSiC**
2.17 Development of an open gate dielectric process for SiC MOSFET Manufacturing **Auburn University**

3 Module Development & Manufacturing

3.1 Power Module Development and Manufacturing **Cree Fayetteville**
3.2: Reliability benchmarking of SiC MOSFETs **Argonne National Lab**
3.3: Reliability Benchmarking of Lateral GaN Power HEMTs on Si **Rensselaer Polytechnic Institute**
3.4 Terrestrial Neutron Induced Reliability Concerns **CoolCAD**

4 Commercialization Applications

4.1 200 kW 1050Vdc SiC Dual-Inverter **John Deere Electronic Solutions**
4.2 Ultra-High Efficiency SiC Modular UPS **ABB**
4.3 SiC Small Commercial PV Inverters **Toshiba**
4.4: MV Power Module for High Density Conversion **NCSU (Hopkins)**
4.5 N/A
4.6 Comparison of SiC and GaN 7.2 kW Chargers **Kettering University**
4.7 EMI Mitigation and Containment in SiC Modular UPS **Virginia Tech (Burgos)**
4.8 DC Data Center with High Frequency Isolation **Virginia Tech (Lee)**
4.9 HybMic Converter **InnoCit**
4.10 SiC Commercial PV Inverter **FSU (Li)**
4.11A Hi Pwr Density DC-DC Conv. for Aux. Pwr. in H-D Vehicles **NCSU (Bhattacharya)**
4.11B Integrated Intelligent Gate Driver and Interface System for Med. V Appl. **NCSU (Bhattacharya)**
4.12 100kW SiC Inverter for EV Traction Drive **NCSU (Husain)**
4.13 WBG Med. V EV Fast Charger **NCSU (Lukic)**
4.14 TBD
4.15 High Perf. PV String and Micro Inverters **ASU**
4.16 MV Gate Drive with Comprehensive Protection Functions **Ohio State**
4.17: Mass Market SiC Solid-State Circuit Breaker Development **AtomPower**
4.18 Open-Source Compact Transformerless Grid-Tied 3kW GaN PV Inverters **Transphorm**

5 Education and Workforce Development

5.1 Program Management
5.2 Institutes, Workshops, Internships
5.3 Business Plan for Sustainability
5.4 Implement EWD Portal
5.5 Shared Specialty Courses

5.11 WBG Workshop Development and Teaching Modules **NCSU (Ozturk)**
5.12 Curriculum Dev. on WBG device Modeling, Simulation **FSU (Andrei)**
5.13: Documentation of Design and Process of GaN Power Devices (**Rensselaer)**
5.14 Technology Transition for the MV EV Fast Charger **NCSU (Lukic)**
5.15 Documentation of Design and Process for GaN Based Devices **UC Davis**
5.16 Technology Transition for SiC inverter for EV traction drive **NCSU (Husain)**

PowerAmerica is a Catalyst for the Commercialization of SiC and GaN Power Electronics

PowerAmerica

Funding Focus Areas (FA):
FA2: Foundry
FA3: Modules, Reliability
FA4: Power Applications
FA5: Education

Large-scale WBG Power Electronics Adoption

↑

Low Cost Devices and Power Electronics

↑

Large Volume Manufacturing — FA2

↑

Creates Device Demand — FA2-5

↑

Develop Peripheral Technologies ↔ Demonstrate Compelling System Advantages — FA4

↑

Establish Reliability — FA3

↑

Improve Material Quality ↔ Streamline Fabrication — FA2

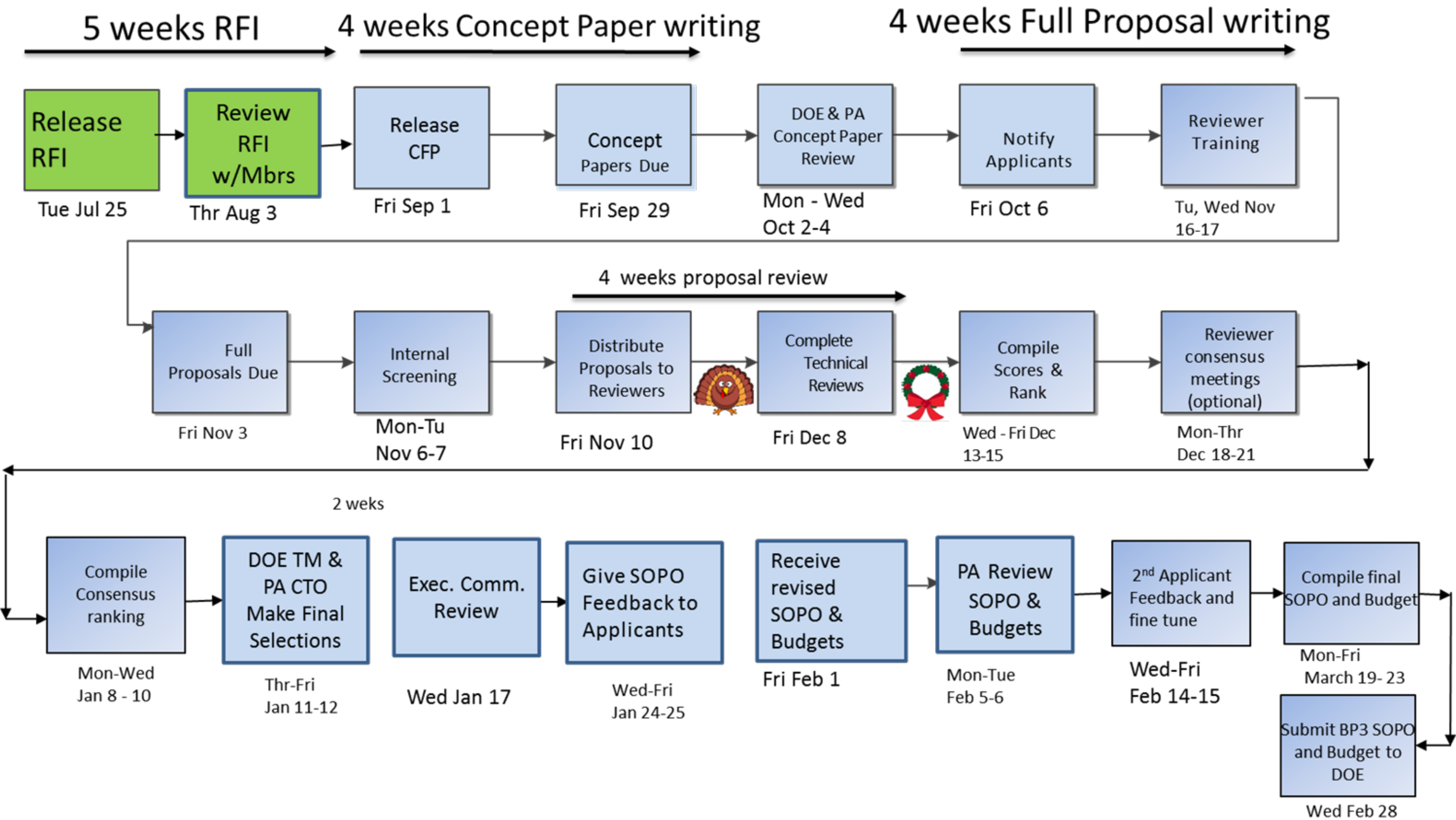
Develop WBG Modules and Circuits, Establish Reliability — FA3-4

Train workforce in WBG — FA5

Carefully Planned Call for Proposals Cycle Allows for Solicitation of High Quality Submissions

PowerAmerica

Tentative July 2017 – June 2018 CFP



PowerAmerica Membership May 2017

POWERAMERICA

Full Sustaining

LOCKHEED MARTIN

Full

Wolfspeed.

XFAB MIXED-SIGNAL FOUNDRY EXPERTS

Affiliate

GM

TOSHIBA

ABB

Infineon

JOHN DEERE

Raytheon

transphorm

Wolfspeed.

USCi United Silicon Carbide, inc.

qorvo

Start-up

Navitas SEMICONDUCTOR

MONOLITH SEMICONDUCTOR INC.

COOLCAD ELECTRONICS

GeneSiC SEMICONDUCTOR

ATOM POWER

AgileSwitch

InnoCit

JENOPTIK

Academic

ASU Arizona State University

UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA

Rensselaer

VirginiaTech

AUBURN UNIVERSITY

KETTERING UNIVERSITY

THE UNIVERSITY OF TENNESSEE KNOXVILLE

UCDAVIS UNIVERSITY OF CALIFORNIA

THE FLORIDA STATE UNIVERSITY

NC STATE UNIVERSITY

THE OHIO STATE UNIVERSITY

Gov. Labs

NAVAL RESEARCH LABORATORY WASHINGTON, DC

Argonne NATIONAL LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Associate Members

PEIC POWER ELECTRONICS INDUSTRY COLLABORATIVE

iNEMI Advancing manufacturing technology

PowerAmerica Foundry Funding Enables Low-Cost Large Volume SiC Device Manufacturing in the U.S.

June 2016 – June 2017

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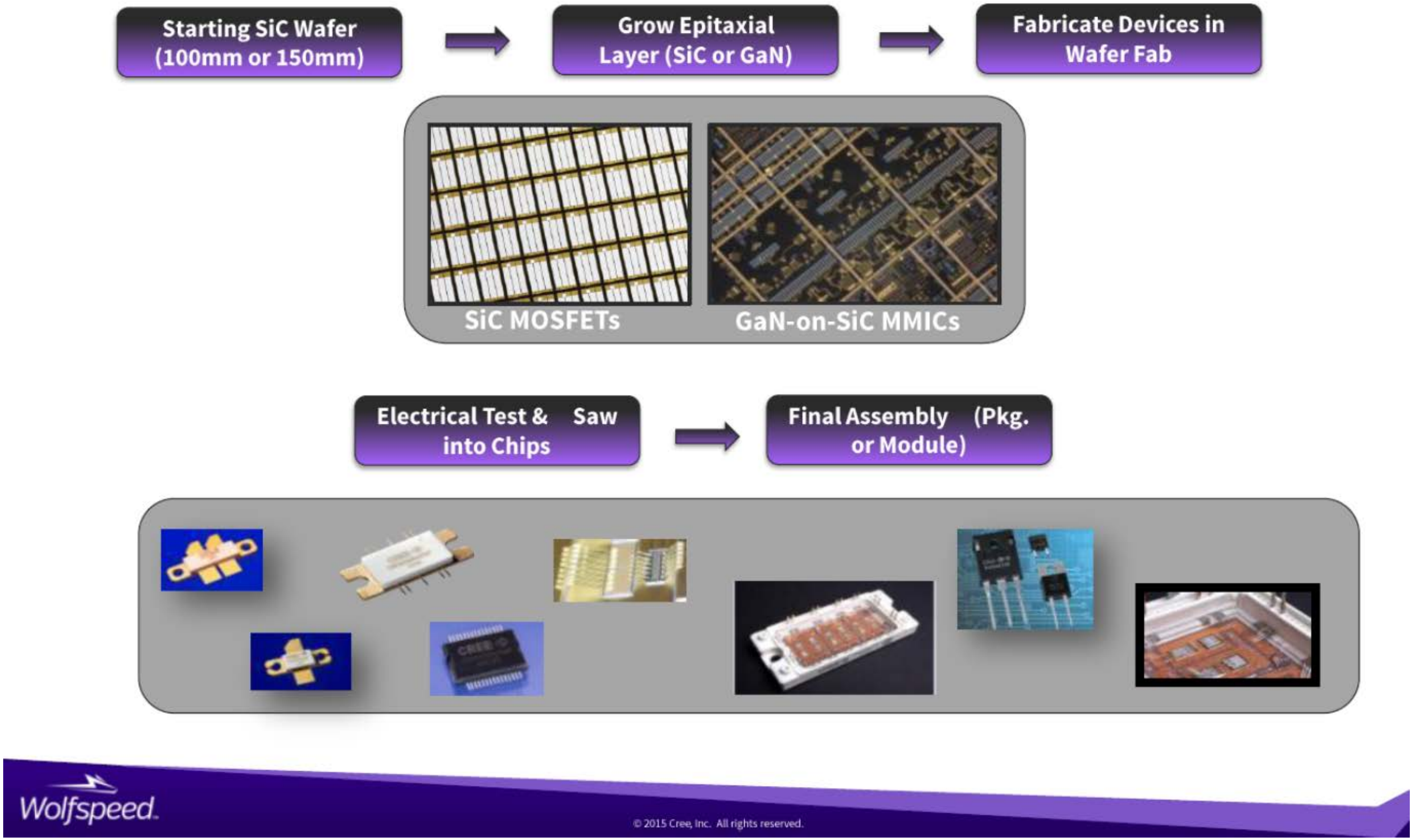
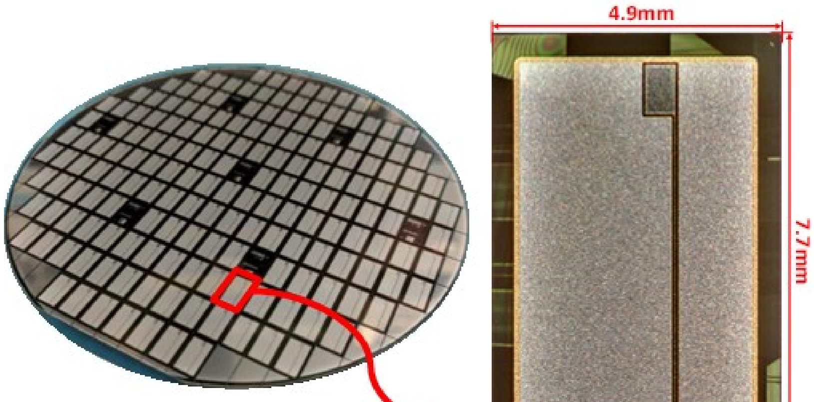
PA Member CREE-Wolfspeed has a Highly Efficient Vertically Integrated WBG Manufacturing Model



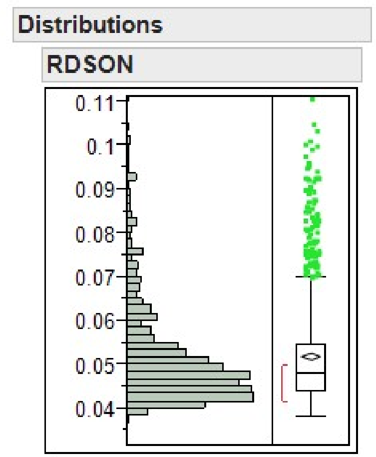
- $171M revenue (FY2016)
- 2240 patents worldwide
- 323,000 sq. ft. of fabrication and office facilities
- Class 10, 100, and 1000 Clean Rooms

CREE-Wolfspeed Foundry Fabrication and Qualification of 3.3 kV/45 mΩ and 10 kV/350 mΩ SiC MOSFETs is Underway

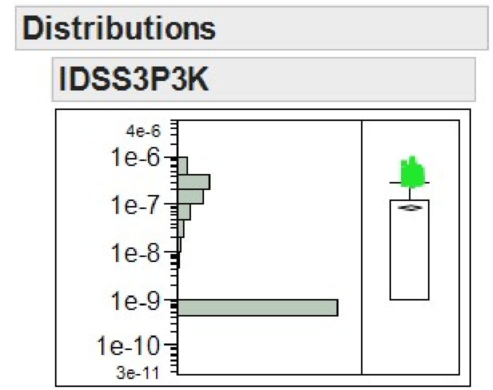


3.3 kV/45 mΩ
SiC MOSFET

Tight $R_{DS,ON}$ Distribution

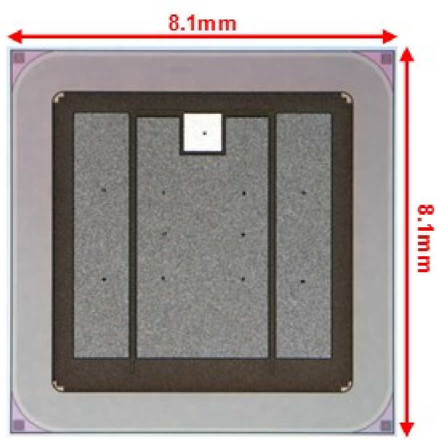


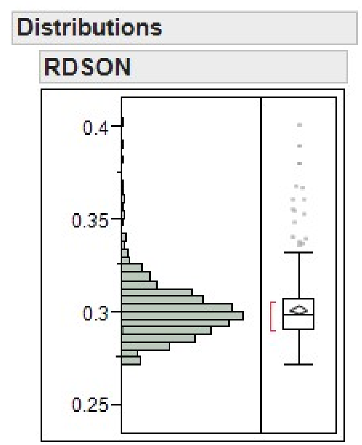
Very Low Blocking Leakage Current

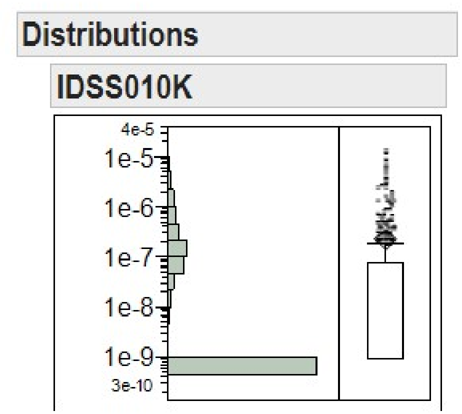


- All 3x 3.3 kV/45 mΩ SiC MOSFET Qualification Fabrication Lots Completed with Good Yields
- 3x25 3.3 kV/45 mΩ SiC MOSFET JEDEC Qualification Activity Underway

10 kV/350 mΩ
SiC MOSFET







- All 3x 10 kV/350 mΩ SiC MOSFET Qualification Fabrication Lots Completed with Good Yields
- 3x25 10 kV/350 mΩ SiC MOSFET JEDEC Qualification Activity Underway

X-FAB 150-mm SiC Open Foundry Leverages Existing Si Economy of Scale to Reduce SiC Manufacturing Cost

X-FAB/PowerAmerica Manufacturing Vision:

SiC Open Foundry at the Economy Scale of Silicon

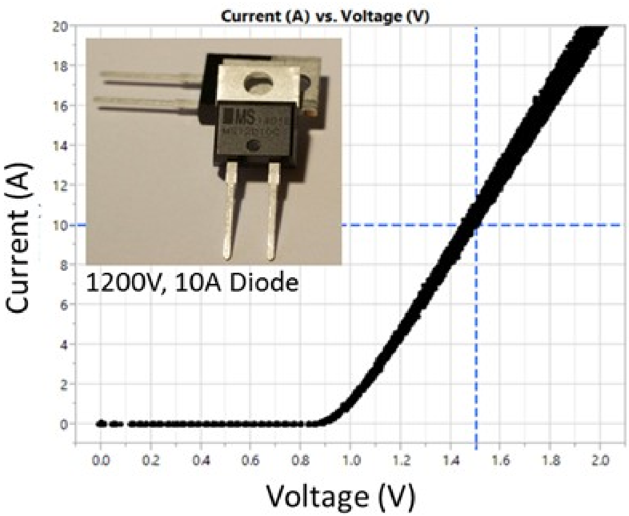
- Wafer fabrication dominated by fixed O/H costs (Management, Quality, EHS, IT)
- Economies of scale the greatest factor in reducing cost: Use the scale established in Si to accelerate SiC

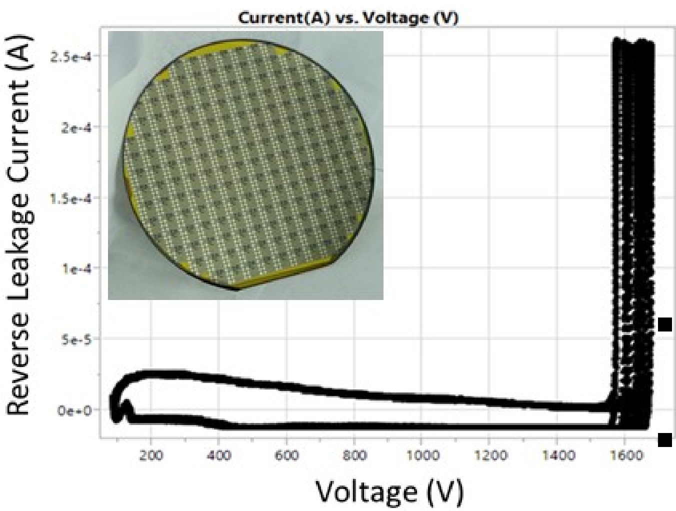
X-FAB 150-mm SiC open Manufacturing is fully integrated within a high volume Si foundry

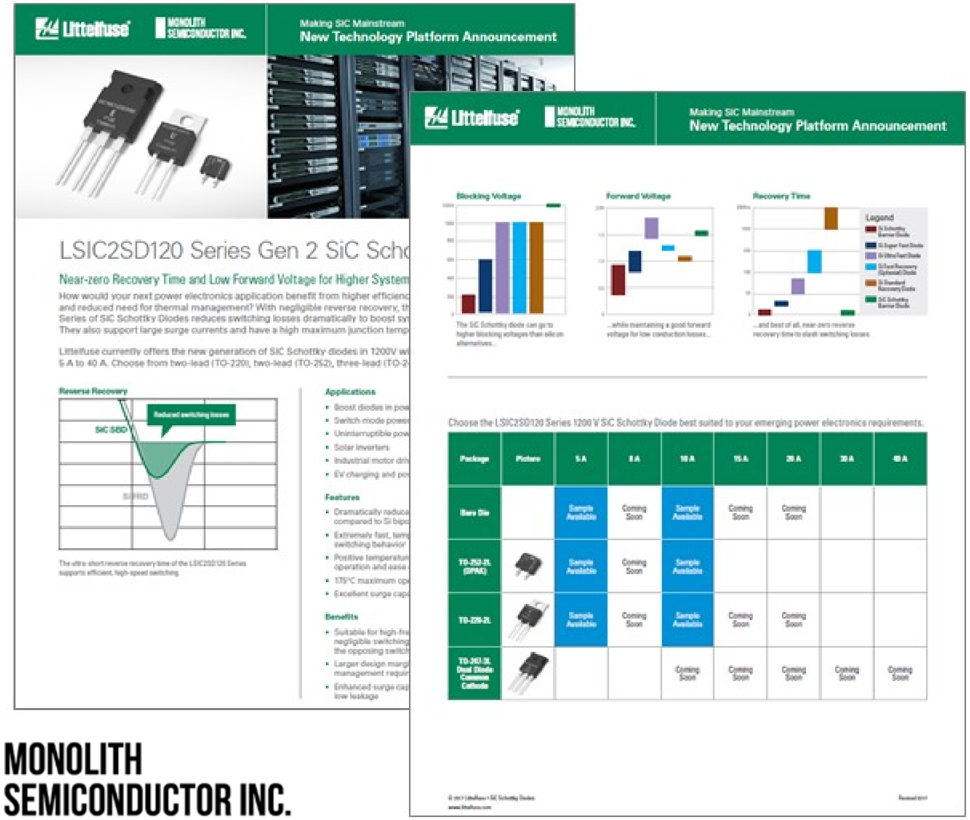
X-FAB SiC Users: ABB, GeneSiC, Monolith, USCi, Global Power, and NCSU

Monolith Announces Fully Qualified 1200-V SiC Schottky Diodes Fabricated on 150-mm Wafers at X-FAB

Objective: Develop manufacturable, high yielding and low-cost 1200 V SiC Schottky diodes with best-in-class performance and reliability at X-FAB's 150-mm SiC foundry.







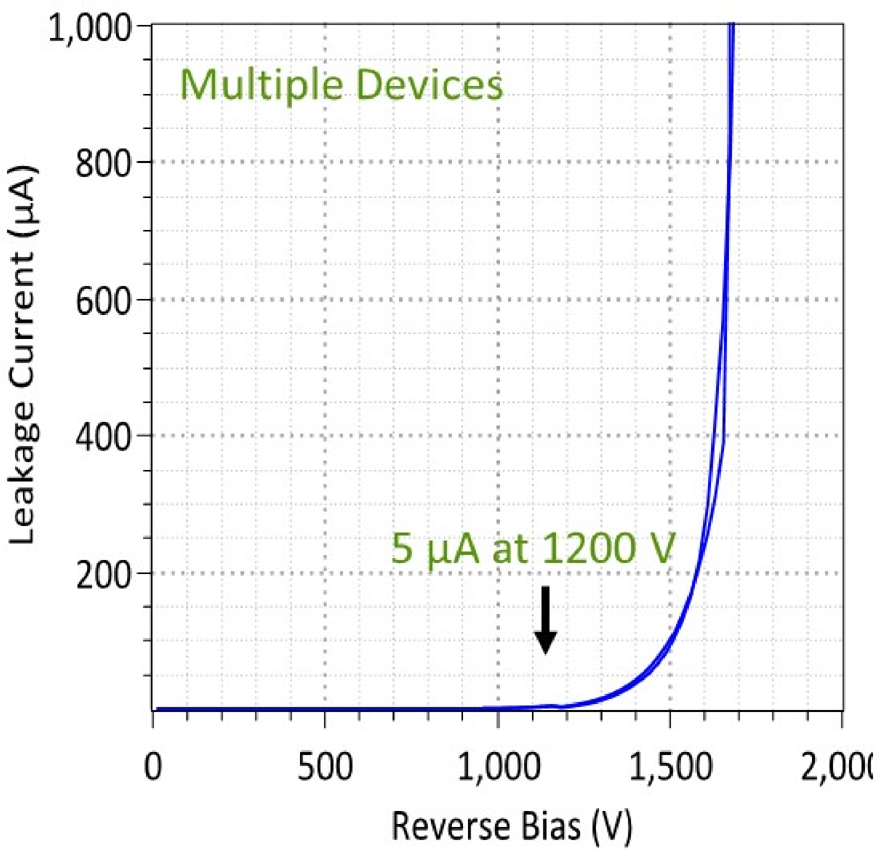
MONOLITH SEMICONDUCTOR INC.

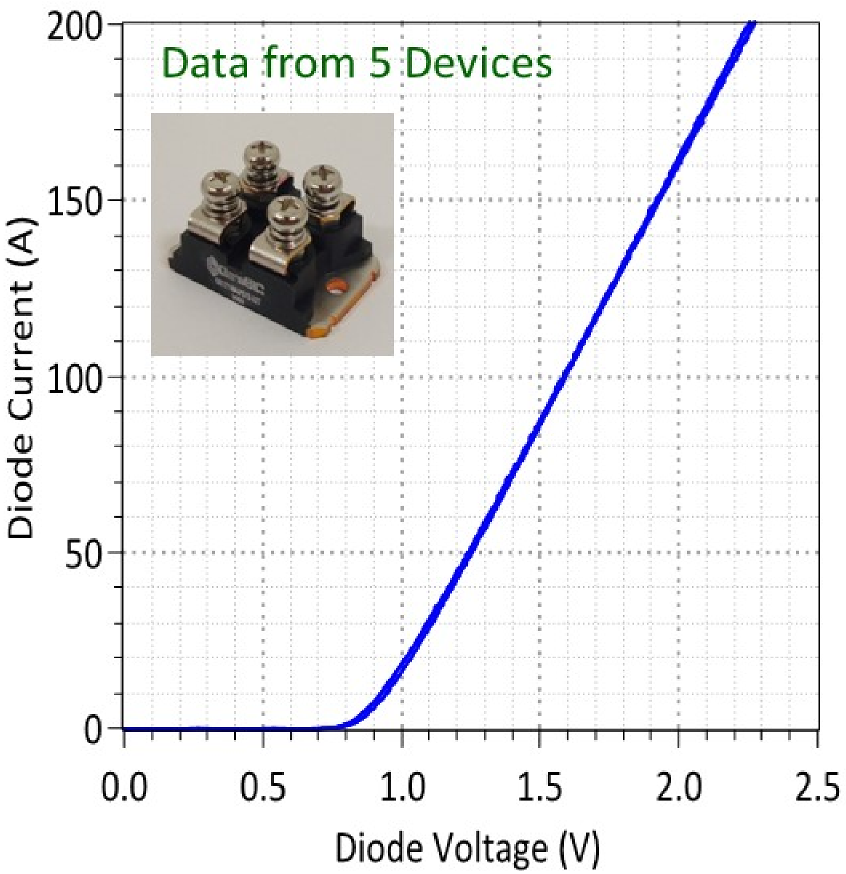
- Monolith is working with Littelfuse in bringing the fully qualified <u>1200V, 5A and 10A</u> diodes to market
- Monolith is currently working on expanding diode portfolio – current rating and packages

GeneSiC Fabricates 1200 V / 200 A Schottky Diodes on 150-mm Wafers at X-FAB Texas

POWERAMERICA

1200 V / 200 A SiC packaged Schottky Diode engineering samples demonstrated with good yields at at X-FAB's 150-mm SiC foundry





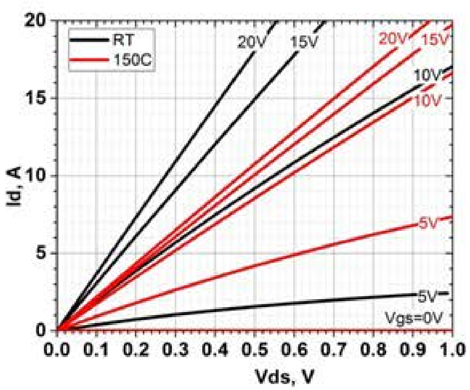
GeneSiC
SEMICONDUCTOR

USCi Fabricates 1200 V Planar MOSFETs on 150-mm Wafers at X-FAB

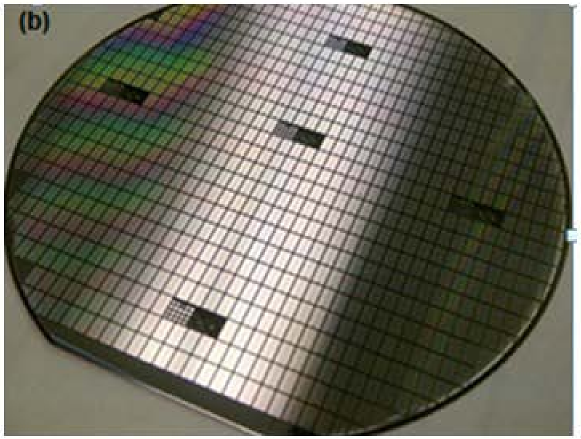
Objective: Develop 40mOhm, 1200V planar MOSFET

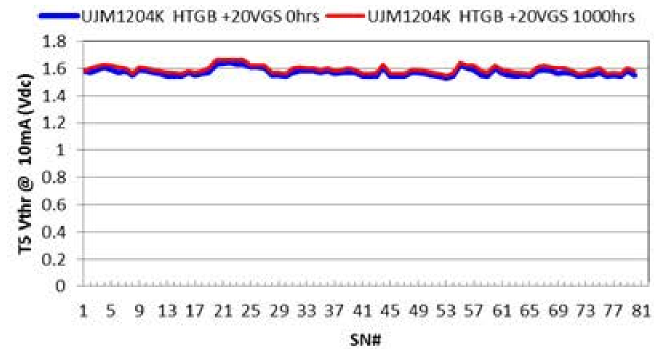
- Breakdown values on target
- Vth lower than target
- On-state behavior looks good
- Basic TO247 Rel test data looks good – see table
- Basic Switching and UIS tests look good

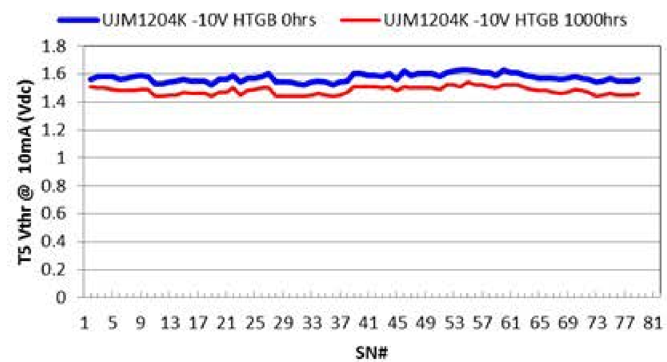
Test	stress condition	duration	sample size	status
HTGB	VGS=+20V, VDS=0, Ta=150C	1000hrs	77	Pass
HTGBR	VGS=-10V, VDS=0, Ta=150C	1000hrs	77	Pass
HTRB	VDS=960V, VGS=0, Ta=150C	1000hrs	77	Pass



Ron = 28mΩ at V_{GS} = 20V and RT







USCi United Silicon Carbide, inc.

ABB Fabricates 3.3 kV SiC Schottky Diodes and MOSFETs on 150-mm Wafers at X-FAB

POWERAMERICA

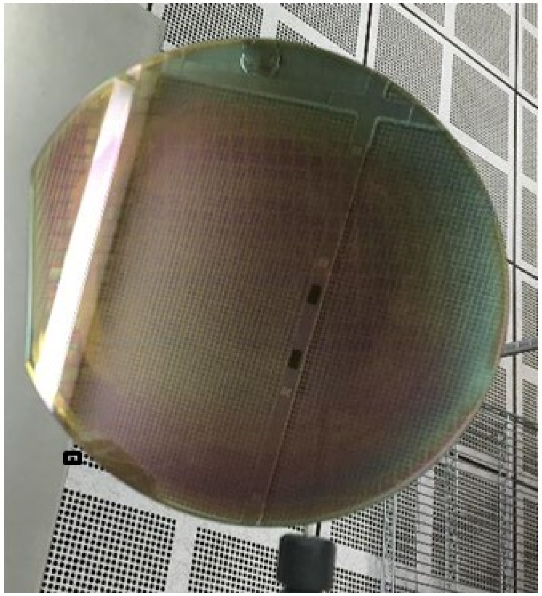
Objective: Qualify 150-mm Si foundry for SiC processing

ABB Processes SiC diodes and MOSFETs on 150 mm SiC wafers for the first time:

- Process routers developed in collaboration with XFAB
- 3.3 kV rated SiC Schottky and MOSFET wafers fully processed with encouraging yields (testing underway)
- Pathways determined for cost reduction in future volume manufacturing

Next Steps: Test a statistically relevant number of dies to evaluate yield/performance

Schematic cross section of 3.3kV SiC JBS diode

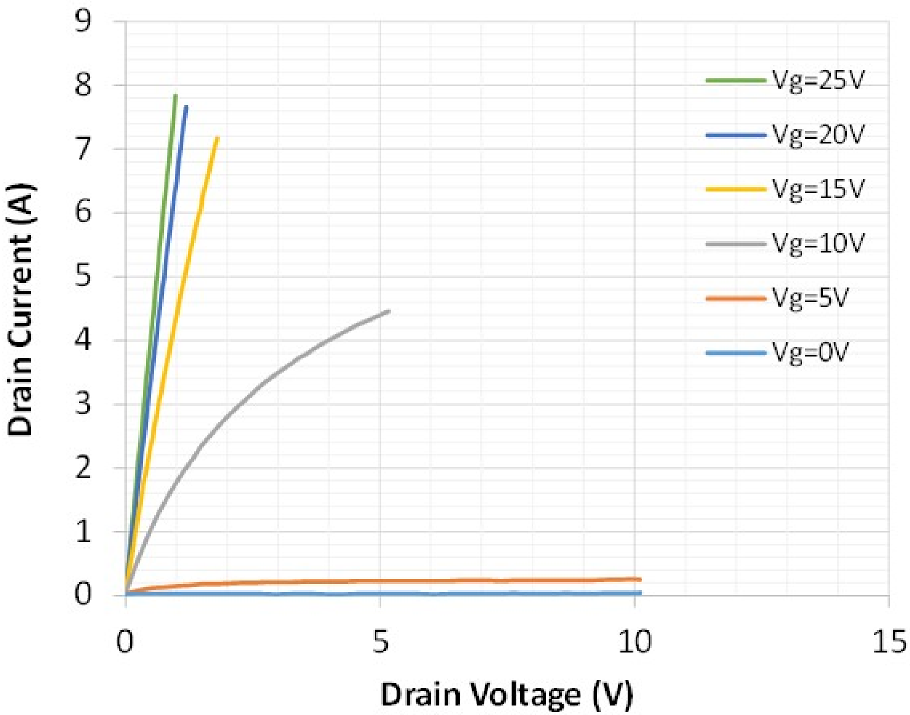

Top view of a 3.3kV SiC JBS diode wafer in process

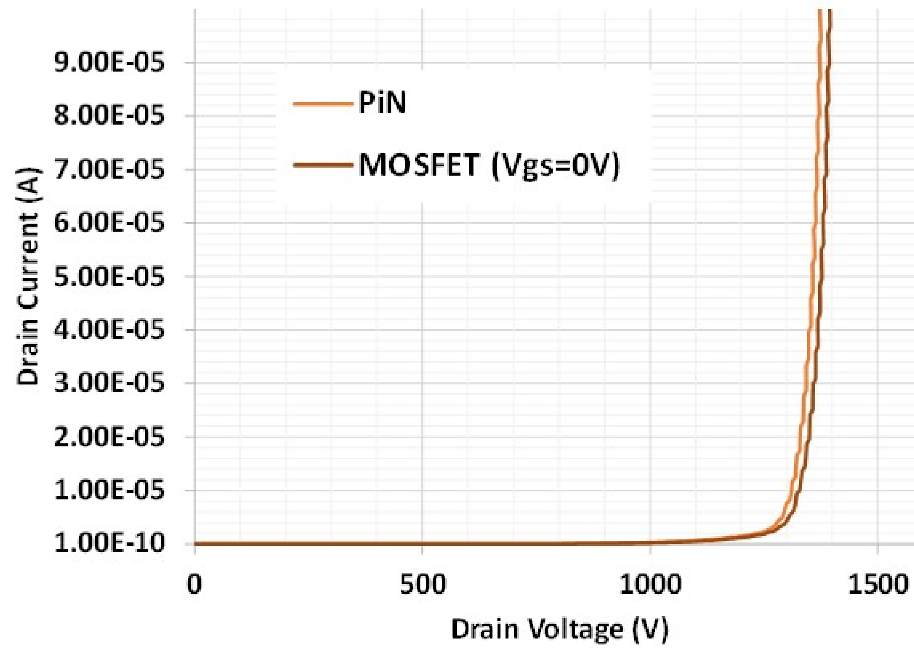
ABB

NCSU Open 1.2 kV SiC MOSFET has an Active area of 4.5 mm^2 and an $R_{ds,on}$ of 5.5 mΩ-cm^2

PowerAmerica

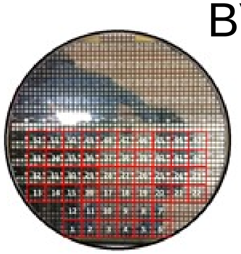
PowerAmerica process yielded 1.2 kV MOSFETs in its first run





Specific on resistance: 5.5 mΩ-cm^2 at 1 A, Vg=20V

Threshold Voltage: 2.8 V @ Id = 1mA



BV 1400V, Id@1200V=1uA

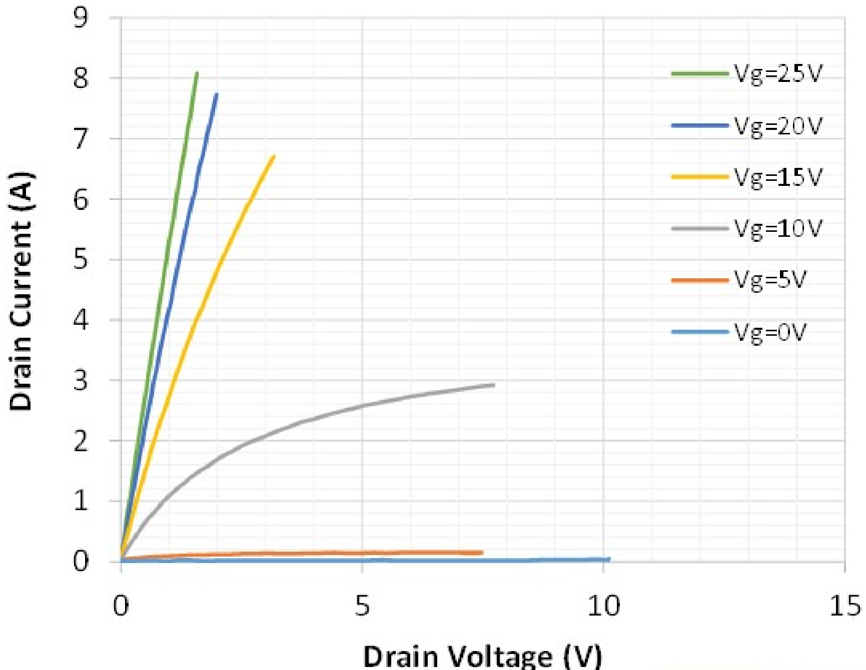
PowerAmerica is developing 3.3-10 kV MOSFET and JBS Baseline Processes

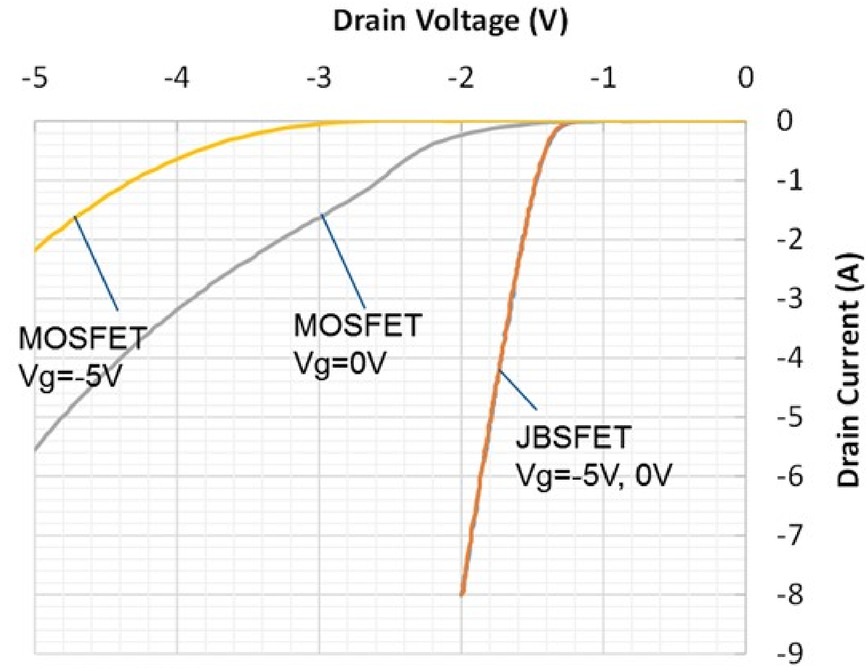
Process by NCSU Dr. Jay Baliga and SUNY Dr. Woongje Sung

NCSU Open integrated 1.2 kV SiC MOSFET/JBS with an Active Area of 4.5 mm^2 and an $R_{ds,on}$ of 12.5 mΩ-cm^2

PowerAmerica

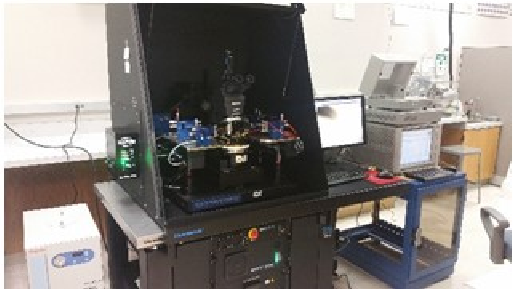
The PowerAmerica process yielded an integrated 1.2 kV MOSFET/JBS





JBSFET 3rd Q Behavior

Specific on-state resistance:
12.5 mohm-cm^2 @ 8A, Vg=20V
9.6 mohm-cm^2 @ 8A, Vg=25V



PowerAmerica developing 3.3-10 kV integrated MOSFET/JBS Baseline Processes

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PowerAmerica's Wafer Procurement Planning is Critical in Timely Execution of Foundry Projects

FA2 Proposal Title	Organization/Team	PI	wafer specs
NCSU Baliga BP-3 Proposal 1	NCSU	Baliga,B.	XFAB has spec
NCSU Baliga BP-3 Proposal 2	NCSU	Baliga,B.	XFAB has spec
1.7KV AND 3.3KV SILICON CARBIDE (SIC) MOSFET SCALE-UP	Micromsemi Corporation	Faheem,Faheem	Proprietary
Commercialization of 1700V SiC Schottky Diodes Manufactured at X-FAB Texas	Monolith Semiconductor Inc.	Chatty,Kiran	
Development of a Manufacturable Gen3, 6.5 kV/100 mOhm MOSFET	Cree, Inc.	Degnan,Sharon	No contact needed for this performer
SiC Power Device Commercial Foundry Development	X-FAB Texas, Inc.	Wilson,Andy	No wafer orders
Development of 3.3kV/6.5kV/10kV SiC MOSFETs, JBS Diodes, and JBS Diode Integrated MOSFETs	State University of New York Polytechnic Institute	Sung,Woongje	Proprietary
Development of 600V SiC JBS Diodes and MOSFETs	State University of New York Polytechnic Institute	Sung,Woongje	
Development and Acceleration of 1200V SiC Device Manufacturing for High Efficiency, High Volume Applications	Alpha and Omega Semiconductor Inc.	Sheridan,David	
3.3kV SiC MOSFET Development	GeneSiC Semiconductor Inc.	Singh,Ranbir	
Advanced SiC Trench MOSFETs: A Path to Record-Low Ron,sp and Record-Low ($/A)	Sonrisa Research, Inc.	Cooper,James	
Manufacturable, Cost Effective, Low RON-SP 3.3 kV SiC DMOSFETs	Global Power Technologies Group, Inc.	Woodin,Richard	

Module and Reliability Funding Bridges the Gap Between Device Readiness and Commercial Adoption

PowerAmerica

June 2016 – June 2017

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1.1 Program and Financial Management
1.2 Technology Roadmap
1.3 Sustainability
1.4 Establish a Device Bank
1.5. Subawards Management
1.6 Open Innovation Fund
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PowerAmerica GaN Members Create High Frequency, High Efficiency, Compact Solutions with Very Large User Potential

PowerAmerica

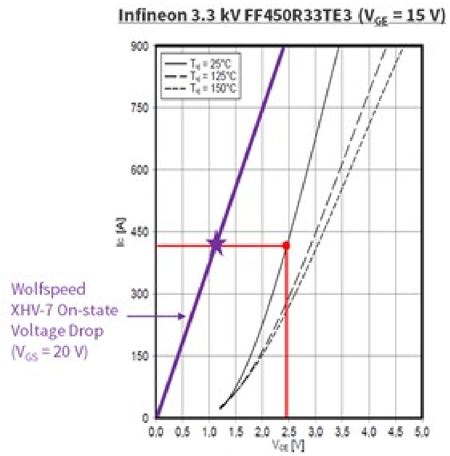
Power Supply market

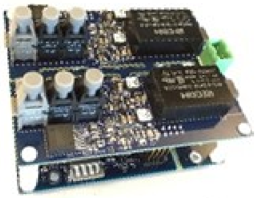
2016: Navitas; 2017: Xiucheng Huang, "High Frequency GaN Characterization and Design Considerations," Ph.D Dissertation, Dept. Electr. Eng., Virginia Tech., Blacksburg, VA USA, 2016.

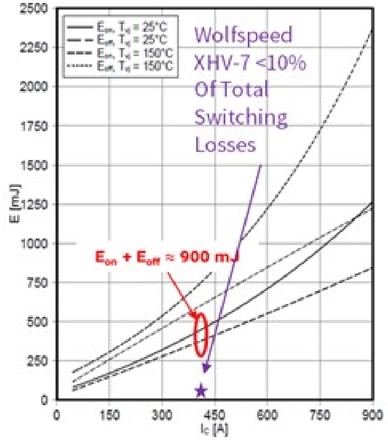
Courtesy of member Navitas

Wolfspeed Fay Develops 3.3-kV and 10-kV SiC Modules with Customizable Device Configuration

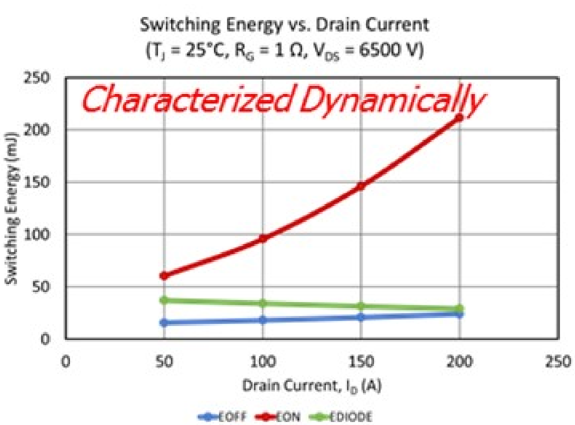
3.3 kV Industry Standard Footprint Module with Low Inductance <20 nH







10 kV Module with Low Loop Inductance <20 nH



CREE

PRELIMINARY & CONFIDENTIAL

XHV-6 High Performance Module

10 kV, 38 mΩ Silicon Carbide
High Performance Half-Bridge Power Module
XPM3 MOSFETs

V_{DS}	10 kV
$R_{DS(on)}$	38 mΩ

Features
- Ultra-Low Loss, Low Inductance
- Ultra-Fast Switching Operation
- Zero Turn-Off Tail Current from MOSFET
- Normally-Off, Fail-Safe Device Operation
- Reconfigurable as 6-Pack
- High Temperature Packaging, $T_{J(max)}$ = 175 °C
- Optional RTD

Package

System Benefits
- Enables Compact, Lightweight Systems
- High Efficiency Operation
- Reduced Thermal Requirements

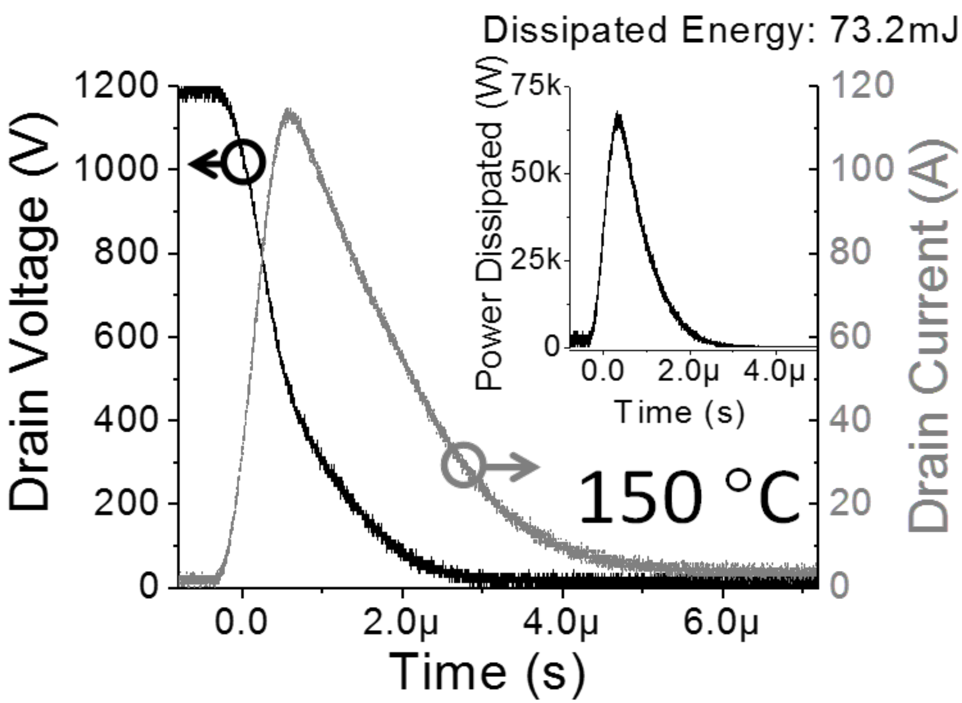
Applications
- Energy Storage Systems
- Medium Voltage Drives
- Smart-Grid / Grid-Tie Distributed Generation
- Solid-State Transformers / Circuit Breakers

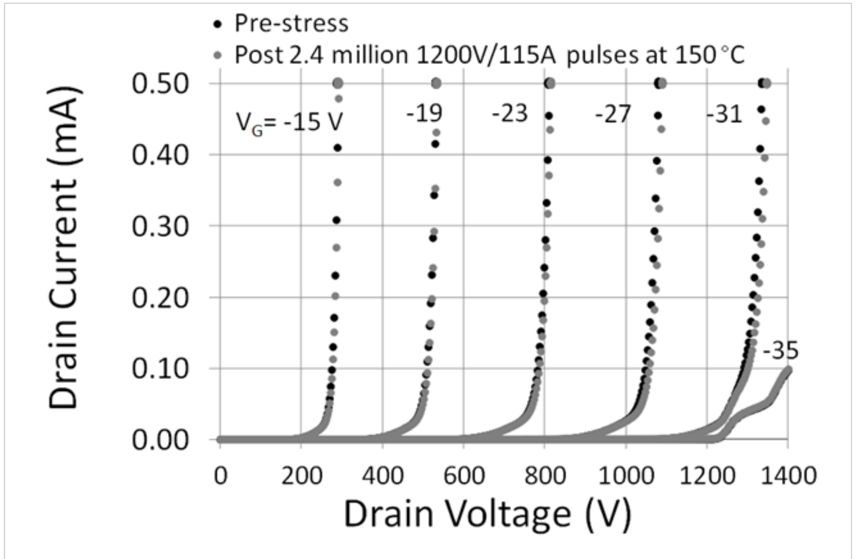
Maximum Ratings (T_C = 25 °C Unless Otherwise Specified)

Symbol	Parameter	Value	Unit	Test Conditions
V_{DSmax}	Drain – Source Voltage	10	kV	
V_{GSmax}	Gate-Source Voltage, Maximum Values	-10/+25		
V_{GSop}	Gate-Source Voltage, Recommended Operational Values	-5/+20	V	
I_D	Maximum Continuous Drain Current	178	A	T_C = 25 °C, T_J = 150 °C
		80		T_C = 125 °C, T_J = 150 °C
P_D	Maximum Power Dissipated	2404	W	T_J = 150 °C
$T_{J(max)}$	Maximum Junction Temperature	175	°C	
T_{stg}	Storage Temperature Range	-55 to 175		

1 XHV-6 10 kV / Gen 3 Rev. 2.1, 04/2017

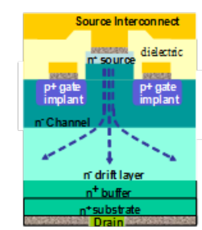
Third Party Testing/Reliability Verification: SiC JFET Electrical Characteristics Do Not Degrade after 2.4 million 1200-V Hard-switch Short-circuit Pulses at 150 °C





Blocking voltage JFET curves do not change after 2.4 million 1200-V/115-A hard-switch pulses at 150 ºC

- Peak current is 115 A: **13 times the JFET's 250 W/cm² rated current at 150 °C**
- Energy dissipated by the JFET during each hard switching event is 73.2 mJ
- Peak dissipated power: 68.2 kW
- Current rise rate was 166 A/µs and the pulse FWHM was 1.8 µs

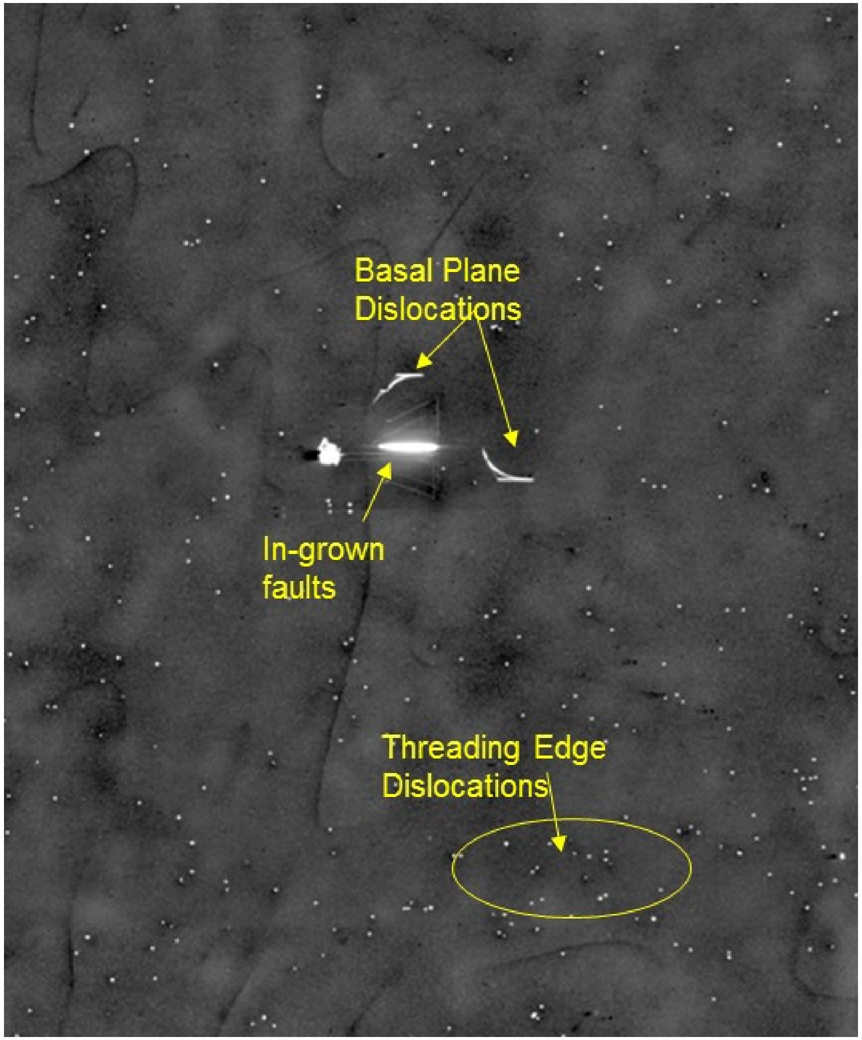


Standardized accelerated testing of large volumes of WBG devices will establish their **Reliability**

TEXAS TECH UNIVERSITY Center *for* Pulsed Power & Power Electronics

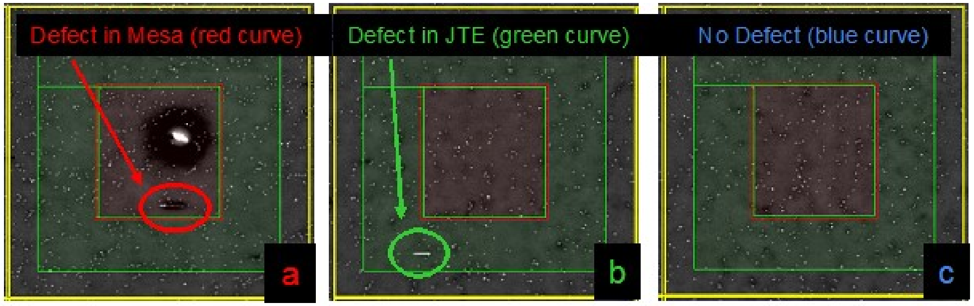
ARL

The Presence of Material Defects Can Degrade SiC Device Performance and Reliability

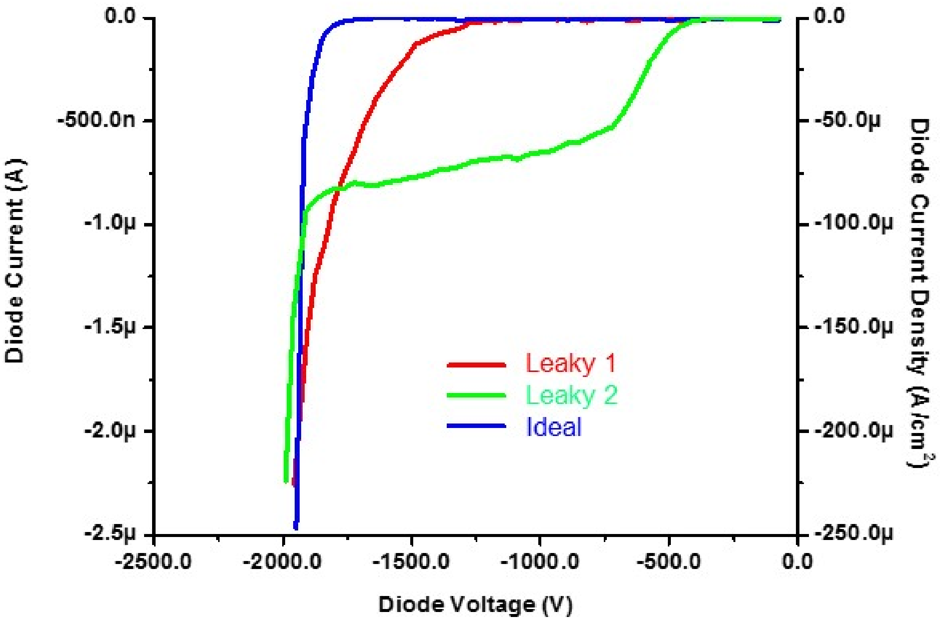


Portion of UV photoluminescence wafer map with various defects identified prior to fabrication

Courtesy of Bob Stahlbush, NRL



UV Photoluminescence maps with diode reticle overlay to show location of defects



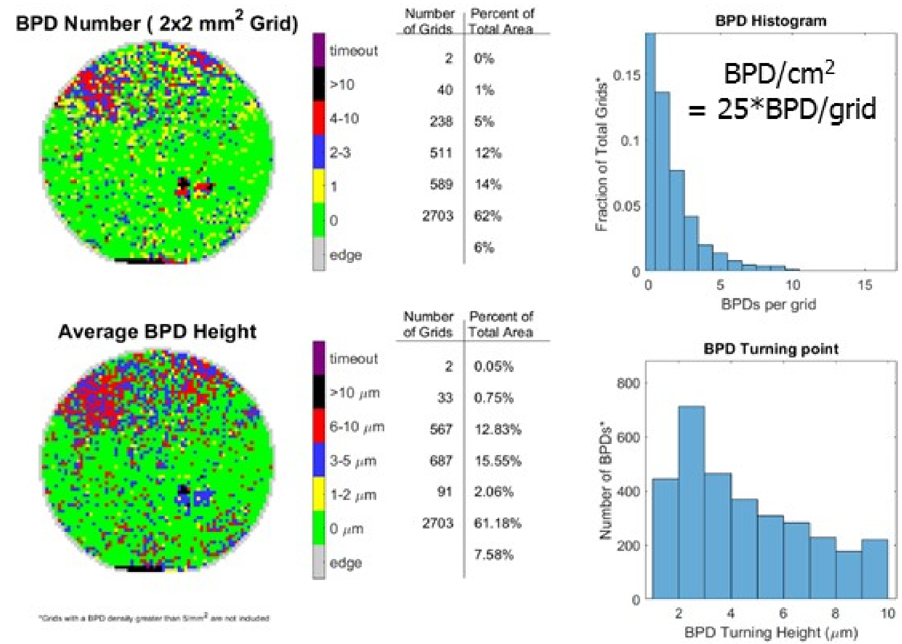
Same wafer 2 kV *PiN* diodes with leakage currents correlating to presence of underlying defects

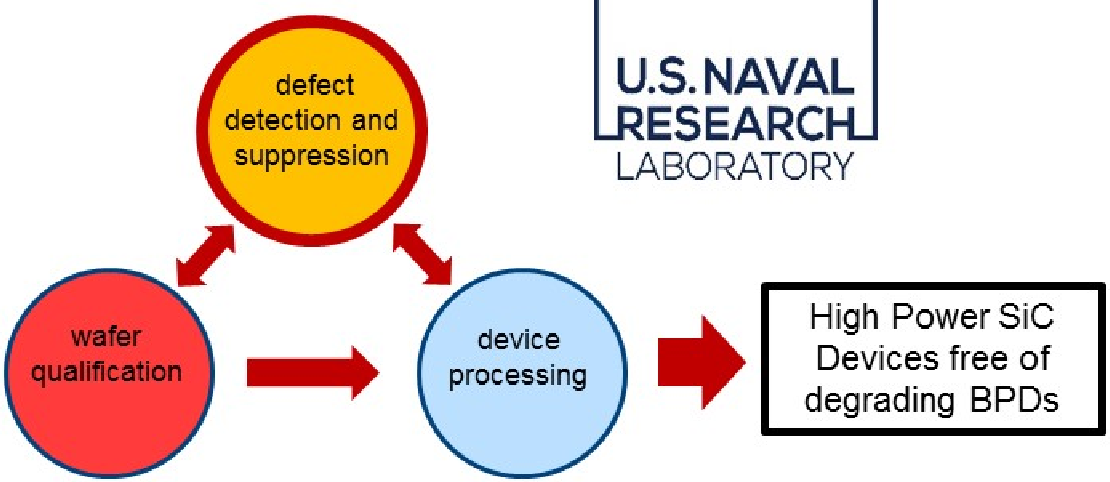
NRL Effort Aims to Suppress BPDs and Killer Defects Generated During Fabrication of SiC Power Devices

PowerAmerica

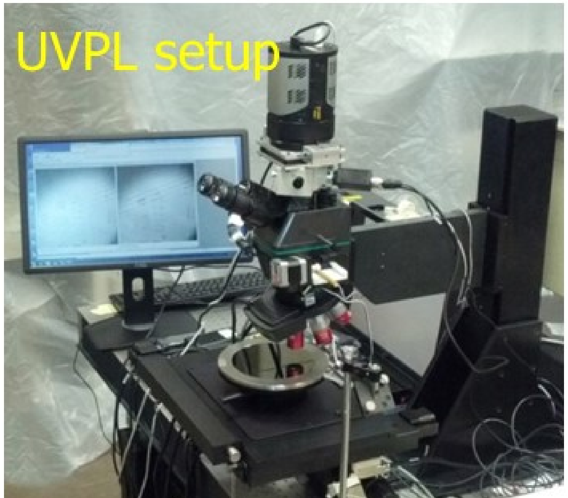
Objectives

- Work with PowerAmerica fabrication partners to screen wafers, pre-fab, for basal plane dislocations (BPDs) and other extended defects that adversely degrade SiC device yield, performance and reliability
- <u>Examine wafers after implantation and implant activation steps, to check for BPDs introduced by these steps</u>
- Compare BPD introduction for room temperature vs. high temperature implantation and vary conditions to eliminate BPDs created





U.S. NAVAL RESEARCH LABORATORY



NRL: U.S. Naval Research laboratory

PowerAmerica Applications Funding Boosts WBG Manufacturing by Showcasing Compelling System Advantages

POWERAMERICA

June 2016 – June 2017

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John Deere Hybrid Loader SiC Inverter has Performance and System Architecture Advantages over Conventional Si-IGBT Inverters

POWERAMERICA

Advantages of SiC Inverter

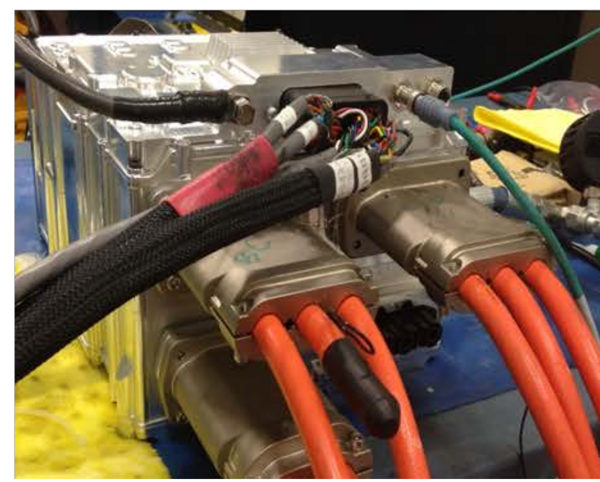
JOHN DEERE

- 18 kW/L power density compared to 9kW/L IGBT inverter in 644K Loader
- Up to 25% more work per gallon fuel as compared to a conventional JD 644K Loader
- Engine radiator fluid cools SiC inverter
- > 96% efficiency (as high as 98.6%) with SiC inverter as compared to < 95% efficiency with IGBT inverter
- Systems benefits and advantages as compared to conventional 644K Loader
  - Reduction in engine size and hence lower fuel consumption during idling
  - Elimination of refueling requirement during day long work cycle
  - Vehicle simplifications:
    - ✓ Elimination of dedicated cooling system/loop for inverter
    - ✓ SiC inverter cooling system integrated with the engine

SiC Inverter Deployed in the JD 644K Hybrid Loader

JDES 644K Loader with SiC Based Inverter Driven by DOE and PowerAmerica Personnel

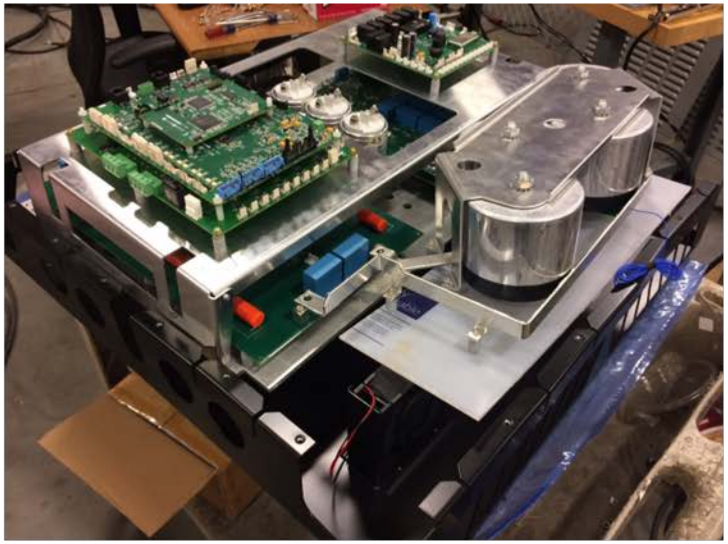
Gen-1 Inverter (18 kW/L) - Apr 17, 2017



Toshiba SiC MOSFET/Diode Based Commercial PV Inverter Exhibits Higher Efficiency and Lower Weight

PowerAmerica

Objective: Commercialize 50 kW SiC MOSFET based PV inverter



Prototype of Final Product

75kHz Switching

Inductor Current

SiC DC/DC Test Result

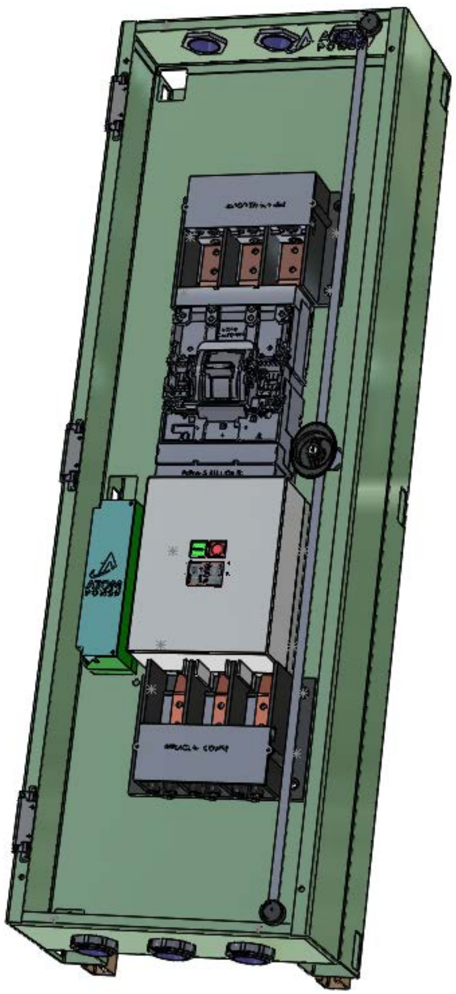
Close to release, moving to production

Weight: 142.77 lbs. / 64.90 kg

CEC Efficiency: 98.2%

Atom Power is Developing Fast and Highly Sensitive Solid-State Circuit Breaker Protection

Objective: Develop higher ampacity SiC solid-state circuit breakers to penetrate the full commercial and industrial building markets.



- Developing an 800-amp 480VAC, 3-phase Atom Switch solid-state circuit breaker using SiC circuit breaking technology based on our existing 100-amp circuit breaker designs

- 200,000-amp interrupting capacity which will be the highest of any circuit breaker on the market today

- Closed a strategic round of funding with Siemens Venture Capital in 1st Quarter of 2017

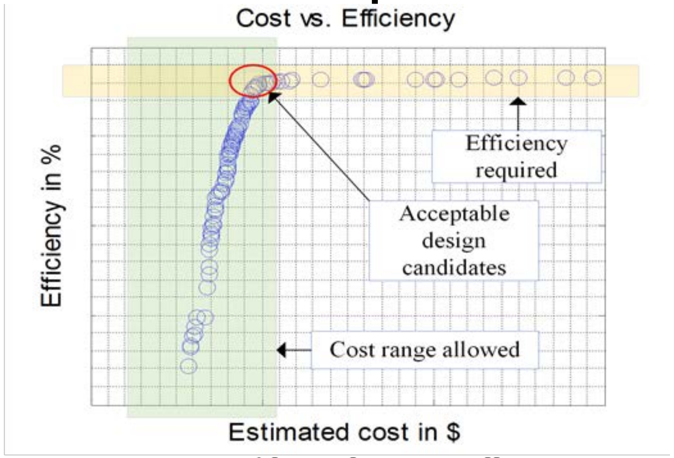
ABB is Improving the Efficiency of its Modular UPS Product with SiC Technology

PowerAmerica

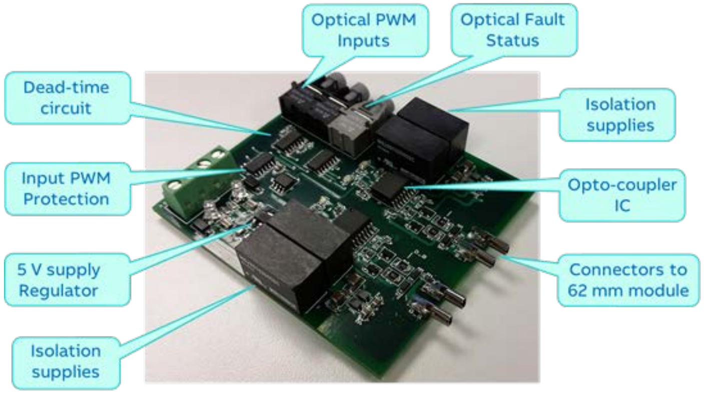
Objective: Improve the efficiency of ABB's 100 kW UPS power stage to greater than 98%

Uninterruptible Power Supply (UPS) power stage design optimized to extract maximum system benefit:

- Genetic algorithm based converter design optimization tool used to select optimal passives filter components including the effect of cost
- Design tool helps in determining crucial parameters such as switching frequency, passive filter inductor core material, etc.
- Custom gate driver developed to fit directly on to the SiC MOSFET module in ABB's 100 kW UPS prototype – design for quick productization
- The 100 kW SiC prototype being developed in this project is an advanced version of ABB's existing DPA500 100 kW Si IGBT based UPS unit, for ease of adoption to product
- Adoption of SiC technology by companies like ABB can increase industry confidence in the commercialization potential of SiC for power applications



Pareto-optimal front of Cost vs. Efficiency

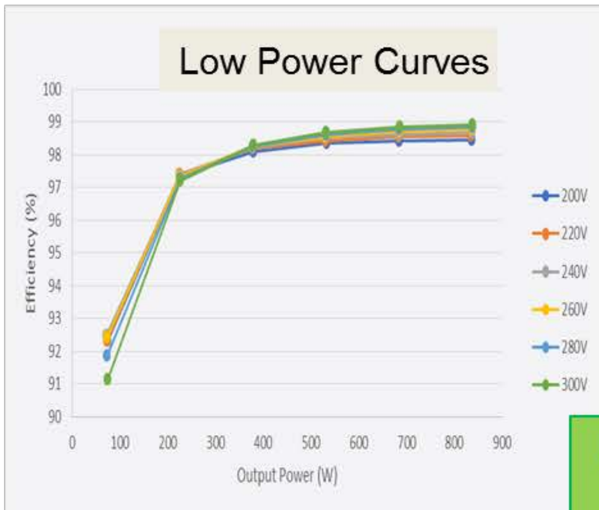


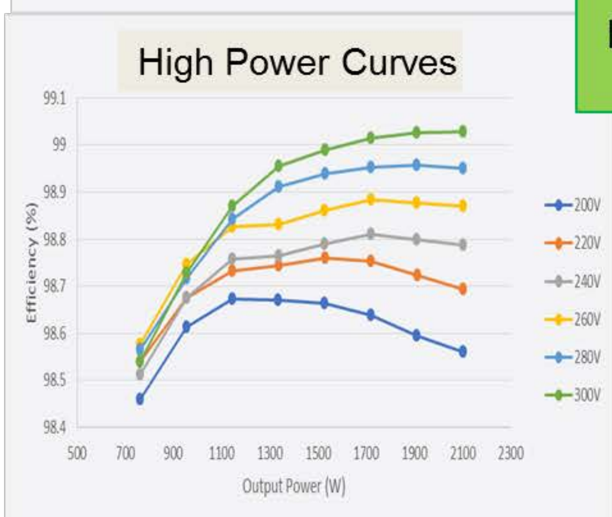
Gate driver version 1.0 for the 62 mm SiC module from CREE developed in this project

4kW-Class Open Source Transphorm PV Inverter Utilizes GaN Power Switches (BP2- In progress)

Objective: Build a manufacturable open-source PV inverter prototype to facilitate GaN adoption by reducing qualification time by more than 50%

Two phase interleaved MPPT prototyped & tested





Interleaved= > 99% at both low and high power

* Inverter tested at various input voltage & power levels;

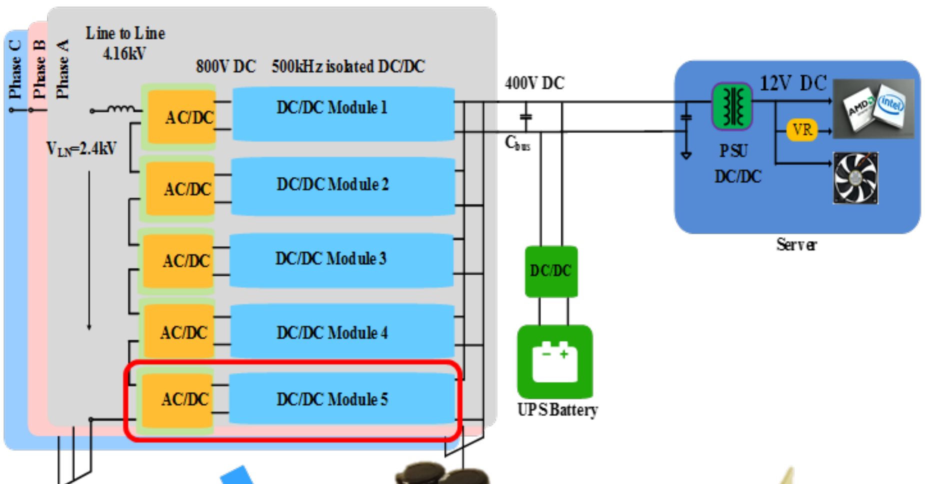
* Filter design & switching algorithms being optimized

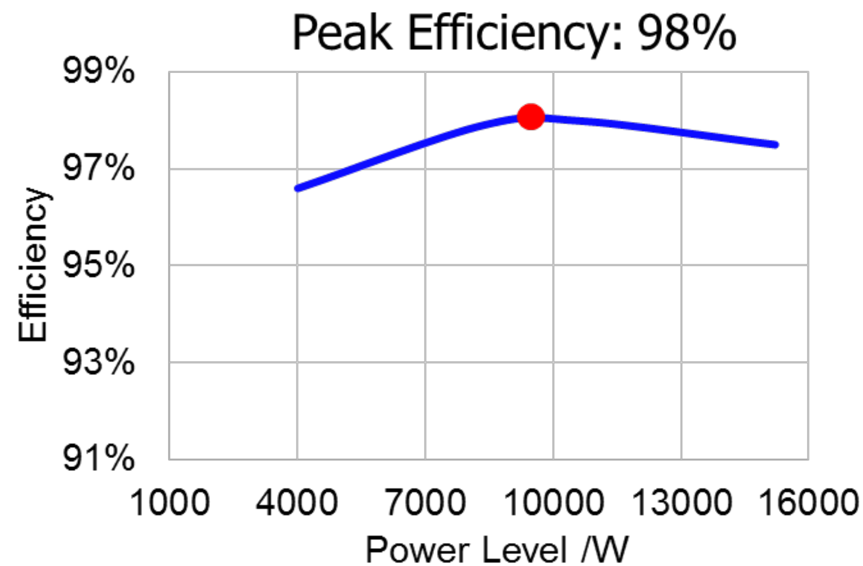
MPPT: Maximum Power Point Tracker

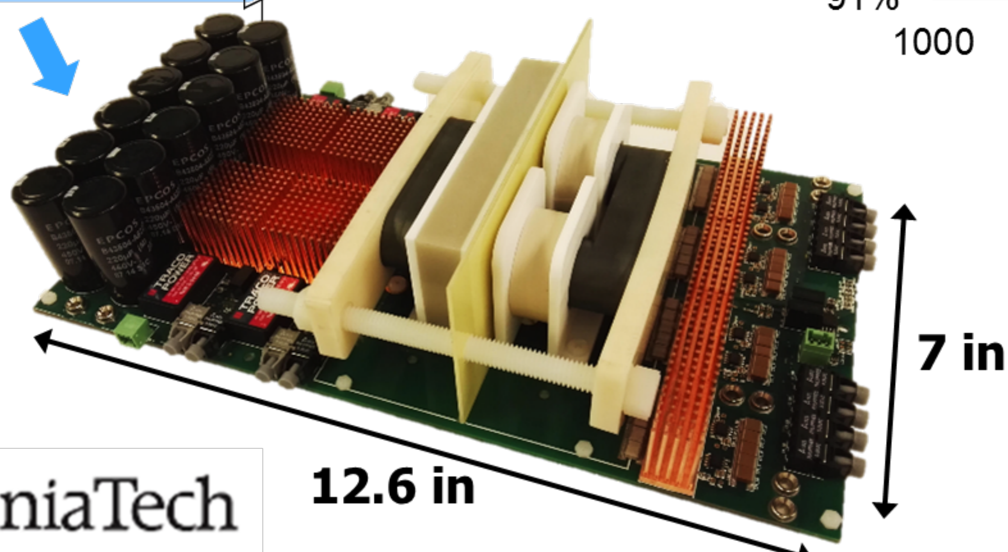
Develop SiC Based DC Data Center with High Frequency Isolation to Dramatically Reduce Power Conversion Loss

PowerAmerica

Objective: Develop a SiC based power conditioning building block, which converts 4.16 kV AC directly to 400 V DC bus with 500 kHz magnetic isolation to dramatically reduce power conversion loss of data center.







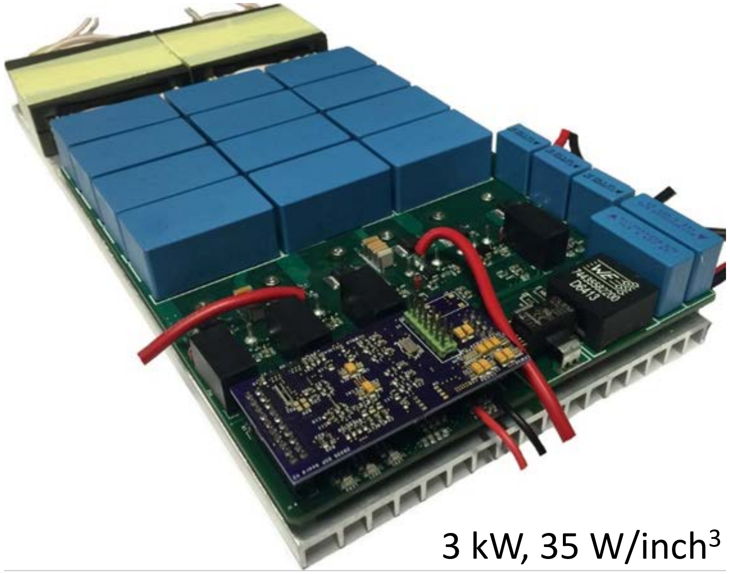
15kW module with shoe box size

48W / in^3

VirginiaTech

ASU Develops High Performance PV String and Micro Inverters

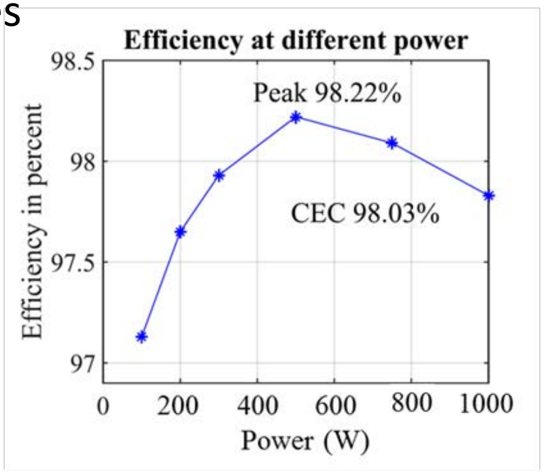
Objective: Develop all-film capacitor, doubly-grounded, transformer-less PV inverters with 98% efficiency and 30 W/inch^3 power density (for string)



3 kW, 35 W/inch^3

Highlights

- Novel, doubly-grounded topology allows PV negative to be grounded even with transformer-less approach eliminating high frequency ground currents
- One of lowest reported µF/kW capacitor requirements allowing an all-film capacitor solution
- Fully exploits characteristics of 1200V SiC and 650V GaN devices
- 35 W/inch^3 power density for 3 kW string inverter
- Wide range of grid support features



BP2 prototype, tested up to 1 kW

Outputs

- 1 patent application and 2 invention disclosures
- 14 papers in prestigious journals and leading conferences (APEC and ECCE) including a Best Presentation Award paper
- Directly impacts > 180 students at ASU through three Power Electronics classes

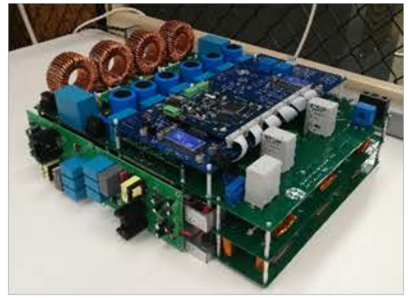
FSU is Developing SiC Based PV Inverters with Mass/Volume/Efficiency Advantages Over Si

State of art 100kW PV inverter

550 kg, 0.18 kW/kg, 98% peak efficiency, 97.5% weighted efficiency

FSU Gen I 50kW SiC PV inverter

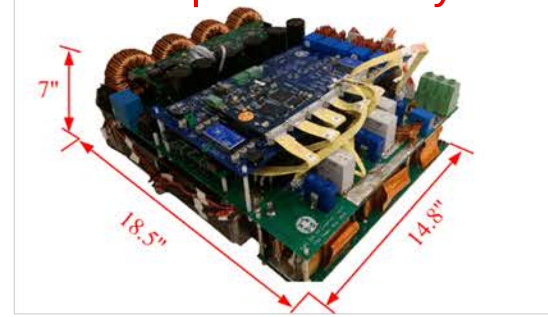
13x power density



20 kg, 2.5 kW/kg, 99.2% peak efficiency, 99.0% weighted efficiency, transformer-less, filter-less (grid side)

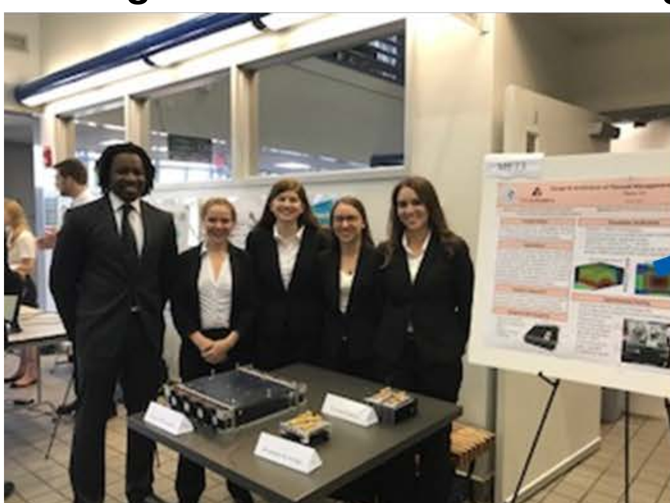
FSU Gen II 100kW SiC PV inverter

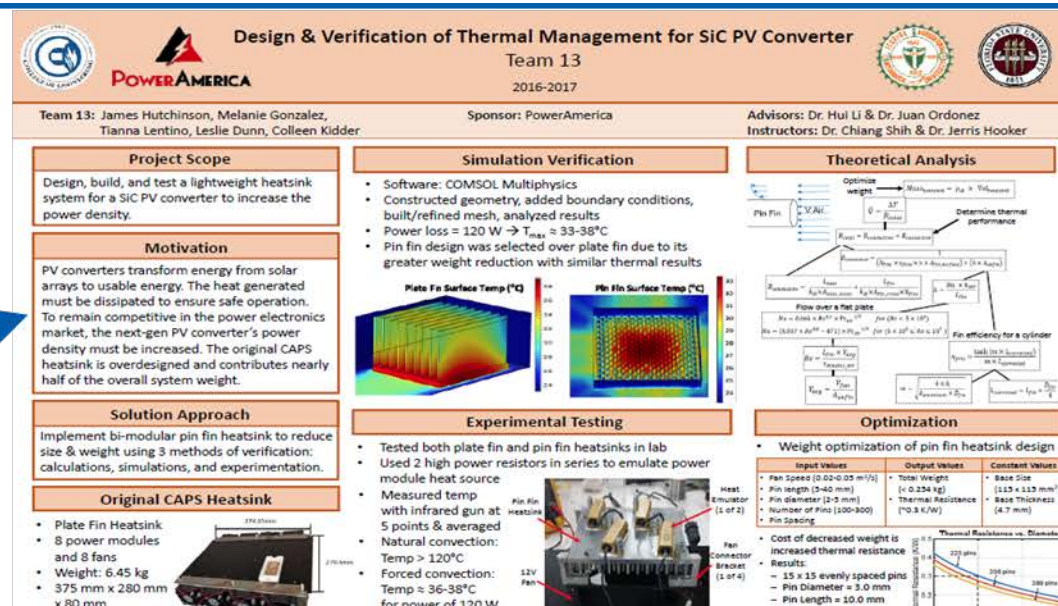
27x power density



20 kg, 5 kW/kg, 98.7% peak efficiency (derived), transformer-less, filter-less (grid side)

Under graduate education/training



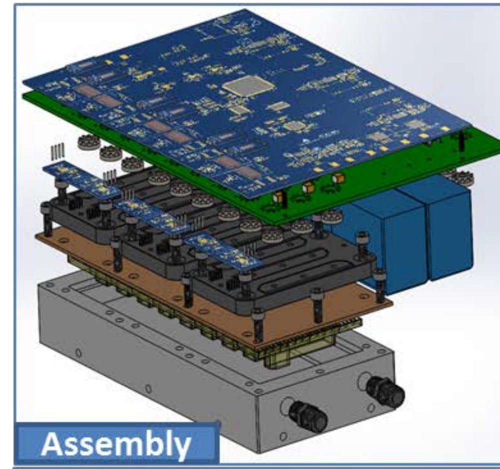


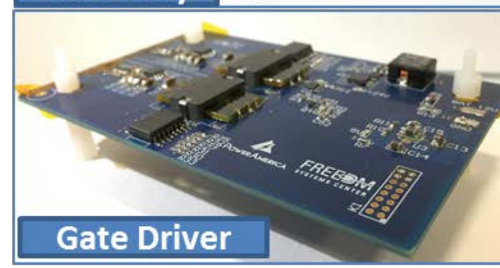
This presentation does not contain any proprietary, confidential, or otherwise restricted information.

NCSU SiC Based EV Traction Inverter has Mass, Volume, and Efficiency Advantages

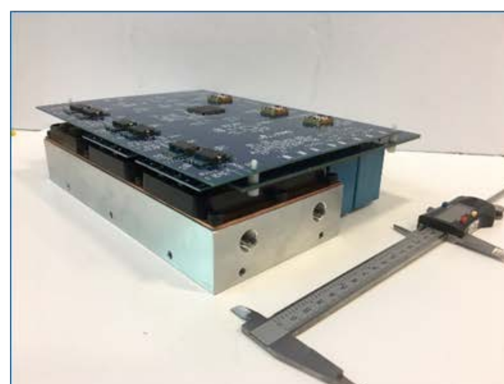
Objective: Develop a 135 kW EV traction inverter with high efficiency and high power density using SiC devices

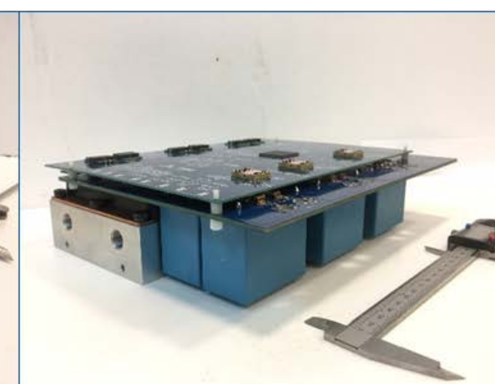
- **135 kW** Boosted Inverter with **1 kV** DC-link
- 1.7 kV/7.5 mΩ Wolfspeed HT-3231 Power Modules
- Planarized design for High Power Density with High Voltage PCB-based Busbar (**<13 nH** loop inductance), innovative heavy duty connector, and 3D cooling
- Ultra Low-profile (**4 mm**) Gate Driver – **70%** height reduction
- Inverter Stage: Volume - 3.9L; Power Density – 26kW/L





	2016 Chevy Volt Si-IGBT Inverter	NCSU SiC-based Boosted Inverter
Peak Power	135 kW	**135 kW**
Volume	10.4 L	**7 L**
Power Density	13.1 kW/L	**19.3 kW/L**
Efficiency	97.5 %	**99%**





NCSU SiC-Based MV Fast Charger is Smaller, More Efficient, and Cheaper to Install Compared to SOA

Objective: Develop a modular Medium-Voltage Fast Charger using commercial 1200 V SiC devices.

- On Track for System Deployment by end of BP2
- Ready for business model based on subscription parking, monetizing data and advertising on charger displays

MVFC Basic Features

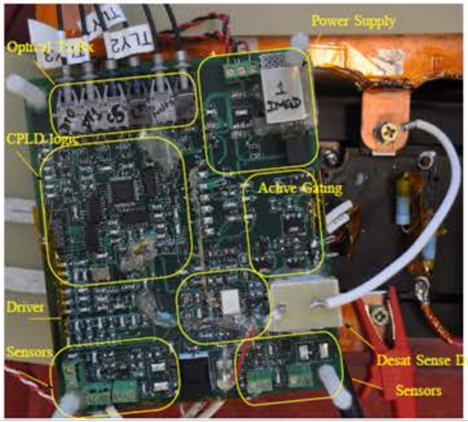
- 50 kW
- 2,400 Vac to 400 Vdc
- 1200 V SiC devices
- η ≥ 96%,
- PF ≥ 0.98, THD ≤ 2%
- 10x size reduction
- 4x weight reduction
- 40% installation cost reduction
- No step-down service transformer

Commercial Fast Charger
V = 800 L
m = 400 kg
η ~ 93.5%

NCSU
MV Fast Charger
V = 82L
m = 100 kg
η ≥ 96%

NC STATE UNIVERSITY

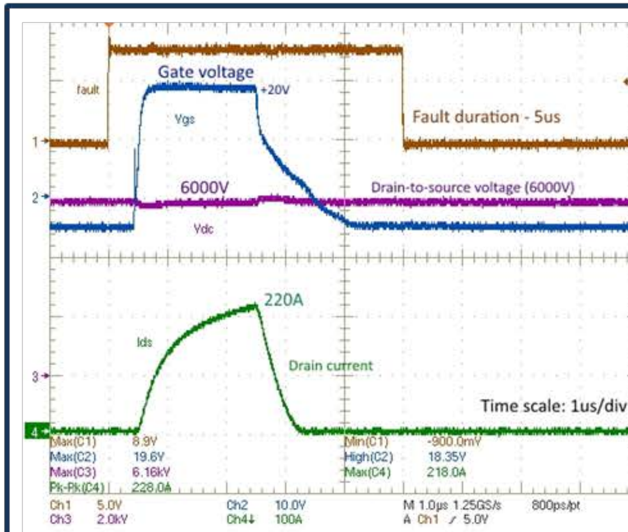
NCSU Develops Integrated Intelligent Gate Driver and Interface System for Medium Voltage Converter Applications



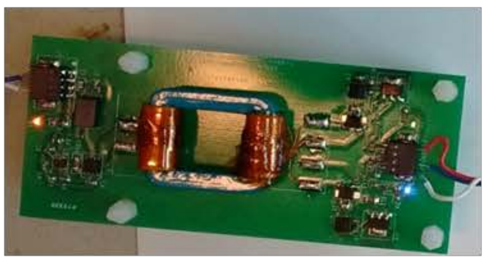
Intelligent Gate Driver

Specification	Value
Turn-on Voltage	18 V -> 20V
Turn-off Voltage	-5 V
Supply Input Voltage	9-10 V
Switching Frequency	Up to 20 kHz
Turn-on Gate Resistance	10-33 Ω
Turn-off Gate Resistance	10-15 Ω
Isolation Voltage	Up to 15 kV
dv/dt capability	> 50 kV/μs
Isolation Transformer Coupling Capacitance	< 5 pF (1- 100 MHz)

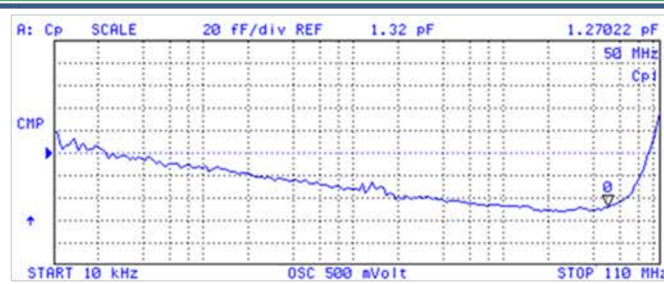
With short circuit protection and diagnosis features



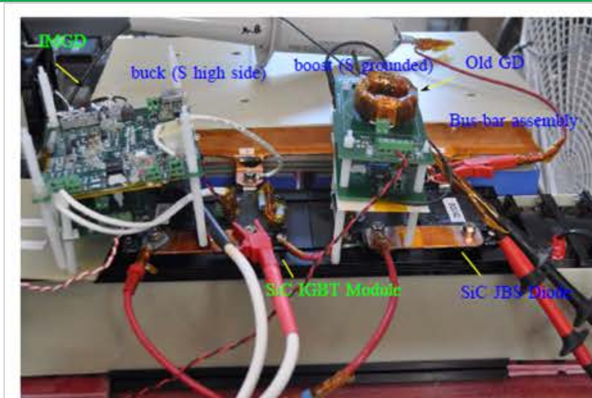
Short circuit protection of 10kV/10A Gen-3 SiC MOSFET at 6kV, 220A current, Trip time: 2.4μs



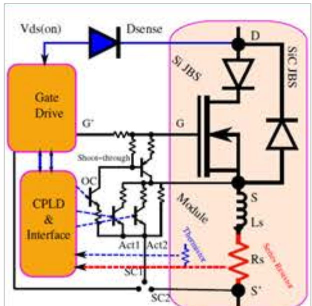
15kV isolated DC power supply



Isolation transformer coupling capacitance: 1.43pF

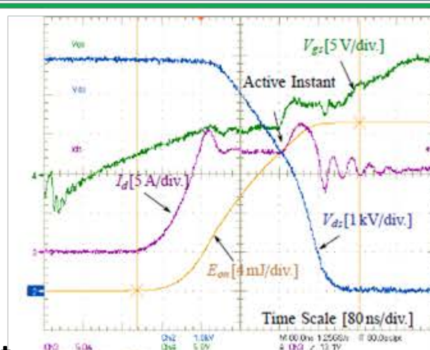


Gate driver validation: Boost-buck setup



Dynamically changing effective gate resistance during module switching

Gate-voltage level reduction



Active gating and protection circuit

PowerAmerica Established a Device Bank to Eliminate the Long Lead Times of Pre-production WBG Engineering Samples

Device Bank Benefit:

The PowerAmerica Device/Module Bank eliminates the long lead times of pre-production WBG engineering samples

Device Bank Fit to PA Mission:

Timely availability of pre-production engineering samples is a catalyst in accelerating next generation WBG power electronics

FA4 Proposal Title AWARD	**Organization/Team**	**PI**	**devices needed**
Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles	John Deere Electronic Solutions (JDES)	Singh,Brij	No action, During BP3 we plan to work with WolfSpeed to develop Six-Pack SiC power module for John Deere Gen-2 SiC inverter. WolfSpeed team has stated that they have Gen-3 SiC die to pack in the Six-Pack
SiC Active Harmonic Filter for Variable Frequency Drives (P.400.0481)	United Technologies Research Center	John, LaSpada	No action, For this project, UTRC will use COTS SiC modules manufactured by CREE-Wolfspeed.
65W High-Efficiency, High-Density Adapter with Improved Manufacturability	Navitas Semiconductor	Sheridan,Gene	No action, using their GaN FETs with inegrated gate drives
5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules	Georgia Tech Research Corporation	Divan,Deepak	Yes, 25 3.3 kV 15 A SiC MOSFET die which are available now in device bank. **Procure 30 3.3 kV 15 A SiC diode die**
SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration	Toshiba International Corporation	Liu,Peter	No action, We use commercial available devices, such as Wolfspeed C2M0040120D and CAS120M12BM2.
High Frequency GaN Power Converter	Lockheed Martin Missiles & Fire Control	Byrd,Tom	No action, EPC Enhancement GaN FET, COTS no lead time
SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck	Bendix, University of Akron	Sozer,Yilmaz	No action, CREE COTS 1200 V 90 A MOSFETs that are readily available: https://www.digikey.com/product-detail/en/cree-wolfspeed/C2M0025120D/C2M0025120D-ND/4807892 modules to be used for testing are:
100 kW Commercial PV Inverter with Efficiency > 99 % Operating in Interleaved Triangular Conduction Mode (iTCM)	Virginia Polytechnic Institute and State University	Burgos,Rolando	No action, 900V and 1700V COTS no need to procure in advance, available from CREE
Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module	University of Tennessee	Wang,Fred	Yes, Assuming an 80% module yield, 60 dies Wolfspeed 10 kV, 20 A MOSFETs. This includes 45 needed for the converter itself (36 actually needed but consider 80% yield the number is 45), and 15 needed for spares and initial testing (one phase leg).
Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid	NCSU	Bhattacharya,Subhashish	(30 10 kV MOSFET die sent to CREE Fay for modules), **60 10kV/15A SiC JBS Diode die + 120 10 kV MOSFET die**
100 kW Commercial PV Inverter	Florida State University	Li,Hui	No action, CREE COTS 1200 V 90 A MOSFETs that are readily available: https://www.digikey.com/product-detail/en/cree-wolfspeed/C2M0025120D/C2M0025120D-ND/4807892, 10 T-type 1200 V SiC MOSFET modules
Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger	North Carolina State University	Lukic,Srdjan	56 10 kV MOSFET die

Strategic University PowerAmerica Funding Provides Hands-on Training to the Next Generation of WBG Engineers

PowerAmerica

June 2016 – June 2017

Funding Focus Areas

1 Management and Operations

1.1 Program and Financial Management
1.2 Technology Roadmap
1.3 Sustainability
1.4 Establish a Device Bank
1.5. Subawards Management
1.6 Open Innovation Fund
1.7 Membership and Industry Relations
1.8 Compliance Program
1.9 External Communications
1.10 Placeholder for Faculty Hiring for Sustainability
1.11 Metrics Reporting
1.12 Management of Foundry Process

2 Foundry and Device Development

2.1 Ion Implanter and PDK **X-Fab Texas**
2.2 1.2 kV Diode and MOSFET Foundry Qualification of SiC 150mm line **USCi**
2.3A Qualification an testing of of Gen 3 3.3kV/40mOhm SiC MOSFETS **Wolfspeed/Cree**
2.3B Qualification and testing of Gen3 10kV/350mOhm SiC MOSFETS **Wolfspeed/Cree**
2.4 Diode Commercialization and Production **Monolith**
2.5 Manufacture Vertical GaN devices on bulk GaN wafers **Qorvo/Triquint**
2.6 N/A
2.7 N-Polar GaN Power Devices **UCSB**
2.8 High frequency 12kV SiC Planar gate Power MOSFETS **NCSU (Baliga and Misra)**
2.9 N/A
2.10 Examine Material Defects in SiC Epilayers by UV Photoluminescence **NRL**
2.11 GaN Power Device R&D **UC Davis**
2.12 & 2.13 N/A
2.14 Low Cost 1200V SiC JBS Rectifiers and SJT Dev. **GeneSiC**
2.17 Development of an open gate dielectric process for SiC MOSFET Manufacturing **Auburn University**

3 Module Development & Manufacturing

3.1 Power Module Development and Manufacturing **Cree Fayetteville**
3.2: Reliability benchmarking of SiC MOSFETs **Argonne National Lab**
3.3: Reliability Benchmarking of Lateral GaN Power HEMTs on Si **Rensselaer Polytechnic Institute**
3.4 Terrestrial Neutron Induced Reliability Concerns **CoolCAD**

4 Commercialization Applications

4.1 200 kW 1050Vdc SiC Dual-Inverter **John Deere Electronic Solutions**
4.2 Ultra-High Efficiency SiC Modular UPS **ABB**
4.3 SiC Small Commercial PV Inverters **Toshiba**
4.4: MV Power Module for High Density Conversion **NCSU (Hopkins)**
4.5 N/A
4.6 Comparison of SiC and GaN 7.2 kW Chargers **Kettering University**
4.7 EMI Mitigation and Containment in SiC Modular UPS **Virginia Tech (Burgos)**
4.8 DC Data Center with High Frequency Isolation **Virginia Tech (Lee)**
4.9 HybMic Converter **InnoCit**
4.10 SiC Commercial PV Inverter **FSU (Li)**
4.11A Hi Pwr Density DC-DC Conv. for Aux. Pwr. in H-D Vehicles **NCSU (Bhattacharya)**
4.11B Integrated Intelligent Gate Driver and Interface System for Med. V Appl. **NCSU (Bhattacharya)**
4.12 100kW SiC Inverter for EV Traction Drive **NCSU (Husain)**
4.13 WBG Med. V EV Fast Charger **NCSU (Lukic)**
4.14 TBD
4.15 High Perf. PV String and Micro Inverters **ASU**
4.16 MV Gate Drive with Comprehensive Protection Functions **Ohio State**
4.17: Mass Market SiC Solid-State Circuit Breaker Development **AtomPower**
4.18 Open-Source Compact Transformerless Grid-Tied 3kW GaN PV Inverters **Transphorm**

University FA2-4 projects provide real world experience to the next generation of WBG Engineers: **$5.5M, 44 undergrad, 38 grad, and 11 Post-doc full-time trainees**

PA WBG Educational Programs Have a Direct and Immediate Impact on Power Electronics Manufacturing

PowerAmerica Select WBG Educational Activities:

- Create an undergraduate power electronics course with a laboratory component, and insert WBG content in NCSU power electronics courses
- Educate the next generation of WBG professionals to staff Universities and industry with qualified personnel who will drive demand, and educate others through their professional activities
- Offer short courses to educate the workforce on the use and application of WBG technologies thereby facilitating their adoption
- Deliver WBG tutorials at conference venues to educate participants and promote PowerAmerica

WBG Tutorial Wins Educate Participants and Promote PowerAmerica Mission and Sustainability

PowerAmerica

PowerAmerica WBG Tutorial wins at prestigious conferences:

- ✓ "Other MOSFET processing (ohmic contacts, implantation, passivation, specific issues related to device geometry)", Veliadis, 160 attendees, European Conference on SiC and Related Materials ECSCRM Sept. 2016
- ✓ "SiC Power Devices", Veliadis, 60 attendees, 11th European Space Power Conference (ESPC) Oct. 2016
- ✓ "SiC Device Fabrication & HV SiC Devices Enabled MV Power Converters", Bhattacharya and Veliadis, 104 attendees, IEEE Applied Power Electronics Conference and Exposition (APEC) Mar. 2017
- "SiC power device design and fabrication, and insertion in novel MV Power Converters", Bhattacharya and Veliadis, IEEE Energy Conversion and Congress & EXPO (ECCE) Oct. 2017

ecscrm 2016 Greece | esa | APEC 2017 | ECCE IEEE ENERGY CONVERSION CONGRESS & EXPO

PA Organizes the ICSCRM 2017 Tutorial with Expert PowerAmerica Member Participation

POWERAMERICA

ICSCRM 2017 Tutorial: “Moving from Silicon to SiC: Learning to Think Differently!”

Introduction: SiC properties and applications, Veliadis Organizer, PowerAmerica

- SiC Material Properties: Advantages, challenges, and solutions
  - E. Balkas, “SiC bulk substrates”, CREE-Wolfspeed
  - A. Burke, “SiC epitaxy”, CREE-Wolfspeed
- SiC MOSFET Design: Advantages, challenges, and strategies
  J. Baliga, NCSU
- SiC Processing: It's not the same as silicon!
  W. Sung, SUNY
- SiC Power Electronic Applications
  - “15 kV IGBT converters and High Voltage Circuit topologies”, S. Bhattacharya NCSU
  - “High-Performance MVA Magnetic Resonance Imaging Gradient Drivers with SiC”, J. Sabaté, GE
  - “Heavy duty vehicle inverter”, Brij Singh, John Deere
- Strategies for Market Insertion through Robust Workforce Development
  A. Agarwal, Ohio State University
- Student Q&A session

ICSCRM 2017 | International Conference on Silicon Carbide and Related Materials
Washington, DC | September 17-22, 2017

PowerAmerica to Offer WBG Short Courses in 2017 to Train Working Professionals

High level activities to formulate 2017 PA short courses:

- ✓ Collect short course duration/content/cost information by polling industry
- ✓ Evaluate data from industry poll and research other short course offerings
- ✓ Devise tentative short course duration and content
- Share tentative short course duration/content with industry for feedback
- Finalize duration/content and select speakers
- Formulate cost, and set date and location
- Engage NCSU "short course group" to market event and provide logistics support

Target PA short course offering date: Oct. 2017

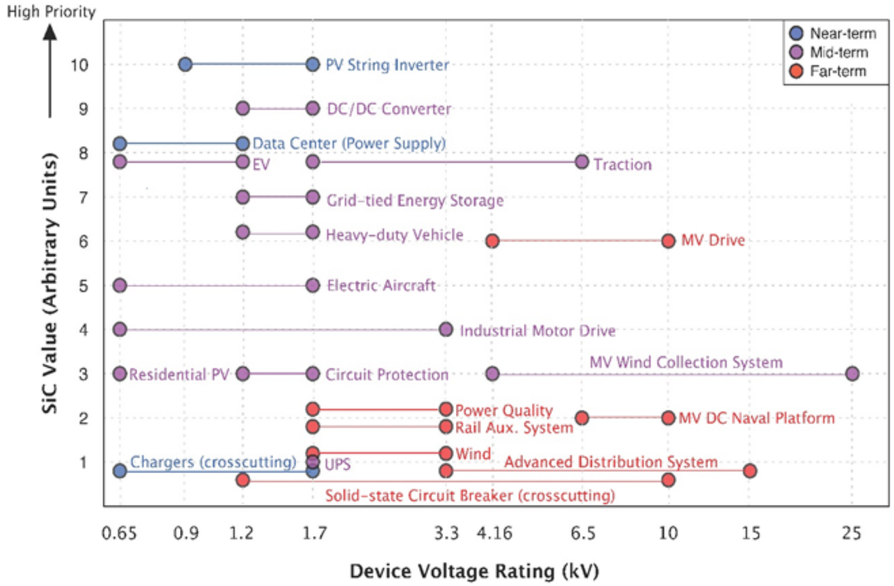
PowerAmerica Developed SiC and GaN Technology Roadmaps Through Expert Interviews and Literature Review

PowerAmerica Roadmap formulated with member participation

- Convened an in-person workshop on June 22, 2016 in Raleigh, North Carolina with ~50 attendees
- Interviewed 21 experts
- Held a second virtual workshop with PowerAmerica working group members
- Convened biweekly working group meetings with members to collect additional information and gather feedback on roadmap components
- Reviewed more than 100 sources as part of a background literature review

PowerAmerica Roadmap guides solicitation and funding decisions

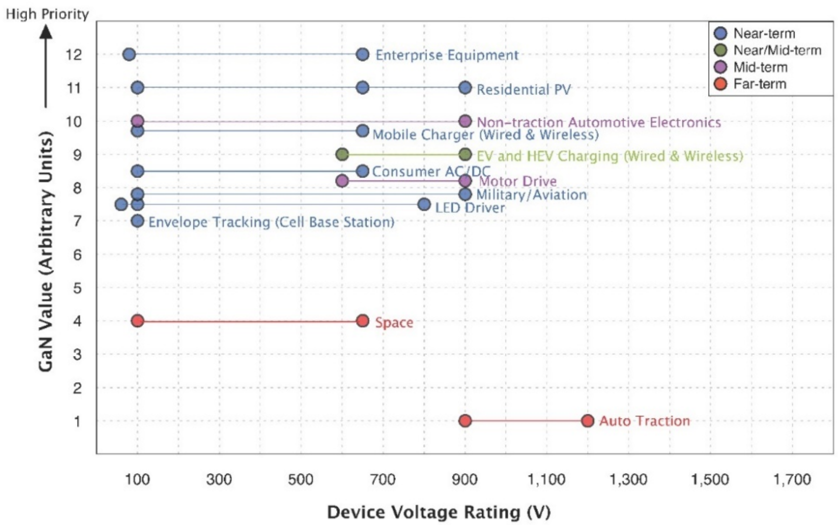
PowerAmerica SiC Roadmap Identifies Primary Markets & Applications



Application	Device Voltage	Application Voltage Rating (V)	SiC Value [1]	Timeline
PV string inverter	0.9–1.7		10	Near-term
DC/DC converter	1.2–1.7		9	Mid-term
Data center (power supply)	0.65–1.2	380 DC	8	Near-term
EV	0.65–1.2	OBC: 0.65 Drive train: 0.9, 1.2	8	Mid-term
Traction (e.g., EV/PHEV and rail traction)	1.7–6.5	Rail traction: 1.7, 2.4, 3.3, and 6.5	8	Mid-term
Grid-tied energy storage	1.2–1.7		7	Mid-term
Heavy-duty vehicle	1.2–1.7		6	Mid-term
MV drive	4.16–10		6	Far-term
Electric aircraft	0.65–1.7		5	Mid-term
Industrial motor drive	0.65–3.3		4	Mid-term
Residential PV	0.65	110–220	3	Mid-term
Circuit protection	1.2–1.7		3	Mid-term
MV wind collection system	4.16–25		3	Mid-term
Power quality	1.7–3.3		2	Far-term
Rail aux. system	1.7–3.3		2	Far-term
MV DC naval platform	6.5–10		2	Far-term
Wind	1.7–3.3		1	Far-term
Advanced distribution system	3.3–15		1	Far-term
UPS	1.7		1	Mid-term
Chargers (crosscutting)	0.65–1.7		1	Near-term
Solid-state circuit breaker (crosscutting)	1.2–10		1	Far-term

Note. 1. SiC value reflects two impacts: 1) system impact on efficiency, power density, or cost; and 2) economic effect (i.e., size of the market and likely SiC adoption)

PowerAmerica GaN Roadmap Identifies Primary Markets & Applications



Application	Device Voltage	GaN Value [1]	Timeline
Enterprise equipment[2] (e.g., AC/DC and HV DC/DC) and 48V telecom DC/DC	80–650	12	Near-term
Residential PV[3]	100/650/900	11	Near-term
Non-traction auto electronics	100–900 [4]	10	Mid-term
Mobile charger (wired & wireless laptops, tablets, mobile devices)	100/650	10	Near-term
EV & HEV charging (wired & wireless)	600–900	9	Near/mid-term
Motor drive	600/900	8	Mid-term
Military/Aviation	100–900	8	Near-term
LED driver	60–100/800	8	Near-term
Consumer AC/DC[5]	100/650	8	Near-term
Envelope tracking (cell base station)[6]	100	7	Near-term
Space	100–650	4	Far-term
Auto traction	900–1200	1	Far-term

Notes.
1. GaN value reflects two impacts: 1) system impact on efficiency, power density, or cost; and 2) economic effect (i.e., size of the market and likely GaN adoption)
2. Enterprise equipment includes DC/DC converters, data center, HV DC/DC, and 48V Telecom DC/DC. The Telecom DC/DC should have a separate application.
3. Voltage: Panel optimizers/US/EU
4. While the device voltage ranges are from 100 to 900V, automotive electronics covers 10 to 650V. Overall applications are mid-term markets but the applications of chargers/inverters for automotive electronics are on-going activities (i.e. near-term)
5. TV, power supplies, audio amplifiers
6. Niche application

PowerAmerica Value Proposition is Key to Sustainability

Wide angle view of SiC and GaN device technology developments and applications;

Participation in SiC and GaN technology road mapping used to select projects for funding; industry driven;

Networking at project reviews, annual meeting, workshops and Webinars;

Participation with 11 university programs; access to professors as well as students with focus in GaN and SiC devices/applications (as future employees);

Benefit from PowerAmerica's promotion of SiC and GaN technology to the industry applications community, including trade show sponsorship;

Benefit from education/workforce development program to increase pool of people trained in WBG technology, including forthcoming courses for career applications engineers;

The PowerAmerica Ecosystem is a Catalyst for the Commercialization of SiC and GaN Power Electronics

PowerAmerica will continue to support:

- Cost-effective device manufacturing
- Module development
- Third party reliability testing and failure analysis
- WBG Circuit reference designs and applications
- Workforce training (short courses, tutorials)
- Graduate Education
- Timely access to engineering samples through PA device bank
- Roadmaps, market direction, industry perspectives, networking opportunities, and talent recruitment