ANNUAL REPORT 2018

TRANSFORMING
U.S. MANUFACTURING

THROUGH ADVANCES
IN WIDE BANDGAP
POWER ELECTRONICS

ONE
INNOVATION
AT A TIME

GaN

SiC

PowerAmerica

THE POWERAMERICA TEAM

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Executive Director

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Principal Investigator

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Chief Technology Officer/
Deputy Director

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Director of Power Device
Technology

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Director of Education
& Workforce Development

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"...one of the single most important things PowerAmerica is doing is changing the mindset of the customer community."

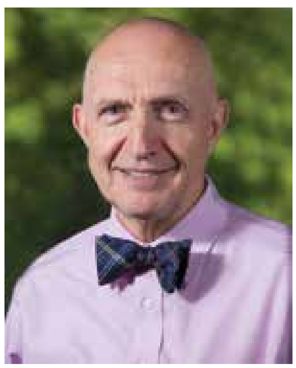
John Palmour, CTO, Wolfspeed, a Cree Company

FROM THE EXECUTIVE DIRECTOR

TO OUR VALUED POWERAMERICA MEMBERS, PARTNERS, AND ASSOCIATES:

This past summer, I listened as Cree founder and Wolfspeed CTO John Palmour spoke about PowerAmerica to an audience of congressional staffers in Washington, DC. Palmour, who we honored with the institute's Distinguished Founding Member Award at our 2018 summer workshop, expounded on why his company chose to become a member of the institute. Of the many excellent points he had, one, in particular, stuck with me – "We're involved because one of the single most important things PowerAmerica is doing is changing the mindset of the customer community." He explained that the innovative, groundbreaking projects demonstrated through PowerAmerica funding increase confidence in the technology and provides the industry with an assurance that the market for these devices is robust and growing.

And growing it is. The market for silicon carbide and gallium nitride semiconductors is at a tipping point, with unprecedented growth forecast over the next decade. As the market takes off, PowerAmerica and its members (with backing from the U.S. Department of Energy) are positioning themselves to lead the charge, building the ecosystem and laying the groundwork for large scale adoption of this power electronics technology. Our membership network now includes 27 industry and 18 university partners, as well as national labs, who are continually innovating in multiple areas of the wide bandgap supply chain and demonstrating the compelling advantages of these devices in power electronics systems. Applications are focused in high-demand industries with significant economic impact potential and include everything from laptop adapters to photovoltaic inverters to uninterruptable power supplies, data centers and electric vehicle fast chargers (you can read more about our projects on pages 13-42). More and more of these projects are nearing the commercialization stage, ready to be widely produced and adopted.



POWERAMERICA EXECUTIVE DIRECTOR NICK JUSTICE

At the same time, we're continuing to establish PowerAmerica as an integral presence in the WBG power electronics industry. We're excited by our relationship with IEEE Power Electronics Society. Because a number of those volunteering in key roles within this world-class organization also have connections to PowerAmerica, the institute plays an essential role in bringing our voice, experience, and expertise to world leaders in this future field. Incredibly, this group brings together nearly 10,000 members that have a continually growing global impact. To each of you involved in our tutorials, in our roadmap, and our international outreach, thank you. To Victor Veliadis (Deputy Executive Director and CTO of PowerAmerica), Tim McDonald (Senior Consulting Advisor at Infineon and Chairman of PowerAmerica's Membership Advisory Committee) and Jon Zhang (Director of Power Device Technology at PowerAmerica), your leadership in the IEEE roadmap committee is opening up a global market for all of us. A special thank you to Alan Mantooth as he passes the reins of the society to a new president for empowering its members to have such a positive impact on the world community.

It's a thrilling time to be a part of PowerAmerica. Attend one of our annual meetings or summer workshops (which attracted hundreds of participants this year), and the excitement surrounding the potential for this technology is tangible. It's obvious we're on the precipice of something big. Together, we'll continue transforming U.S. manufacturing through advances in SiC and GaN power electronics – one innovation at a time.

THE DRIVING FORCE BEHIND A $12B REVOLUTION IN POWER ELECTRONICS

The PowerAmerica Institute at N.C. State University, a member of Manufacturing USA, is saving energy and creating manufacturing jobs by accelerating the large-scale adoption of wide bandgap semiconductor devices in power electronic systems. PowerAmerica is backed by $70 million in funding from the Department of Energy, with matching funds from industry partners and the State of North Carolina.

$20,430,566

Distributed to

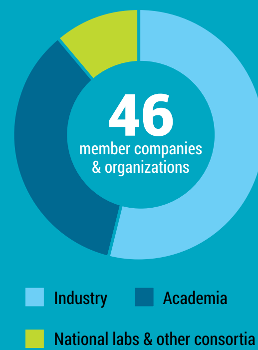
28 Projects

Including, for the first time, 3 Open Innovation Fund Projects

AWARDED TO DATE

$80 MILLION

95 TOTAL PROJECTS



POWERAMERICA FUNDS PROJECTS IN THE FOLLOWING AREAS:

$7,958,000 — **Foundry and Device Development**
Enable low-cost, large volume silicon carbide device manufacturing in the U.S.

$2,791,000 — **Module Development and Manufacturing**
Bridge the gap between device readiness and commercial adoption

$9,044,248 — **Commercialization Applications**
Boost manufacturing by showcasing compelling wide bandgap system advantages

$637,318 — **Education and Workforce Development**
Educate the next generation of wide bandgap power engineers

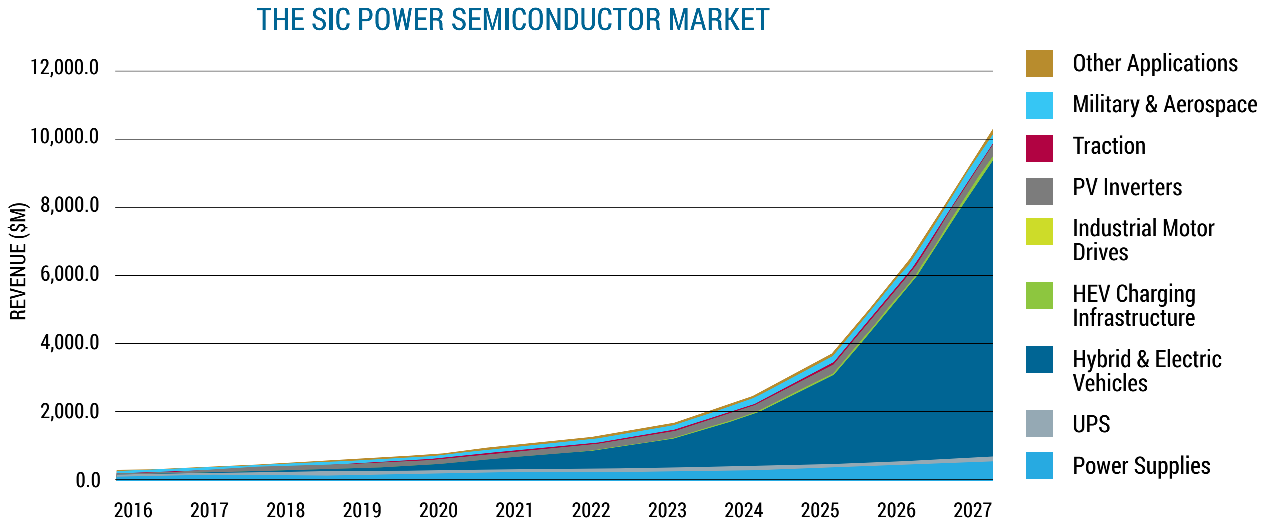
Financials derived from Budget Period 3 (BP3)

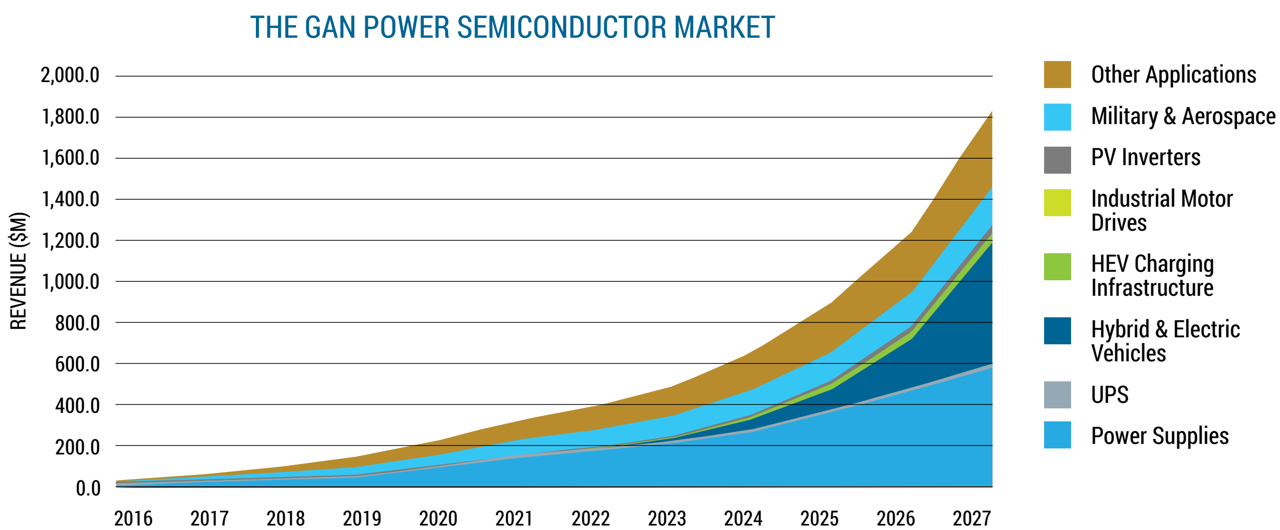
5 INVENTION DISCLOSURES

600+ PARTICIPANTS

At the PowerAmerica 2017 & 2018 summer workshops & 2018 annual meeting

SIC AND GAN MARKET PROJECTIONS





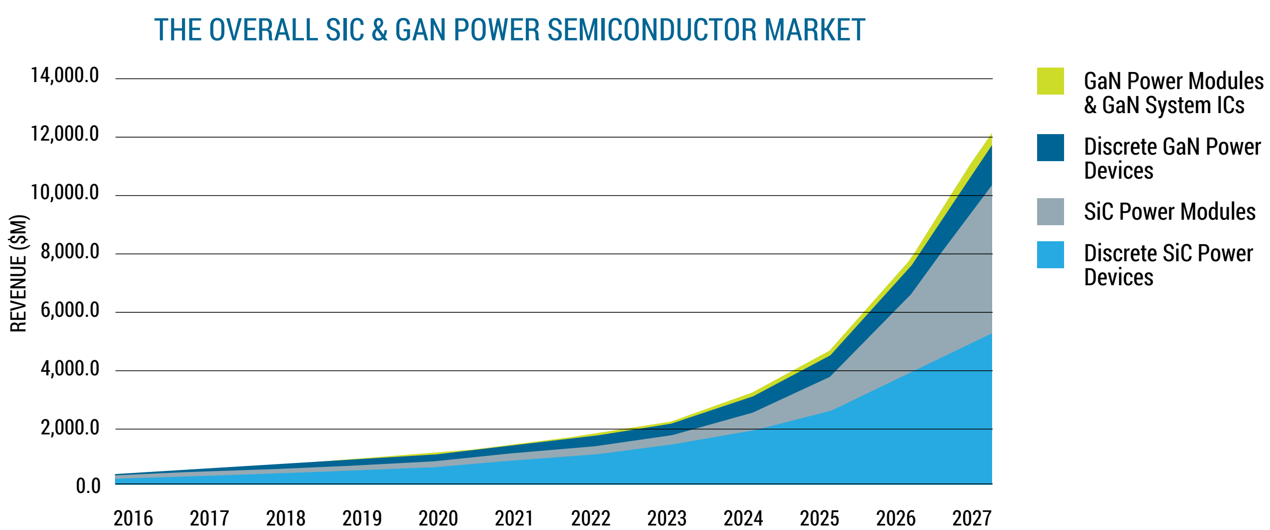


Chart Source: IHS Markit: SiC and GaN Power Semiconductors Report – 2018

POWERAMERICA: CREATING COMMERCIAL SUCCESS




SIC AND GAN-BASED TECHNOLOGY IS CREATING A WHOLE NEW LANDSCAPE OF OPPORTUNITY FOR AMERICAN BUSINESSES AND WORKERS.

Navitas

With support from PowerAmerica, Navitas set out to establish a commercially compelling platform with GaN integrated circuits (ICs) that sets an industry standard in energy efficiency, power density and manufacturability for consumer adapters and charger application. The shift to high-density, high-efficiency adapters creates an opportunity for U.S. suppliers to capture a significant portion of this market. Navitas' technology (pg.34) has been adopted in the world's thinnest universal 45W power delivery adapter, and other designs are in process.

GeneSiC

GeneSiC Semiconductor is manufacturing 3.3kV SiC power MOSFETS at the X-FAB foundry, and leveraging its international distribution and sales networks to make these devices available on a global scale – already attracting interest from international customers. "PowerAmerica's program is critical toward making high-voltage silicon carbide devices, like MOSFETS, competitive with traditional, widely used silicon devices," said GeneSiC CEO Ranbir Singh. "The establishment of a robust supply chain, engagement with a high-quality foundry, and the infrastructure to produce high volumes, which are enabled by PowerAmerica, allows SiC MOSFETS to become competitive in the applications marketplace."

Monolith

Acquired by Littelfuse

With PowerAmerica support and the use of X-FAB's facilities, Monolith has successfully developed manufacturable, high-yielding 1700V SiC Schottky diodes with best-in-class performance that have passed key engineering reliability tests. These high-voltage diodes are being produced to meet the needs of higher power density targets for the next generation of solar and wind inverters, and other applications such as data centers, industrial motor drives, and rail traction. Monolith is now a wholly owned subsidiary of Littelfuse, Inc. after being fully acquired earlier this year.

United Silicon Carbide

United Silicon Carbide (UnitedSiC) announced the release of 650V and 1200V SiC FETs in numerous packages, which have met stringent, international automotive qualification standards, making them ideal for automotive applications. PowerAmerica assistance helped UnitedSiC to fully qualify the SiC FETs, which are shipping in volume for use in electric vehicles and industrial power supplies. The dominant applications where these devices are being used are on-board chargers, DC-DC converters and fast DC chargers. The devices have been designed for use in virtually every large global market including the United States, China, Korea, Japan, Europe, and Australia.

X-FAB

The X-FAB Texas foundry in Lubbock, Texas is a silicon wafer foundry that, with funding from PowerAmerica, was upfitted to produce silicon carbide wafers. The foundry operates under a collaborative model, providing access to SiC semiconductor companies that lack their own fabrication facilities. Together with PowerAmerica, X-FAB is leveraging the existing silicon economies of scale to fulfill the institutes' mission of utilizing small investments to lower the cost of manufacturing SiC devices and make them more accessible for wide-scale commercial adoption. Today, X-FAB Texas serves 13 customers with 25 projects, including nine members of PowerAmerica. X-FAB expanded its silicon carbide production in 2017, an investment the company estimates will add 50 new jobs.

HELPING
STUDENTS & PROFESSIONALS
BUILD & APPLY WBG KNOWLEDGE

WORKING PROFESSIONALS:
We provide the information power electronics professionals need to understand, design and implement the latest innovations in SiC and GaN technology. Members expand their skill sets through technical webinars, tutorials and hands-on short courses presented by industry experts and designed with commercial application in mind.

EMPLOYMENT PIPELINE:
A vital part of our mission is matching students with WBG experience to companies looking to grow their WGB workforce. We facilitate the connection for internships and employment.

GRADUATES:
At the PowerAmerica member universities, graduate students are working with top researchers in the field of wide bandgap power electronics. Our member students are already contributing to the advancement of WBG technology and are ready day one to apply that knowledge in a professional setting.

UNDERGRADUATES:
PowerAmerica and our partners at the FREEDM Systems Center at North Carolina State University offer academic year and summer programs for undergraduates interested in gaining technical and professional skills to equip them for a career in wide bandgap power electronics.

27 INDUSTRY PARTNERS

18 ACADEMIC PARTNERS

130+ RESEARCH STUDENTS

12 POST DOCS

74 GRADUATE STUDENTS

44 UNDERGRAD STUDENTS

21 TECHNICAL WEBINARS

PRESENTED TO **800** ATTENDEES


hnology Gap/Need
need to close technology/ investment gaps to achieve
er switching speeds, lower switching &
duction losses with >10X lower cost/Amp compared
state of the art SiC MOSFET.

Project Summary
he project is to demonstrate 100mm wafer scale vertical
aN/GaN FET in Qorvo's production scale, commercial
ab, for the applications of high voltage, high current
power GaN transistor.

Accomplishments
Since the start of the program, several key technical achievements have been demonstrated towards the 100mm wafer scale vertical GaN-on-GaN transistor goal.

First, Qorvo has demonstrated 100mm wafer scale, high quality GaN-on-GaN epitaxy that serves as the foundation for the vertical transistor fabrication. Qorvo's GaN-on-GaN epi has been demonstrated to be able to support a vertical GaN PN Junction with Vbr>1200V and low on-resistance (Ron = 0.11 mΩcm2) simultaneously in a parallel effort. Figure 1 is the epi design and the structural, electrical properties and

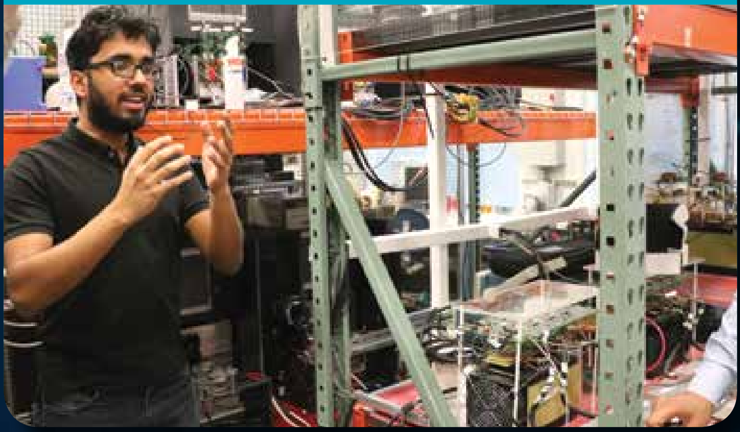
Properties of Qorvo 100mm GaN-on-GaN epi.

process and validation of gate metallization sch
All these individual processes have been applie
the vertical GaN transistor demonstration lots
described below.

Last, using the 100mm vertical GaN epi, the ne
designed high uniformity mask sets and indivi
process elements developed above, Qorvo has
lots of GaN vertical transistor fab run. As of t
lots are still in the fab line and we expect to f
fabrication by end of September 2017. The d

1200 WBG SPECIALISTS

ATTENDED OUR TUTORIALS, HANDS-ON COURSES, CONFERENCES AND ANNUAL MEETINGS, AND ARE ENGAGED WITH UNIVERSITY PROJECTS.



POWERAMERICA
MEMBERS

ACCESS
A NETWORK OF
INNOVATION

BENEFITS OF MEMBERSHIP INCLUDE:

- Access to the best source of business and technical information about developments in the wide bandgap technology ecosystem, including PowerAmerica's 18 member universities.
- Participation in making updates to PowerAmerica's SiC and GaN technology roadmaps.
- Use of device designs according to member's specifications and applications, and cost-effective device manufacturing in high-volume U.S. fabs.
- Testing services for devices and modules.
- Timely access to PowerAmerica device bank engineering samples.
- Periodic webinar presentations about SiC and GaN technology developments at PowerAmerica's member universities.
- Access to PowerAmerica's member-only web portal profiling undergraduate and graduate students in many universities who are pursuing an engineering education focused on SiC and/or GaN technology.
- Participation in semi-annual member meetings focused on SiC and GaN business and technology developments and member networking.
- Funding of projects to demonstrate the benefits of SiC and GaN devices in power electronics systems.
- Promotion of SiC and GaN technology through media and trade shows.

Through participation in the PowerAmerica ecosystem, industry members grow their business by expedited product introduction, and university members engage in collaborative projects with industry.

2018 MEMBERS

FULL SUSTAINING MEMBERS

Lockheed Martin

FULL MEMBERS

Wolfspeed – A Cree Company
X-FAB – Mixed-Signal Foundry Experts

AFFILIATE MEMBERS

Raytheon
Wolfspeed – A Cree Company
Hella
ON
Toshiba
GM
USCi – United Silicon Carbide, inc.
ABB
Infineon
Microsemi
GE
John Deere
Bendix
VPT
United Technologies Research Center
BAE Systems
Monolith Semiconductor Inc.

START-UP MEMBERS

Atom Power
GeneSiC Semiconductor
CoolCAD Electronics
Navitas Semiconductor
GlobalPower Technologies Group
Jenoptik
Sonrisa Research, Inc.

ACADEMIC MEMBERS

Arizona State University
NC State University
Auburn University
Florida State University
UC Davis – University of California
The University of Alabama – College of Engineering
Texas Tech University
Kettering University
The Ohio State University
Michigan Dearborn
SUNY Polytechnic Institute
Rensselaer
Virginia Tech
UCSB
Georgia Tech – Center for Distributed Energy
UNC Charlotte – EPIC
The University of Tennessee Knoxville
The University of Akron

FEDERAL PARTNERS

Argonne National Laboratory
NREL – National Renewable Energy Laboratory
Sandia National Laboratories

ASSOCIATE MEMBERS

E4 Carolinas
iNEMI
PESC
Research Triangle Cleantech Cluster

SPONSOR

U.S. Department of Energy

MEMBER REPORTS

Together we are transforming U.S. manufacturing with SiC & GaN power electronics.

REDUCING COST

IMPROVING RELIABILITY

ENHANCING PERFORMANCE CAPABILITIES

BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Contents

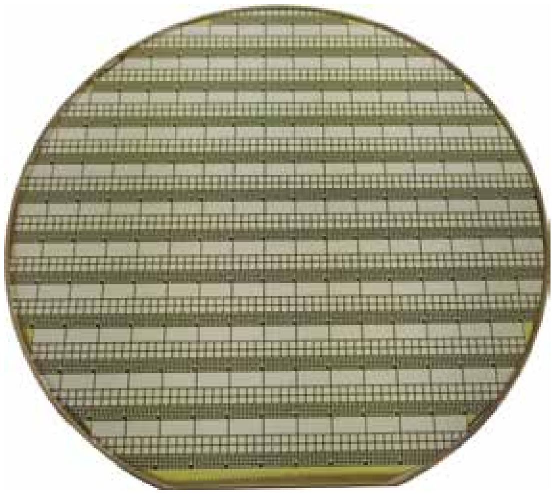
FOUNDRY AND DEVICE DEVELOPMENT

MODULE DEVELOPMENT & MANUFACTURING

COMMERICIALIZED APPLICATIONS

EDUCATION AND WORKFORCE DEVELOPMENT

3.3kV SiC MOSFET Development



GeneSiC SiC wafer.

GeneSiC Semiconductor, Inc.

Contact:
Ranbir Singh
ranbir.singh@genesicsemi.com

PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- RAIL TRACTION
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES

Project Summary

GeneSiC Semiconductor is developing and maturing device designs, layouts and process technology towards realizing high-performance 3.3kV SiC MOSFETs. GeneSiC is manufacturing 3.3kV SiC power MOSFETs on a 150mm foundry to achieve low costs using economies of scale, higher manufacturing quality and standardization of the supply chain. The company is using its strong international, top-tier distribution network to make these devices available worldwide. The sales network is being utilized to reach volume customers. GeneSiC has already received strong interest in these devices from international customers, including a major Department of Defense customer, who have immediate requirements for these devices.

Technology Gap/Market Need

3.3kV SiC MOSFETs will compete with Silicon IGBTs of similar ratings. They offer 100X lower switching losses and 2-3X higher power density as compared to Si IGBTs to achieve compact power conversion systems.

Accomplishments/Deliverables

3.3kV SiC MOSFETs were successfully fabricated on 100mm wafers and fabrication of SiC MOSFETs in a 150mm foundry were completed, and salient performance parameters were verified. Full flow 3.3kV SiC MOSFETs on 150mm wafers are also nearly complete. Comprehensive electrical characterization was performed on the fabricated devices and were confirmed to meet the target specifications.

Impact/Benefits

This program is critical towards making high-voltage SiC devices, like MOSFETs, competitive with incumbent Silicon devices, like IGBTs. While the technical benefits of SiC MOSFETs over IGBTs are indisputable, the adoption of these superior devices requires a reasonable reduction in costs, verification of reliability, and presentation of appropriate end-use cases. The establishment of a robust supply chain with SiC epiwafer supplies, high-quality foundry engagement and high volume characterization infrastructure enabled by this program allows >2kV SiC MOSFETs to become competitive in the applications marketplace.

1.7kV and 3.3kV SiC MOSFET Scale-Up

Microsemi

Microsemi, a wholly owned subsidiary of Microchip

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Avinash Kashyap,
Avinash.kashyap
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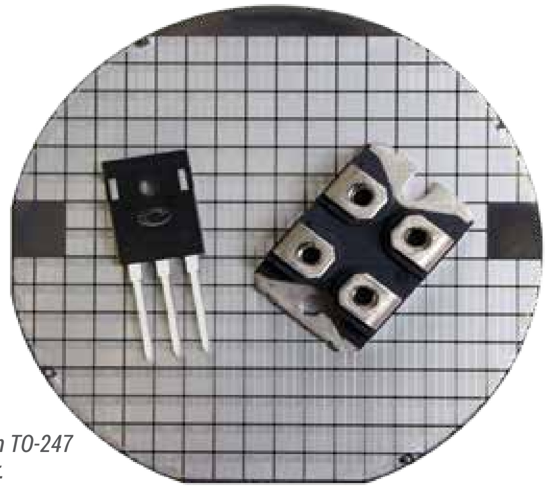
PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- RAIL TRACTION
- UPS DATA CENTER
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES



Microsemi SiC devices assembled in TO-247 and SOT-227 packages on SiC wafer.

Project Summary

This project aims to take 1.7kV SiC Schottky barrier diodes (SBDs) and MOSFETs designed by Microsemi into high-volume production, for the industrial market. The second part of this project focuses on transferring the development of 3.3kV SiC SBDs and MOSFETs to a 6" foundry (X-FAB) to accelerate introduction into the market focused on high power traction applications.

Technology Gap/Market Need

The rapid commercialization of Microsemi's 1.7kV devices would increase the supply available to industrial customers and reduce the price of the device.

The 3.3kV development and transfer opens up a new voltage node for the WBG industry and allows the traction market to innovate faster and reduce their carbon footprint.

Accomplishments/Deliverables

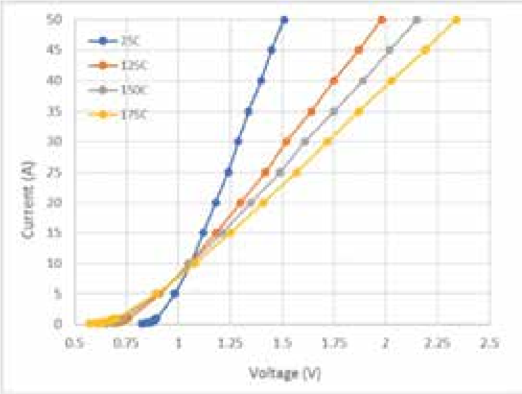
1.7kV and 3.3kV SBDs & FETs successfully transferred to X-FAB, electrical performance better than specs outlined in preliminary datasheet.

Deliverables: (a) 100 1.7kV diodes, (b) 100 1.7kV FETs, (c) 100 3.3kV diodes, (d) 100 3.3kV FETs to PowerAmerica device bank.

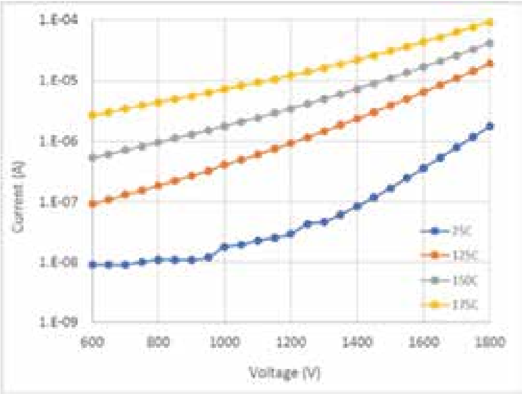
Impact/Benefits

Using a 6-inch fab that shares several tools with a larger-volume Si line can substantially decrease cost per amp and increase market penetration of WBG devices. Through this project, both design and manufacturing of SiC devices are being performed in the U.S., keeping high-tech manufacturing onshore.

Commercialization of 1700V SiC Schottky Diodes Manufactured at X-FAB Texas



Room and high temperature forward I-V characteristics of 1700V, 50A diode assembled in 2L TO-247 package.



Reverse I-V characteristics of 1700V, 50A diode at 25C, 125C, 150C and 175C.

Project Summary

The key objectives of Monolith's PowerAmerica BP3 project was to develop manufacturable, high-yielding 1700V SiC Schottky diodes with best-in-class performance and reliability at the X-FAB Texas 150mm SiC foundry. Monolith has successfully developed 1700V, 10A, 25A and 50A SiC Schottky diodes and passed key engineering reliability tests.

Technology Gap/Market Need

The higher power density targets for the next generation of solar inverters and inverters for wind turbine is driving the use of higher bus voltages requiring 1700V devices and modules. 1700V diodes are also needed for high-current, hybrid modules for traction inverter applications. Monolith's approach to address the need for cost-effective and high-reliability devices is to manufacture in a high-volume 150mm Silicon CMOS fab. Monolith's process development approach has focused on compatibility of the majority of SiC MOSFET and diode process steps with the tools and processes already available at X-FAB Texas. Silicon process steps have been re-used when possible and new process steps have been developed only when existing process steps were inadequate.

Through smart process integration, exploiting the strengths of an advanced Silicon CMOS fab with innovative device design and through the Monolith team's long experience in SiC R&D and Si power device manufacturing in foundries, Monolith aims to achieve the technical objectives of the PowerAmerica program.

Accomplishments/Deliverables

Monolith has successfully developed 1700V, 10A, 25A and 50A SiC Schottky diodes at X-FAB Texas. As a first step towards product qualification, the engineering reliability testing (HTRB, Temperature Cycle, H3TRB, UHAST) was performed on these diodes and no failures were observed. Engineering samples of 1700V, 50A diodes assembled in 2L TO-247 were provided to the PowerAmerica die bank.

Impact/Benefits

By developing cost-effective, high-reliability SiC devices using an automotive-qualified 150mm Si fab, we are supporting the widespread adoption of these devices in commercial power electronic systems – consistent with PowerAmerica and DOE's mission.

MONOLITH SEMICONDUCTOR INC.

Monolith Semiconductor Inc.

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PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- RAIL TRACTION
- UPS DATA CENTER

1.2kV SiC Shielded Trench Gate Power MOSFETs

NC STATE UNIVERSITY

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

North Carolina State University and X-FAB

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

HYBRID/ELECTRIC VEHICLES

RENEWABLE ENERGY

INDUSTRIAL MOTOR DRIVES

POWER QUALITY

UPS DATA CENTER

AEROSPACE

MOSFET Structure	Cell Pitch (μm)	$R_{on,sp}$ (mΩ-cm²)	$C_{GD,sp}$ (pF/cm²)	HF-FOM $R_{on,sp}{}^*C_{GD,sp}$ (mΩ-pF)	Blocking Voltage (V) ($E_{ox,max}$=4 MV/cm)
Basic UMOSFET	1.3	1.80	734	1321	139.6
UMOSFET with Dual P+ Shielding Regions	1.3	2.68	289	775	1672
UMOSFET with thick bottom oxide	1.3	1.89	417	788	1610
Double trench MOSFET (Rohm Product)	3.0	2.44	366	893	756 (Reach-Through)
Double trench MOSFET (Infineon Product)	2.8	3.77	10	37	1538

Project Summary

The goal of the project is to create a PowerAmerica foundry process kit for manufacturing 1.2kV trench-gate SiC Power MOSFETs at the X-FAB foundry. The specific on-resistance of planar-gate SiC power MOSFETs with breakdown voltages below 3kV is well known to be limited by the channel resistance. The trench-gate structure has been found to reduce the specific on-resistance of silicon power MOSFETs by eliminating the JFET component and increasing the channel density. Trench-gate SiC power MOSFETs have been manufactured by Rohm in Japan and Infineon in Germany with specific on-resistance similar to the planar-gate devices. The goal of our project is tocreate a device architecture and process flow that can allow manufacturing trench-gate SiC power MOSFETs at the X-FAB foundry for the first time. We intend to demonstrate that the specific on-resistance of our 1.2kV trench-gate devices is at least 50% better than that of planar-gate devices. A SiC trench etching process was first established at X-FAB this year. Trench-gate SiC power MOSFET structures with thick trench bottom oxide and a P+ shielding region were proposed. A process flow for creating these structures was defined in cooperation with X-FAB to ensure compatibility with their manufacturing capability. A mask set was designed at NCSU for the fabrication of these structures and approved by X-FAB. The fabrication of the first 1.2kV trench-gate SiC power MOSFETs with thick trench bottom oxide was initiated.

Technology Gap/Market Need

A trench-gate manufacturing process for SiC power MOSFETs is not available at the X-FAB foundry. The creation of a new trench-gate SiC power MOSFET design and process that can be manufactured at X-FAB allows U.S. companies to remain competitive in the world.

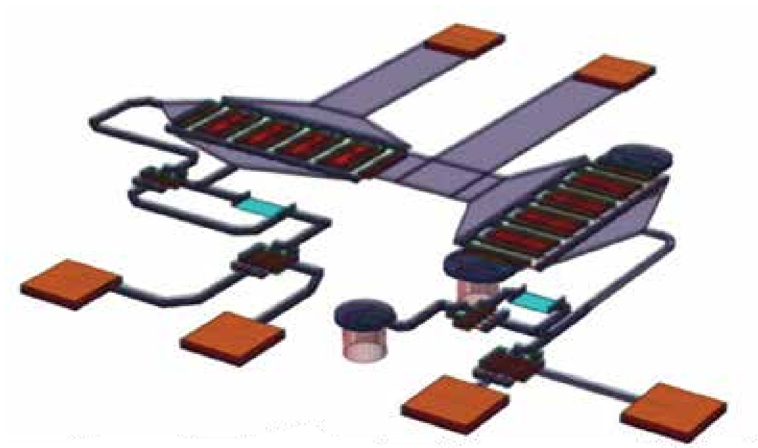
Accomplishments/Deliverables

Two process flows for creating trench-gate SiC power MOSFETs were defined in cooperation with X-FAB to ensure compatibility with their manufacturing capability. The first process flow allows making trench-gate SiC power MOSFETs with a thick oxide at the trench-bottom. Numerical simulations were performed at NCSU to demonstrate that the specific on-resistance of these devices is at least 50% smaller than for planar-gate devices. A mask set was designed at NCSU and approved by X-FAB for the fabrication of these devices. A process lot was started at X-FAB to demonstrate the first trench-gate SiC power MOSFETs. The second process flow allows fabrication of trench-gate SiC power MOSFETs with a P+ shielding region at the bottom of the trenches. Numerical simulations were performed at NCSU to demonstrate that the high frequency figure of merit for these devices is at least 50% smaller than for planar-gate devices. A mask set was designed at NCSU and approved by X-FAB for the fabrication of these devices. The fabrication of these devices was not completed due to the lack of sufficient funds.

Impact/Benefits

This project will ensure that leadership in SiC power MOSFET technology will remain in the United States.

GaN RF DC-DC Converter Design



Design for GaN DC-DC Converter.

NC STATE UNIVERSITY

LOCKHEED MARTIN

North Carolina State University and Lockheed Martin

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Application

ENVELOPE TRACKING

Project Summary

This task seeks to reduce energy consumption in telecom infrastructure through the development of a high-speed DC-DC GaN converter. The goal is to create a converter with sufficient bandwidth that can modulate modern cellular and wireless communication signals directly on the supply of power amplifiers in telecom base-stations. These power amplifiers are the dominant source of power loss in telecom system and owing to the large modulation of communication signals, are very lossy. By modulating the supply voltage, we hope to operate the amplifiers at maximum efficiency while maintaining modulation through the supply modulation.

Technology Gap/Market Need

Previous DC-DC based designs have used discrete GaN to achieve high power and efficiency. These converters have achieved high power and efficiency, but their bandwidth is an order of magnitude or more too slow to provide supply modulation for communication systems. In this project we seek an integrated design with ultra-low parasitics and high speed devices that can exceed switching speeds of 100MHz.

Accomplishments/Deliverables

We have completed a design for a GaN DC-DC converter design that surpasses state-of-the-art performance in transient speed, providing < 10ns Rise time for 200W loads with greater than 20MHz bandwidth.

Impact/Benefits

High-speed DC-DC converters can be used to increase efficiency of RF and wireless systems, notably in telecom and radar applications. Currently telecom base-stations consume 60TWH per year and are dominated by RF power amplification which is currently < 40% efficiency. The research conducted in this task has the potential to increase that efficiency significantly.

Development of 600V SiC JBS Diodes and MOSFETs

State University of New York Polytechnic Institute – Colleges of Nanoscale Science and Engineering (SUNY-POLY CNSE) and X-FAB

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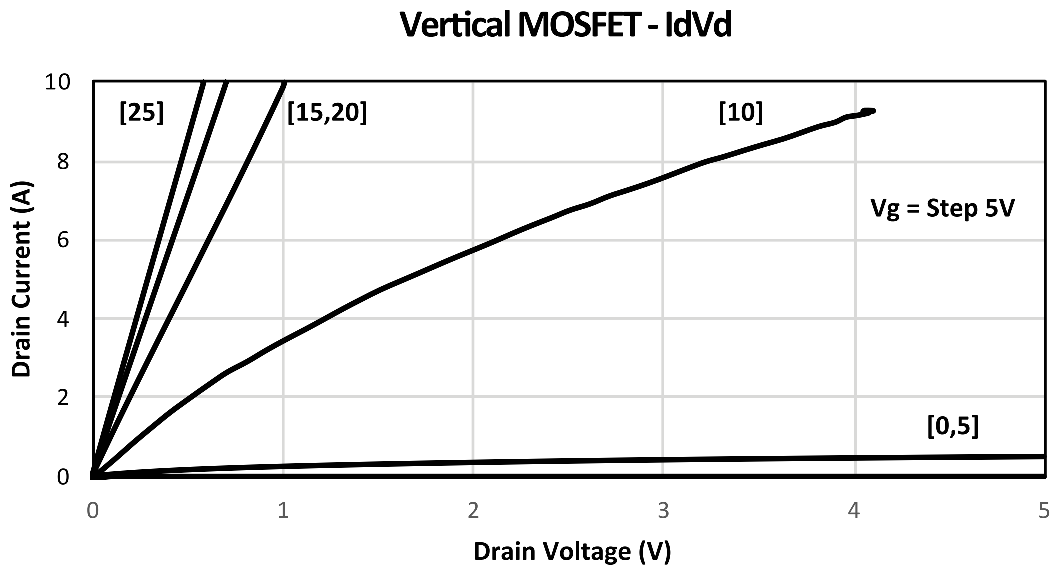
PowerAmerica Roadmap Targets

- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- MOBILE CHARGER ADAPTER
- INDUSTRIAL MOTOR DRIVES
- UPS DATA CENTER



A typical output characteristics of fabricated vertical and novel lateral SiC MOSFETs, conducted at the room temperature.

Project Summary

This project aims to develop low voltage (<600V) SiC JBS diodes and MOSFETs. Both conventional vertical structures and novel lateral structures were fabricated using the same mask-set. The elimination of the substrate resistance and the adoption of the RESURF design on a conventional epi-stack (n-drift layer on n+substrate) allow the proposed SiC lateral devices to provide a comparable on-resistance (forward voltage drop) at <600V blocking capability to their vertical counterparts. The fabrication step is much simpler and more efficient by eliminating the yield-concerned backend process of the vertical device. In addition, the gate to drain capacitance in the lateral MOSFET is expected to be lower than that of the vertical MOSFET offering improved high frequency figure of merit (Ron, sp×Cgd, sp).

Technology Gap/Market Need

There has been tremendous research towards developing the state-of-the-art vertical architecture of the SiC MOSFETs. This effort has successfully led to the commercialization of the vertical SiC MOSFETs. On the other hand, research on developing the lateral architecture of SiC devices is limited, even though lateral devices are promising for high voltage power integrated circuits (ICs). The elimination of the edge termination in lateral devices result in area saving of the devices, and therefore the cost. More development of SiC lateral architectures is needed to open a new roadmap for SiC itself to further reduce the manufacturing cost of SiC devices.

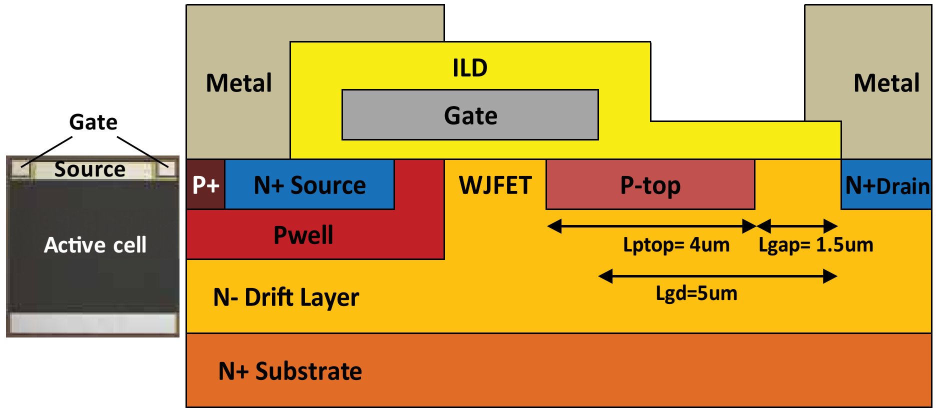
Accomplishments/Deliverables

Both conventional vertical structures and novel lateral structures of 600V SiC devices were successfully demonstrated. Lateral SiC MOSFETs will compete with Silicon LDMOS gearing up for future IC applications, opening another new roadmap for SiC devices.

Impact/Benefits

The substrate resistance accounts for a large portion of the total on-resistance with the lower voltage rating of the devices. This unavoidable substrate resistance in the vertical architecture can be bypassed by introducing a lateral architecture. It is demonstrated that 600V SiC lateral devices provide similar electrical performance as their vertical counterparts. For the same electrical characteristics, it is important to discuss the difference between the proposed lateral structures and the conventional vertical ones in regards to the process flow, and chip size. These two aspects are directly related to the chip price.

Development of 6.5kV/10kV SiC MOSFETs, JBS Diodes, and JBS Diode Integrated MOSFETs



Typical forward blocking behavior of fabricated 10kV SiC MOSFETs, measured at room temperature.

Project Summary

This project intends to develop 6.5kV/10kV SiC MOSFETs, JBS diodes, and JBS diode integrated MOSFETs. All devices and their design variations were included in a single mask-set. The proposed devices were successfully fabricated at X-FAB. This project will supply MV, HV SiC devices to PowerAmerica members that are otherwise difficult to attain from commercial vendors.

Technology Gap/Market Need

As of today, only a voltage rating of 1.2kV SiC device process baseline is available through PowerAmercia/X-FAB. This project aims to develop high voltage SiC devices that are otherwise difficult to attain from commercial vendors. The critical considerations for the successful development include: efficient edge termination techniques, highly rugged cell designs, and efficient layout approaches of diode integration into the MOSFET structure. An efficient edge termination design is the most critical technical aspect in developing power devices, since more than half of the device size is composed of the edge termination area.

Accomplishments/Deliverables

The critical considerations for the successful design includes: efficient edge termination techniques, highly rugged cell designs, and efficient layout approaches of diode integration into the MOSFET structure. Well-optimized drift layer specification and the edge termination design will compromise a high blocking behavior with a low leakage current.

Impact/Benefits

High voltage SiC devices will enable the demonstration of an efficient fast EV charger, an inverter for heavy duty vehicles, medium voltage PV inverters, MW inverters for wind applications, microgrid power conditioning system, motor drive inverter, converters for smart power grid, and so on. Currently, only a few companies are able to produce >3.3kV SiC MOSFETs. The development of 6.5kV & 10kV SiC MOSFETs, JBS diodes, and JBS diode integrated MOSFETs becomes a very important task for PowerAmerica to secure a large amount of chips for partners on power electronics and to gear up for future customers seeking engineering samples or packaged chips.

SUNY POLYTECHNIC INSTITUTE

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

State University of New York Polytechnic Institute – Colleges of Nanoscale Science and Engineering (SUNY-POLY CNSE) and X-FAB

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PowerAmerica Roadmap Targets

- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- INDUSTRIAL MOTOR DRIVES
- RAIL TRACTION
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES

Development of Manufacturable Gen 3 6.5kV/100mOhm SiC MOSFET and Establish HTRB, HTGB, and TDDB Reliability Qualification

Cree Fayetteville, Inc.

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PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- RAIL TRACTION
- ELECTRIC POWER GRID
- MILITARY

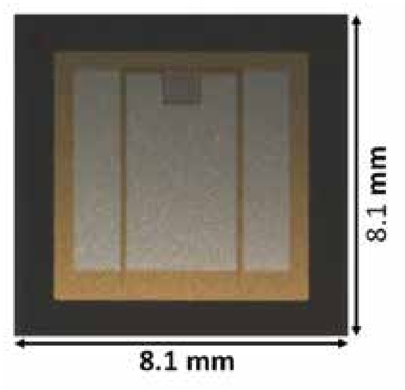

Figure 1. Photograph of Wolfspeed/Cree Gen 3 6.5kV/100mOhm SiC MOSFET Device Die

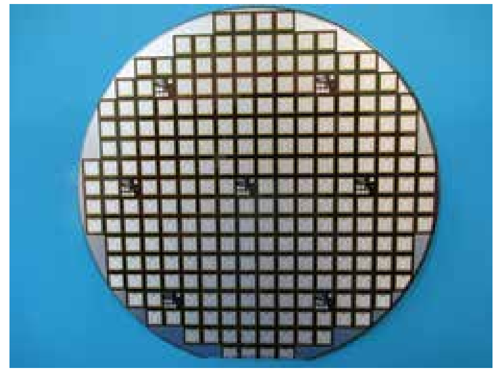

Figure 2. Photograph of 150mm 4HN-SiC wafer with Wolfspeed/Cree Gen 3 6.5kV/100mOhm SiC MOSFET Device Die

Project Summary

This project will develop a manufacturable Gen 3 6.5kV/100mOhm SiC MOSFET device fabrication process on 150mm 4HN-SiC wafers at the Wolfspeed/Cree 150mm SiC power device fabrication facility. In addition, this project will complete the High Temperature Reverse Bias (HTRB), High Temperature Gate Bias (HTGB) and Time-Dependent Dielectric Breakdown (TDDB) JEDEC qualification testing of these Gen 3 6.5kV/100mOhm SiC MOSFET devices. These JEDEC qualification tests are a critical step in the process at Wolfspeed/Cree for the formal release of these large area, medium voltage Gen 3 6.5kV/100mOhm SiC MOSFETs as commercial products for the sale of 6.5kV SiC MOSFET device die and ultimately 6.5kV SiC power modules using these devices.

Technology Gap/Market Need

Currently, there are no JEDEC-qualified 6.5kV SiC MOSFET die products from any vendor in the world even though there is an abundance of applications that would greatly benefit from the lower conduction and switching losses enabled by medium voltage unipolar 6.5kV SiC MOSFET power devices and the 6.5kV SiC power modules which would utilize these devices. This project helps to fill this market gap by completing the critical initial JEDEC qualification testing (i.e., HTRB, HTGB, and TDDB) of these Gen 3 6.5kV/100mOhm SiC MOSFETs that is required for ultimate commercial product release of these Gen 3 6.5kV/100mOhm SiC MOSFET devices and ultimately 6.5kV SiC power modules using these devices.

Accomplishments/Deliverables

- Completed 150mm Fabrication Lot #1 of Gen 3 6.5kV/100mOhm SiC MOSFETs
- Completed 150mm Fabrication Lot #2 of Gen 3 6.5kV/100mOhm SiC MOSFETs
- Completed 150mm Fabrication Lot #3 of Gen 3 6.5kV/100mOhm SiC MOSFETs
- Completed 150mm Fabrication Lot #4 of Gen 3 6.5kV/100mOhm SiC MOSFETs
- High voltage device packaging is underway for Gen 3 6.5kV/100mOhm SiC MOSFET device die from 150mm Fabrication Lots #1, #2, #3, & #4
- When packaging of Gen 3 6.5kV/100mOhm SiC MOSFET devices from 150mm Fabrication Lots #1, #2, #3, & #4 is completed, HTRB, HTGB, and TDDB JEDEC qualification testing (25 devices each from 3 fabrication lots) of these Gen 3 6.5kV/100mOhm SiC MOSFETs will be carried out
- Further characterization of Gen 3 6.5kV/100mOhm SiC MOSFETs from 150mm fabrication lots is underway to generate a preliminary datasheet for these Gen 3 6.5kV/100mOhm SiC MOSFETs

Impact/Benefits

SiC MOSFETs, such as the Gen 3 6.5kV SiC MOSFETs being developed and JEDEC qualified on this project, allow for the realization of higher efficiencies when used in place of the incumbent Silicon IGBT technology. This comes from the unipolar nature of the SiC MOSFET, which all but eliminates losses incurred during each switching cycle of a power converter. The unipolar operation of the SiC MOSFET also eliminates the conduction "knee" that is present in Silicon IGBT bipolar devices, which incurs a heavy efficiency penalty when operating at less than 100% load, as is typical for real world traction and medium voltage motor drive applications. Therefore, this Gen 3 6.5kV SiC MOSFET power device technology allows for next-generation power electronics systems present in trains, industrial motor drives, grid-tied energy storage systems, and electric vehicle fast charging stations to operate more efficiently, enabling cost savings for the system owners in the form of less energy use, as well as enabling the design of smaller and lighter products.

SiC Power Device Commercial Foundry Development

The X-FAB Texas open fab leverages existing silicon processing equipment to produce SiC wafers in volume.

Project Summary

With PowerAmerica support, X-FAB Texas has established an open 6-inch silicon carbide (SiC) commercial foundry, enabling companies with a variety of device technologies to utilize the foundry for volume production. Rather than building a SiC fab from scratch, X-FAB's existing 6-inch silicon foundry is utilized to process SiC wafers. This approach leverages existing silicon processing equipment, with the addition of select specialized equipment unique to SiC processing. To provide scalability, a Process Installation Kit will be developed. This kit will contain documented and characterized standard process blocks that can be integrated with proprietary process blocks such that the foundry customer can bring highly differentiated products to the market.

Technology Gap/Market Need

For SiC power devices to move into mainstream applications, they must compete directly with existing Silicon devices. Silicon devices have an enormous cost advantage due to the economies of scale that has been established with these mature technologies. Silicon Carbide faces the dilemma of how to generate the volumes that would produce the economies of scale of Silicon given that the current scale of SiC produces a cost structure that limits these devices to low-volume, high-price applications.

Accomplishments/Deliverables

X-FAB Texas completed the installation of the SiC pilot line and continued the implementation toward high-volume manufacturing required for SiC manufacturing supporting the foundry model. Our initial device partners continued their ramp toward volume production on the devices already qualified. Additional customers are delivering products to the marketplace and are on track to pass reliability and qualification which will continue into volume production. The success of this implementation and our customers has proven that the scalable foundry business model will support the needs of the SiC industry.

In the strategy to provide scalability, planned steps were completed toward the development of a Process Installation Kit. A generic unit process was installed, referred to as the PowerAmerica process flow. Additionally, an initial design rule set is documented and released based on PowerAmerica process flow. X-FAB completed the tape out of an internal monitor chip for the PowerAmerica process flow which will be utilized to document and characterize the standard blocks that will make up the Process Installation Kit.

Impact/Benefits

X-FAB's charter is to leverage the scale established in our Silicon foundry to provide SiC device partners with the cost-effective, scalable and high-quality manufacturing support required to bring their innovative products to market.

XFAB
MIXED-SIGNAL FOUNDRY EXPERTS

X-FAB Texas, Inc.

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PowerAmerica Roadmap Targets

REDUCING COST

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- RAIL TRACTION
- UPS DATA CENTER
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES
- MOBILE CHARGER ADAPTER
- ENVELOPE TRACKING

Gate Oxide and Body Diode Reliability of SiC Power MOSFETs

Argonne National Laboratory

Argonne National Laboratory, Kyma Technologies, Illinois Institute of Technology

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PowerAmerica Roadmap Targets

IMPROVING RELIABILITY

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- RAIL TRACTION
- UPS DATA CENTER
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES
- MOBILE CHARGER ADAPTER
- ENVELOPE TRACKING

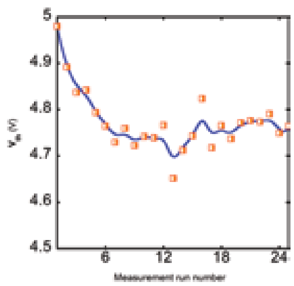


Figure 1: Repetitive measurement of static characteristics of a SiC power MOSFET to erase transient charge.

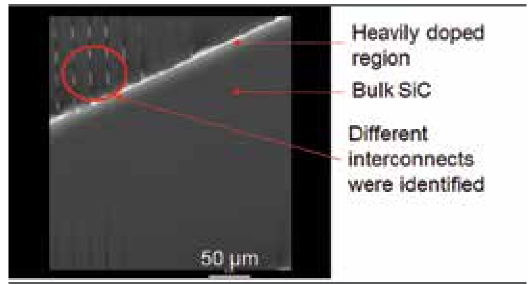


Figure 2: Single point SEM Electron Beam Absorbed Current (EBAC) measurement to find a junction in a SiC Power MOSFET.

Project Summary

In this project, 1200V/20A SiC power MOSFETs obtained from multiple vendors were systematically evaluated for gate oxide and body diode reliability performance. Conventional stress testing as well as reliability investigations under conditions present in typical PWM power converter circuits were performed. The results were benchmarked against silicon power MOSFETs and silicon IGBTs with identical ratings and assembled in similar packages. Static characterization was performed at ambient temperature (TA). Stress testing was performed at 120°C for 200hrs. Extensive electrical characterization before and after stressing the devices was performed. The degradation in the key gate oxide, MOS channel, and body diode static parameters were closely monitored with increasing electrical and thermal stresses. Stress conditions that cause device degradation were identified. Measurements were performed on 60 devices and statistical data analysis tools were used to estimate the trends and spreads in key device parameters such as threshold voltage. Advanced material analysis including SEM EBIC/EBAC (Electron Beam Induced/Absorbed Current) were used to probe the material damage caused by specific electrical and thermal stresses in order to identify the root cause of reliability degradation.

Technology Gap/Market Need

A compelling argument for the use of WBG power devices is the potential for converter miniaturization owing to their higher frequency power switching capability compared to silicon power devices. Smaller converters invariably lead to lower material costs, but the power density increase due to converter miniaturization poses field-reliability concerns. Improved design methodologies are needed to avoid deleterious effects such as electromagnetic interference (EMI). To benefit from performance and cost advantages of WBG power devices, refined methods of power converter design and assembly are needed. This requires retraining of practicing engineers and updated academic curriculum to train students.

Accomplishments/Deliverables

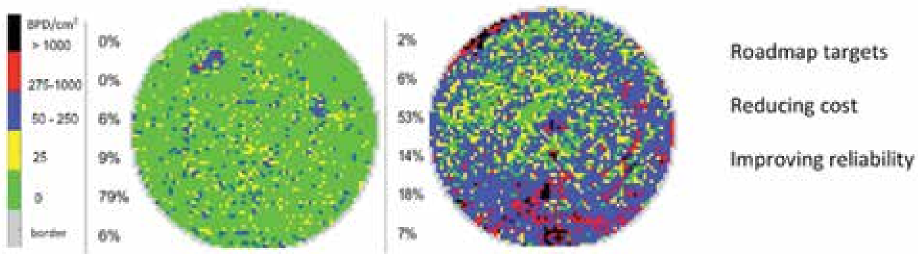
1. Procured and tagged single-chip 1200V/20A SiC MOSFETs in die form as well as in packaged assembly from three manufacturers. Performed pre-stress evaluation of all devices to assess the static electrical characteristics and select devices for various types of stress testing.
2. Constructed stress-testing circuits and verified full functionality. Constructed automated signal processing and data acquisition circuitry and demonstrated full functionality. Performed forward bias stressing of the body diode, and gate bias and temperature stressing of the main MOSFET using stress circuits. Performed material analyses of stressed and unstressed devices in order to detect specific defects causing device degradation. Validated gate oxide and body diode reliability testing and modeling methodologies. Communicated initial stress testing results with device manufacturers.
3. Developed and validated new reliability bench marking criteria. Identified the root cause of reliability degradation. Submitted final project report with testing results, and specific recommendations for future reliability investigation. Performed static characterization on devices for repetitive cycles. Repetitive cycling can help erase the history of the device by resetting transient charges and therefore provide a more accurate measure of irreversible failure.

Impact/Benefits

The impacts of the project could be summarized as:

- A better understanding of device reliability and a fast turnaround in reliability testing of SiC devices will help to accelerate the transition to market and will provide additional feedback to manufacturers and device suppliers.
- Increasing confidence on the reliability of SiC devices with respect to Si will help to accelerate the adoption of WBG power devices.
- Increasing the confidence of end users will likely increase the demand of WBG power devices, which will translate on an increase on manufacturing jobs in the US across the supply chain.

Developing a BPD-Free Room Temperature Al Implant and Activation Anneal Process for P-Wells in SiC MOSFETS



Two maps of BPD density illustrating the wide range of wafer quality in wafers screened. The maps are derived from UVPL images and counting the number of BPDs in 2x2 mm areas.

Naval Research Laboratory

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PowerAmerica Roadmap Targets

REDUCING COST

IMPROVING RELIABILITY

Commercial Applications

HYBRID/ELECTRIC VEHICLES

RENEWABLE ENERGY

MOBILE CHARGER ADAPTER

INDUSTRIAL MOTOR DRIVES

POWER QUALITY

RAIL TRACTION

UPS DATA CENTER

ELECTRIC POWER GRID

MILITARY

AEROSPACE

HEAVY VEHICLES

Project Summary

The goal of this project is to assist fabrication members of PowerAmerica to reduce their cost and increase the reliability of their devices by reducing materials defects. Currently, MOSFETs are fabricated using elevated-temperature (≥ 500°C) aluminum implantation for forming the p-well and the p+-contact to prevent the introduction of BPDs (basal plane dislocations), as well as improve activation efficiency of implanted impurities, and maintain wafer crystallinity. However, the elevated temperature increases the complexity and costs of the Al implantation unit processes. This project is developing an implantation process using room temperature implantation to decrease the complexity and reduce its cost.

This project also assists fabrication members by screening wafers before fabrication for BPD and other extended defects that decrease device yield and reliability.

Technology Gap/Market Need

A significant factor in the development of commercially viable SiC power devices has been the improvement of SiC material quality. SiC MOSFETs and JBS diodes rated up to 1.7kV are now commercially available and have a small but steadily growing segment of the power electronics market. MOSFETs rated at 3.3kV are about to become routinely available. However, SiC technology is far from reaching its full potential. To continue attaining that potential and increasing its market share will demand both reducing device costs and introducing higher voltage devices. The suppression of materials defects in the starting wafers is an important factor for increasing yield, which will decrease cost. Another factor is developing less expensive processing steps such as developing a BPD-free room-temperature Al implantation to form p-wells and p+-contacts. There is also an ongoing push to attain higher voltage and current ratings. This necessitates thicker epitaxial layers and larger die. Defect suppression becomes more difficult as the epitaxial layer thickness increases and larger die require lower concentrations of materials defects to maintain high device yield.

Accomplishments/Deliverables

Working with X-FAB, we have designed and started the fabrication of a MOSFET fabrication run to test the effects of processing parameters on BPD formation during the Al implantation and activation anneal. This run examines a number of process variations suspected of affecting the formation of BPDs. The splits include p+-contact dose, p-well dose, room-temperature vs. elevated temperature implantation and examining the effect of sacrificial oxidation to remove surface damage after dry etching steps.

The deliverables included the pre-fab screening of 40 wafers for PowerAmerica fabrication members, the design and start of a run to test the feasibility of reducing MOSFET fabrication cost by replacing elevated temperature implantation with room temperature implantation, and x-ray analysis of wafers showing the contribution of lattice plane mismatch to defects in the epitaxial layer.

Impact/Benefits

To continue the progress in reducing SiC power device cost, while increasing their reliability and yield requires a continuing push to decrease material defects in SiC wafers and the development of lower cost processing steps such as room-temperature Al implantation. Defect suppression in the epitaxial layers will continue to be a challenge as the voltage rating of SiC devices increases since thicker epitaxial layers will be needed and the difficulty of suppressing defects increases as the epitaxial thickness increases.

Reliability Analysis of Wide Bandgap Power Devices

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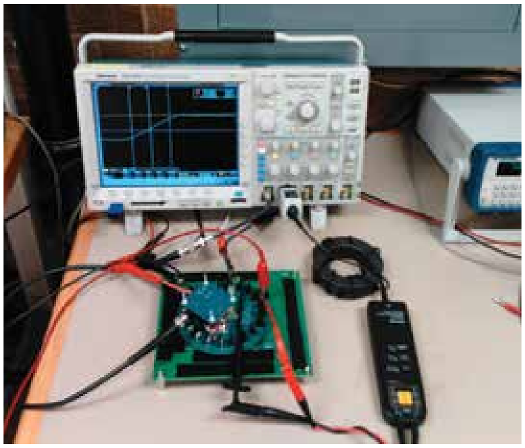
PowerAmerica Roadmap Targets

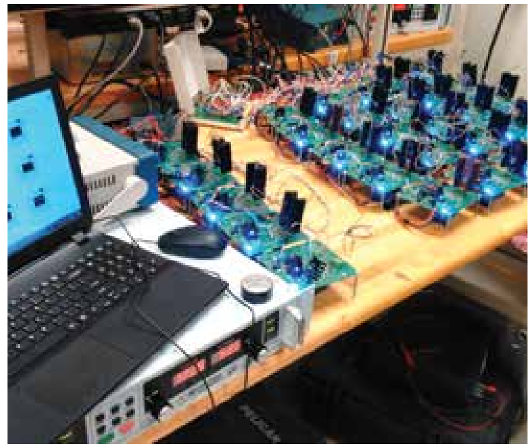
- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- MILITARY
- AEROSPACE
- OTHER (HIGH VOLTAGE DC/DC CONVERTERS)



Di/dt testbed.



HTOL testbed.

Project Summary

Characterize and test commercially available Silicon Carbide MOSFETs and JBS diodes, perform failure analysis on degraded/failed devices, and report the results.

Technology Gap/Market Need

This project seeks to improve the confidence level in WBG semiconductors as used in commercial applications.

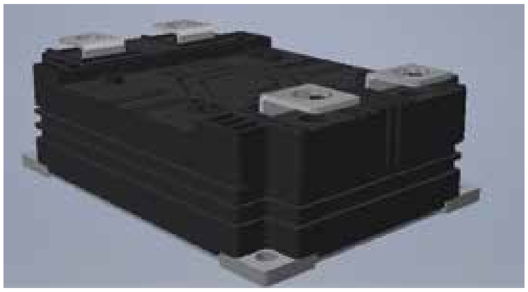
Accomplishments/Deliverables

1. Submitted testing protocol to PowerAmerica.
2. Developed device electrical characterization procedures and characterized 350+ devices.
3. Designed, built, and successfully tested the following testbeds: HTRB, HTGB, HTOL, avalanche, diode surge current, di/dt, dv/dt, short circuit, TDDB, and hard switching.
4. Completed 1000 hours of HTGB and HTRB testing on multiple MOSFETs and JBS diodes from 3 different manufacturers.
5. Collected reliability data on MOSFETs and JBS diodes using the following testbeds: HTOL, avalanche, diode surge current, di/dt, dv/dt, short circuit, TDDB, and hard switching.
6. Performed SEM and electrical failure analysis on failed devices.

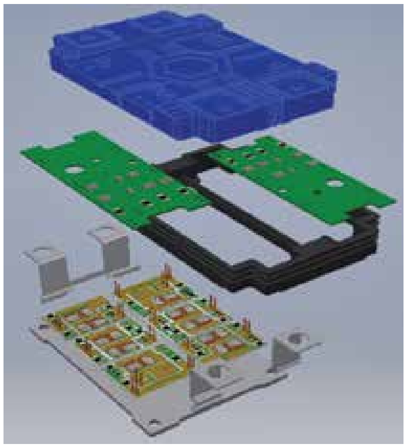
Impact/Benefits

The reliability data can be used by device manufacturers to improve future generations of products.

100A, 6.5kV Half-Bridge Module



Perspective view of the 6.5kV-100A SiC power module.



Exploded view of the 6.5kV/100A SiC power module.

Project Summary

This project develops and demonstrates a 6.5kV/100A SiC half-bridge power module in an open-standard phase-leg module package LinPak. The module is built with an innovative supercascode approach using the components (1.7kV SiC JFETs and low-voltage Si MOSFET) from production released technology platforms, and therefore has a lower cost and a much higher technology readiness level and can be brought into production quickly.

The preliminary testing results show the module can block over 7100V, has an on-resistance of 40mΩ and a threshold voltage of 3.1V at 150°C junction temperature. The knee voltage of the built-in antiparallel diode is only 0.7V independent on the negative gate bias. The preliminary switching tests also show the module can switch 10X faster than its Si counterparts. With this excellent performance, the proposed module will revolutionize the design of megawatt power converters with higher switching speed, higher efficiency, and higher power density.

Technology Gap/Market Need

Conventional medium-voltage power modules are built by paralleling multiple medium-voltage Si IGBT or SiC MOSFET/JFET chips. The medium-voltage Si IGBTs have a poor switching performance and the medium-voltage SiC MOSFETs/JFETs have a prohibitively high cost. The supercascode approach realizes a medium-voltage power module in a different way by series-connecting multiple low-voltage SiC normally-on JFETs, which yields not only high performance, but also low cost. Package and module manufacturing capabilities are needed to support WBG manufacturing.

Accomplishments/Deliverables

- A 6.5kV-100A SiC supercascode switch has been built and the balancing network has been optimized to achieve equal static and dynamic voltage sharing and synchronized switching transients
- The measured DC performance of the optimized 6.5kV supercascode switch meets the project targets.
- The module housing, DBCs, and auxiliary PCB have been designed and ordered.
- Deliverables: three engineering samples to the PowerAmerica device bank.

Impact/Benefits

- The 100A-6.5kV SiC module would be the first commercially-available SiC medium-voltage power module, enabling the quick penetration of SiC into multi-megawatt power conversion applications.
- The supercascode approach provides a high-performance and cost-effective solution to implement 4.5kV to 15kV medium-voltage SiC power modules. The target cost structure is < $0.25/A.
- UnitedSiC will launch engineering modules, which will add growth for the foundry and expand the supplier base for SiC-based medium-voltage modules. Impact on U.S. and worldwide energy efficiency will be significant. SiC power business growth creates employment opportunities for SiC supply chain providers, as well as advanced system developers.

UnitedSiC
Simply More Efficient

United Silicon Carbide, Inc.

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PowerAmerica Roadmap Targets

- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- RAIL TRACTION
- ELECTRIC POWER GRID
- MILITARY

Enable High Voltage 6.5kV & 10kV Power Module Commercialization and Manufacturing

Wolfspeed
A CREE COMPANY

Cree Fayetteville, Inc.

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PowerAmerica Roadmap Targets

- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES
- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- RAIL TRACTION
- UPS DATA CENTER
- ELECTRIC POWER GRID
- MILITARY
- HEAVY VEHICLES

XHV-6 10kV all-SiC power module. Low inductance design providing maximum junction temperature operation and highest current density available through use of rugged body-diodes.

Project Summary

Cree Fayetteville addressed issues to enable an increase in the availability of commercial WBG module choices by advancing SiC product offerings past 3.3kV with the productization of two SiC half-bridge power modules: one new design capable of 6.5kV/100A and another capable of 10kV/100A. Three major tests were performed to verify and subsequently improve the electrical ruggedization of both proposed modules: clamped inductive load testing for full dynamic characterization/ gate resistance optimization, partial discharge testing for insulation voltage verification, and initial qualification testing to verify the reliability of the package design. Samples of both the 6.5kV and 10kV modules were iteratively built for the aforementioned testing, to provide a benchmark for the performance of the first 6.5kV SiC MOSFET and the 10kV SiC die based on work done previously in BP2. The module design was then improved based on the results of the testing to a robust solution viable across diverse application conditions. In addition, Open Innovation Funding (OIF) from PowerAmerica allowed for the industry to be polled for quick-start optimized bussing solutions, and the design of this bussing solution, with critical sensor options, will be made available in the institute's next budget period.

Technology Gap/Market Need

Prior to this program, there were no 6.5kV all-SiC power modules available to industry that could provide the power density and efficiency that SiC devices promise. This effort took the SiC module through die insertion, stress testing, isolation/partial discharge testing, and provided gate drivers and bussing solutions for ease of insertion of 6.5kV and 10kV SiC modules.

Accomplishments/Deliverables

Work was completed on time and significantly advanced with a completed design. Specific outputs include:

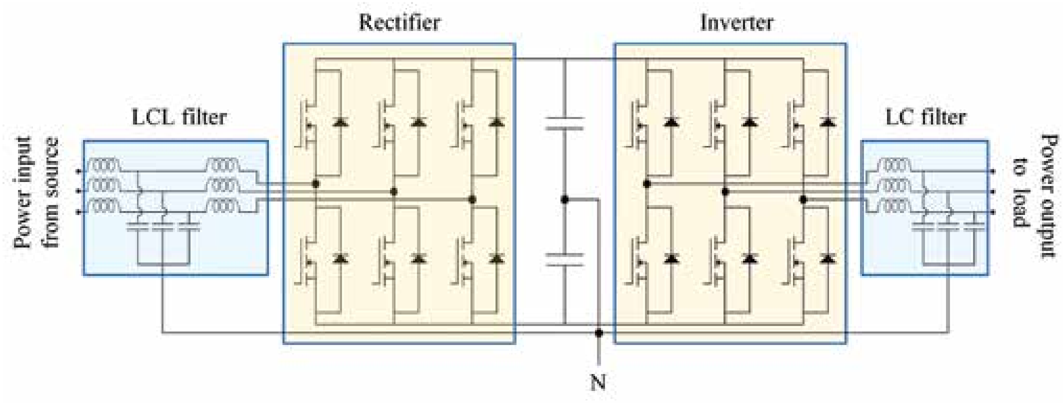
- Multiple conference and workshop presentations around the world given by Wolfspeed on MV module performance/availability.
- Commercial customers and partners, many under NDA, with PowerAmerica members and DOE-funded programs leading the way to enable the game-changing, highpower systems to be attempted using the WBG.
- Samples and pre-production modules & drivers to customers across industries for system prototyping:
  - Motor drives (1200 & 1700V)
  - Grid-tied applications (1200V, 1700V, 3300V, 6500V & 10kV)
  - Automotive (900V, & 1200V)
  - Transportation (3300V)
  - Heavy vehicles/machinery (1700V & 3300V)
  - DoD (10kV)
- As a result of this work, 6.5kV and 10kV SiC power modules are available to the module bank. Datasheets, circuit models, gate driver availability, application notes, and example bussing are also available, coinciding with the modules

Impact/Benefits

This project was designed to align with industry need and provide a fit to mission for PowerAmerica that leveraged the funding to enhance U.S. manufacturing. Specifically, it aligns with the high-level goals of PowerAmerica by:

1. Enabling a U.S.-based, all-SiC 6.5kV & 10kV power module commercialization pathway by advancing the modules for sampling and using the already developed sales/distribution network to quickly spread the technology.
2. Enabling U.S.-based, all-SiC high voltage power module production manufacturing capability by providing the means to develop a robust module manufacturing process and allow for proper demonstration on the manufacturing line.
3. Communicating the present state-of-the-art for all-SiC medium-voltage (MV) power module simulation, testing, design optimizations necessitated to qualify to and extend existing industry standards.
4. Delivering 6.5kV and 10kV all-SiC MV power modules to the module bank, with various current ratings for an immediate source of MV all-SiC power modules and gate drivers, as well as the engineering support to insert the technology.
5. Hastening the all-SiC MV power module Virtuous Cycle through stakeholder education (presentations, papers, & tutorials) leading to subsequent adoption, thereby enabling MV 24/7/365 applications that exhibit significant financial/economic and environmental returns for all.

Ultra-High Efficiency Full SiC-Based Modular UPS



Double conversion system using SiC MOSFETs for the rectifier and inverter, and filter components.

Project Summary

Using SiC power semiconductor technology, the efficiency of a 100kW SiC modular UPS has been greatly improved. Two 100kW prototypes were designed, built and demonstrated. The first prototype is a hybrid solution using Si IGBT and SiC diodes. The losses have been reduced by up to 15% over the entire load range in the double conversion path. In the second prototype, a full SiC solution was implemented. This involved a complete system optimization to determine important systems parameters such as switching frequency, and the choice and design of appropriate filter components. Gate drives with fast protection functionalities, controls updates, and other system components were designed and developed. In this full SiC prototype, losses have been reduced by 35% to 45% over the entire load range in the double conversion path.

Technology Gap/Market Need

Double conversion UPS are used widely in data centers and in other critical power applications. During regular operation, losses occur 24/7 in the power conversion stages. By reducing these power conversion losses using SiC technology, the efficiency is improved, saving operation expenditure and reducing power consumption.

Accomplishments/Deliverables

Two 100kW SiC modular UPS prototypes have been designed, built, and demonstrated. A 15% reduction in power loss over the entire load range was demonstrated with the hybrid Si IGBT + SiC diode prototype. A 35% to 45% reduction in loss was also shown experimentally with the full SiC 100kW prototype over the entire load range.

Impact/Benefits

The efficiency gains shown in this project will foster growth of the UPS market with innovative products, which will, in turn, result in U.S. economic growth with job creation and maintaining U.S. technology leadership in this area. In addition, adoption of SiC technology in UPS will boost confidence in electrical engineers about the commercialization potential of SiC in various applications.

ABB Inc.

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

POWER QUALITY

UPS DATA CENTER

SiC Based Power Electronic Fan Driver for Class 8 Mild Hybrid Truck

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PowerAmerica Roadmap Targets

REDUCING COST

Commercial Applications

HYBRID/ELECTRIC VEHICLES

HEAVY VEHICLES

Bendix Front End Motor Generator system.

Project Summary

Bendix Commercial Vehicle Systems, in collaboration with The University of Akron, proposes to develop a fuel-efficient mild hybrid for class 6, 7 and 8 trucks. An integrated inverter system with motor architecture based on wide bandgap power devices is proposed to enable the implementation of an electrically driven accessory drive belt in the engine compartment. 70kW SiC-based inverter will be developed to use a single drive motor to power all the accessories currently driven from the engine crankshaft pulley. This would include the engine cooling fan, air conditioning compressor and any other required accessory device. High bandwidth of the power converter will enable using a higher power density electric machine with higher pole numbers. The SiC-based inverter will be packaged and attached to the end plate of the motor. The overall system will have higher efficiency and smaller size to fit into the engine compartment of various commercial vehicles.

Technology Gap/Market Need

- Utilization of an inverter that employs wide bandgap devices in the commercial vehicle industry.
- Size reduction of inverter and motor such that the assembly fits in a P0 position
- SiC half-bridge MOSFET modules specifically for switched reluctance machines are not commercially available.

Accomplishments/Deliverables

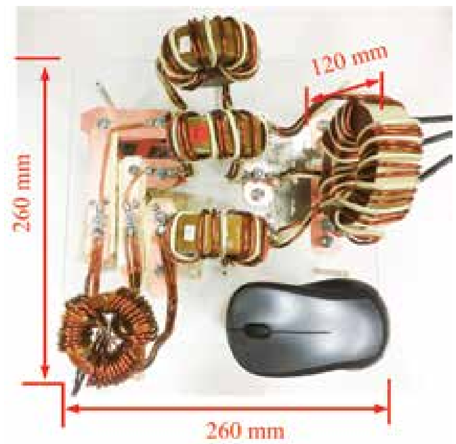
The following accomplishments were achieved during the 15 months of the project:

- A switched reluctance motor with an integral inverter that employed SiC MOSFET modules was designed and built. The unit was designed specifically for a commercial vehicle application.
- The efficiency of the SiC-based inverter was increased from 94.6% to 97.5%, compared to Si IGBT based inverter and the volume for the active power devices is reduced three times.
- A novel control algorithm was developed to reduce the DC link ripple current while preserving the high performance of the SRM operation. The proposed algorithm reduces the DC link capacitor requirement 9 times for the same DC link current performance. This achievement is only possible with the high bandwidth inverter.
- The project has documented the advantages of the switch reluctance motor (SRM) for this application on the front of a diesel engine.
- A clutch and gearbox were designed and built to mate the motor to the front of a diesel engine. Challenges related to engine torsional vibration, sealing and space constraints were overcome.
- A thermal management system has been designed that not only cools the battery, power electronics and motor but also heats and cools the vehicle sleeper berth.
- The project has affirmed that the system is viable and has provided knowledge to further reduce the size of the system.

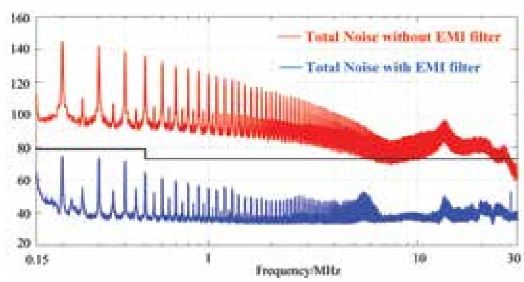
Impact/Benefits

- This project has identified the need for SiC half-bridge MOSFET modules. If the Bendix Front End Motor Generator (FEMG) system moves to production then we will pursue a SRM module for production. The SRM specific module will reduce size and cost of the inverter.
- The University of Akron (UA) has applied for a patent related to an algorithm for reducing current ripple that will result in a reduced size of the inverter by reducing the number of capacitors in the system. By reducing the size of the inverter the system becomes small enough to fit in the vehicle engine compartment between the engine and radiator.
- Bendix is filing a patent related to the integration of the inverter onto the side of the SRM which results in a very thin motor/inverter assembly. This thin assembly has never existed before and can fill requirements having only a narrow envelope.

SiC Commercial PV Inverter



A prototype with proposed EMI filter design method.



Conducted EMI test results.

Project Summary

We have designed and will build a Gen-II PV inverter with power density of 5 kW/kg. In order to bring the proposed technology one more step toward market, one important aspect still needs to be researched — the EMI noise analysis/EMI filter design. Because the EMI noise of SiC MOSFETs can be much worse than that of Si IGBTs; and as the weight of our PV inverter is much smaller than Si counterparts, a commercial EMI filter for Si IGBT PV inverters will weight 25% of our Gen-II inverter. In BP3, we have proposed, designed, built and experimentally verified a lightweight, low-cost EMI filter that meets the EMI standards without lowering the power density and efficiency of the converter. By the end of BP3, we have delivered and demonstrated a 100kW transformerless photovoltaic inverter prototype with CEC efficiency >= 98.5%, averaged conducted emission ≤ 66dBμV at 150kHz - 500kHz, and ≤ 60dBμV at 500kHz - 30MHz.

Technology Gap/Market Need

WBG-based converters can achieve higher efficiency, smaller heatsink size, increased switching frequency, and reduced filter size. However, with high switching frequency and high dv/dt, the EMI issue became more severe. Some research even found the total filter size of a SiC-based inverter can be higher than its Si based counterpart because of increased EMI filter size. The industry needs a new EMI filter design method that is specifically targeting WBG-based applications to achieve lightweight and low cost.

Accomplishments/Deliverables

- A lightweight EMI filter that weighs 3.8kg.
- Improved heatsink design using 3D printing to reduce 3kg.
- PWM that prevents the non-ideal interleave effect.
- Test results show the inverter can meet the requirement of 47 CFR 15.107 with at least 4dB margin.
- System CEC efficiency=98.6%, with EMI filter.
- Filter-less grid-tied operation without oscillation.
- Several graduate students who are currently in the business of WBG-based converter design.
- A series of technical papers published and one patent has been issued.

Impact/Benefits

The commercial transformer-less PV inverter can adopt the developed technology to achieve higher efficiency, lighter weight and lower system cost. The developed technology can also be applied to other applications including motor drive and energy storage system.

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PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES
- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- UPS DATA CENTER
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES

5kV DC to LV DC or 3-Phase AC Microgrid Power Conditioning Modules

Georgia Tech Center for Distributed Energy

Georgia Institute of Technology, Southern Company

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PowerAmerica Roadmap Targets

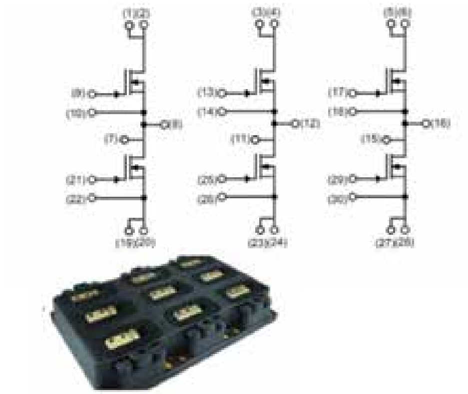
ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

RENEWABLE ENERGY

ELECTRIC POWER GRID

MILITARY



3.3kV SiC custom module from CREE.

25kVA, 2.5kV/600V DC or 480V AC converter module.

Project Summary

In recent years, there has been increasing interest in the concept of a 5kV DC distribution system fed from the 13/22kV AC system, to feed loads in the 100kW to 5MW range. This can provide significant system-level benefits, including lower losses, smaller size and lower cost, when compared with a 480 volt AC distribution system. A critical requirement for such a DC microgrid is the availability of compact, reliable and cost-effective power conversion modules that can provide a building block to implement a variety of end-use applications. The basic need is for converting the 5kV DC to 480 volts AC or < 1000 volts DC, with high-frequency isolation, high efficiency, full four-quadrant operation with bidirectional power flow, arbitrary frequency and power factor on the load side, and robust and reliable operation. The main objective of this project is to develop a SiC-based ~5kV DC to LV DC or 3-Phase AC bidirectional four-quadrant converter module with integrated high-frequency isolation. The module is based on soft switching solid-state transformer topology.

In addition, the project addresses the following:

- Modular architecture that would allow scaling to higher voltages
- Medium voltage scaling issues like voltage balancing of series connected modules, EMI etc.

Technology Gap/Market Need

MVDC converters are technically feasible using Si IGBT devices, but the need for series-connected devices and the need for multiple power conversion stages have resulted in an unacceptably high level of complexity and losses. Alternatively, the use of high voltage Si IGBTs (3.3kV or higher) limits the switching frequency to under 500Hz, dramatically impacting the size and performance of the overall converter system. This performance limitation and high solution cost has limited the commercial viability of such DC microgrids. The advent of high voltage SiC devices make building MVDC converters attractive, however simply replacing Si with SiC can result in other issues such as EMI due to high dv/dt. The technology developed in this project presents a way to achieve controlled dv/dt resulting in lower EMI and higher efficiency, allowing realization of the full potential of medium voltage (>3.3kV) SiC devices.

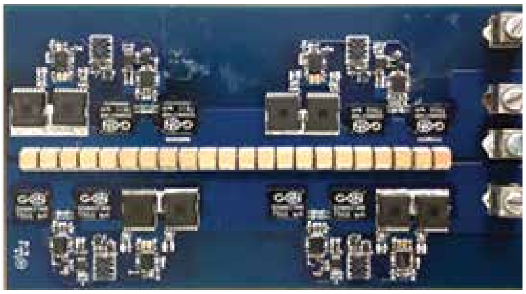
Accomplishments/Deliverables

- A 3.3kV 45A custom module consisting of six current switches has been developed working with CREE.
- The 3.3kV current switch has been characterized under soft switching conditions. It was shown that with soft switching the switching losses reduce by 98% compared to hard switching and the dv/dt can be controlled to be < 2kV/μs.
- A model predictive priority switching (MPPS) control method has been developed to realize control of series stacked low-inertia converters.
- A 50kVA MVDC converter, consisting of two 25kVA 2.5kVDC/600 V DC or 480V AC stacked together has been built.
- The 25kVA 2.5kV/600V DC converter module has been tested at 1.5kV and 4kW verifying the proposed MPPS method, soft switching and controlled dv/dt.
- Two undergraduate students and two graduate students have been trained on this project.

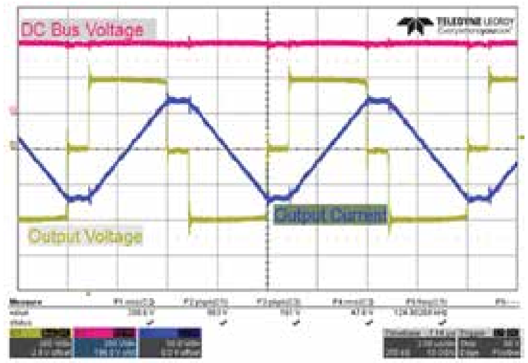
Impact/Benefits

- A major challenge with high voltage SiC devices is the large dv/dt. The project presents a way to achieve controlled dv/dt across all operating conditions and across all switches in the converter.
- Even with medium-voltage devices, the converter modules need to be stacked to realize grid connected converters. The project developed control techniques that can ensure voltage sharing across series connected modules.
- Addressing dv/dt and series sharing issues may allow realization of the full potential of MV SiC devices, resulting in increased market adoption.

A High-Efficiency, Low-Cost 22kW Fast On-Board Charger for EVs Using Hybrid Switches Combining GaN HEMTs with Si MOSFETs



Hybrid Module PCB.



Scope Image Hybrid Module.

Project Summary

Design of a 650V/60A GaN HEMTs-based, 97%-efficiency, 20kW battery on board charger (OBC) for electric vehicles that utilizes a Si/GaN Hybrid Switching module instead of a pure GaN Switching module.

The Si/GaN hybrid switching module optimizes the OBC performance by exploiting the complimentary aspects of the GaN and Si devices in a way that their strengths are utilized, and their inherent weakness are neutralized. More specifically, this idea exploits GaN HEMT's high-performance switching characteristics and Si MOSFET's low switching and low conduction loss.

Technology Gap/Market Need

GaN devices have been used in OBC designs and there is no lack of evidence that these devices improve performance characteristics like efficiency and power density. The next challenge then is to accelerate the adoption of the automotive applications using these device by maintaining the high levels of performance and reducing the costs of these applications. The hybrid module strikes a better balance between cost and performance that entices automotive OEMs to adopt GaN-based OBCs sooner than is anticipated with pure GaN-based OBCs.

Accomplishments/Deliverables

- Identified appropriate Si switches that met performance and cost constraints of the hybrid switching module.
- Designed two different gate-drive circuits to trigger the hybrid switches effectively and reliably.
- Designed the bottom cooling method to enhance the thermal performance of hybrid switching modules.
- Simulated and tested Si solutions to ensure performance was within 10% of applications with solely GaN devices.
- Quantified the impact of parasitics of Si on GaN.
- Characterized two different hybrid switching modules and compared with 4-GaN application, in terms of the electrical stress and thermal performance.

Impact/Benefits

This project and its results have helped accelerate HELLA's entry into the automotive OBC market. The work that HELLA is doing with GaN devices has sparked the interest of OEM customers. Internal to HELLA, this project has served as a catalyst to deploy resources for the qualification of WBG devices for use in future designs and for investigating the processing of designs with WBG devices in its manufacturing plants.

The achieved hybrid module has achieved performance levels on par with an equivalent pure GaN solution achieving efficiency of 98% and power density of 4kW/L. Cost savings are anticipated and will be finalized at the end of the project.

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The University of Tennessee – Knoxville

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PowerAmerica Roadmap Targets

REDUCING COST

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

HYBRID/ELECTRIC VEHICLES

HEAVY VEHICLES

Design, Fabrication, and Vehicular Testing of 200kW 1050VDC Bus SiC Dual Inverter for Heavy-Duty Vehicles

JOHN DEERE

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

John Deere Electronic Solutions, Inc. (JDES) – a business unit of Deere & Company

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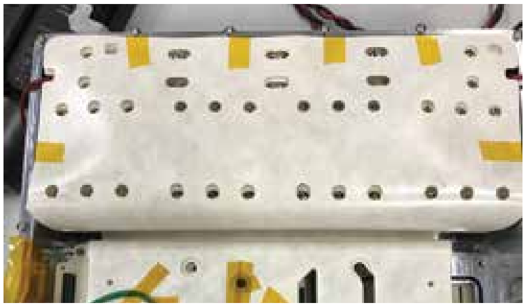
PowerAmerica Roadmap Targets

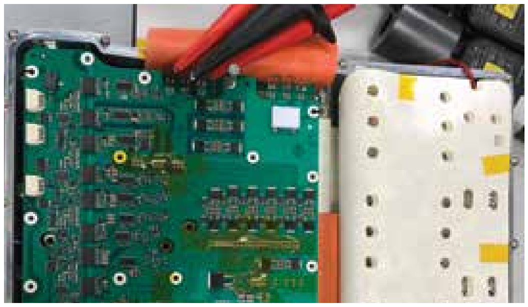
- ENHANCING PERFORMANCE CAPABILITIES
- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- MILITARY
- HEAVY VEHICLES



Gen-2 SiC inverter.



JD 644 WBG Loader used for SiC inverter testing.

Project Summary

The major improvements executed during design and fabrication of the Gen-2 SiC inverter are:

- Use of core-less current sensor: This supports cost reduction, requires smaller footprint, eliminates heating caused by iron losses in the magnetic-core based current sensor, and eliminates failure modes in the ASIC embedded within magnetic-core that heats-up with the increase in fundamental frequency, switching frequency, and magnitude of the measured current.
- Reduction in number of PCBs: The Gen-1 SiC inverter has used four PCBs to integrate the power stage of dual-inverter while the Gen-2 SiC inverter uses only two PCBs in its power stage. This reduction in PCBs has significantly supported JDES to accomplish a power-dense (increase from 18kW/L in Gen-1 inverter to 43kW/L in Gen-2 inverter) SiC inverter design while lowering BOM and manufacturing costs.
- Reduction in DC bus capacitor: The Gen-2 SiC inverter uses only 440μF 1100V rated (85°C hot-spot) film-capacitor verses 560μF 1100V rated (85°C hot-spot) film-capacitor used in the Gen-1 SiC inverter. This has significantly supported simplification of the inverter case and DC bus bar within the inverter, which should help in cost reduction of pre-production intent Gen-3 SiC inverter to be designed and manufactured during BP4.
- Simplification for system level integration: Power connector on one side of Gen-2 SiC inverter, coolant ports on one-side one side of Gen-2 SiC inverter, and far smaller case used for Gen-2 SiC inverter
- Development of six-pack SiC power modules:
  a. Simplified AC output terminals ready to place output connectors
  b. Simplified DC connection, elimination of bolted joints
  c. Built-in coolant channel, easier manufacturing of inverter

Technology Gap/Market Need

JDES/NREL project together has developed a six-pack SiC power module using engineering services from GE Aviation Systems. The power-dense high-temperature six-pack SiC power module didn't exist before execution of JDES's project tasks and completion of project milestones. The six-pack power module has allowed JDES to develop a high-temperature SiC inverter, which has ability to operate with the WEG coolant that could go up to 115°C. A coreless current sensor has never been used with WBG power electronics in 100kW power range, because coreless current sensor could allow higher switching and higher fundamental frequencies to exploit benefits of WBG devices. This is necessary to cover a wide power range 50kW to 250kW by modular design of the SiC inverter during the next phase of the JDES project.

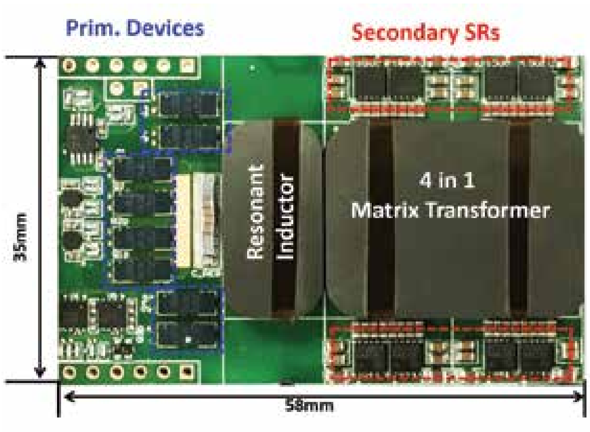
Accomplishments/Deliverables

The key accomplishment achieved was that a power dense energy-efficient, high-temperature SiC inverter was designed, manufactured and tested. This inverter was fabricated using miniaturized six-pack SiC power modules manufactured by GE Aviation Systems. The six-pack SiC power module with 250V/1700V rating didn't exist before the start of this project.

Impact/Benefits

- The real-world application or use of the final product is a WBG dual inverter for hybrid construction equipment capable of full engine cooling operation.
- JDES's Gen-2 SiC can eliminate dedicated cooling-pack for the inverter and this inverter can be cooled by running engine-coolant through mini-channels engraved in SiC power modules base-plate.
- Engine-coolant capable SiC inverter could result in significant simplification of the heavy-duty off-highway vehicles.
- WBG power electronics technology development work in JDES could allow John Deere to launch differentiating products provided SiC inverter offers a system-level, cost-neutral alternative to the silicon IGBT inverter.

High-Frequency GaN Power Converter



High frequency GaN power converter.

Project Summary

Lockheed Martin worked with Virginia Tech Center for Power Electronics Systems (CPES) and VPT to understand the capabilities of GaN power MOSFETs and their performance switching at high frequencies in a power module. The project investigated the performance of high switching frequencies and the ability to achieve high power density using these technologies. Virginia Tech developed a very high-density power converter using GaN power switches achieving 700W/in3 power density. Lockheed Martin and VPT leveraged the knowledge derived from VT CPES' work to realize similar designs that provide understanding of the performance using the high frequency switching GaN power MOSFETs. The development of these power modules helped investigate the capabilities of the surrounding components that enable fast switching power conversion. Through these combined efforts the project helps enable workforce education for VPT and Lockheed Martin providing the capability to realize GaN power converters for their products.

Technology Gap/Market Need

Mobile systems benefit greatly from the reduction in weight and volume of the power conversion system. High-frequency switching power converters can achieve significant weight and volume savings while still maintaining a good switching frequency. The project provided detailed data on how wide bandgap power switches perform in these applications and show what kind of power densities are available.

Accomplishments/Deliverables

Virginia Tech CPES provided prototype power modules to Lockheed Martin. VPT manufactured modules and provided them to Lockheed Martin for testing. Lockheed Martin developed internal designs for internal testing and provided feasibility of GaN power converters for military applications.

Impact/Benefits

This project provided the opportunity for VPT and Lockheed Martin to look at the capabilities to limit the touch labor required to produce power converters. In addition, the product provided insight on how implementing high-frequency designs with their components impacts the normal processes and procedures for power converter assembly, resulting in a good understanding of how to design these products for manufacturing.

Lockheed Martin Corporation, VPT Power and Virginia Tech

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PowerAmerica Roadmap Targets

- ENHANCING PERFORMANCE CAPABILITIES
- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- UPS DATA CENTER
- MILITARY
- AEROSPACE
- HEAVY VEHICLES

High-Density, High-Efficiency Adapter with Improved Manufacturability

Navitas Semiconductor

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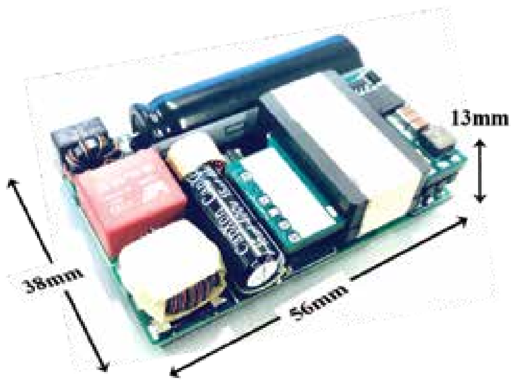
PowerAmerica Roadmap Targets

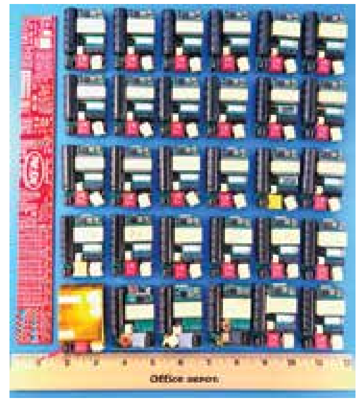
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES
- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Application

- MOBILE CHARGER ADAPTER



500kHz GaN ICs based 65PD adapter employing planar winding transformer.



30 manufactured high density 500kHz GaN-based adapter units.

Project Summary

Establish a commercially compelling platform with GaN ICs that sets an industry standard in energy efficiency, power density, eco-cost and manufacturability for consumer adapters/chargers application.

Technology Gap/Market Need

The existing AC-DC adapter market is dominated by Asian suppliers. The shift to high-density and high-efficiency adapters creates an opportunity for U.S. suppliers to capture a significant portion of the market. Initial attempts by U.S. suppliers, such as start-up Finsix, set a good standard in density but fell short in efficiency and manufacturability. This project will establish a new benchmark in high-efficiency and high-density adapters while promoting automation in manufacturing and reduced labor content to give U.S. suppliers an opportunity to establish global leadership in this market.

Accomplishments/Deliverables

Completed design with verified efficiency, density, thermal and EMI. Efficiency exceeds stringent DOE Level 6 and CoC Tier 2 regulatory standards. Scope has been enhanced to include USD-PD power delivery interface joined with type C connector. Reliability is improved by component count reduction through GaN integration, well protected and controlled GaN power FET gate drive and switching behavior, and transformer manufacturing automation with reduced wiring and soldering. To achieve this high-frequency design, collaboration was necessary with control IC suppliers for advanced new active clamp flyback topology and high-frequency synchronous rectification. Highest performance magnetic materials have been researched and adopted in the design, as well as optimized planar transformer PCB-based winding designs.

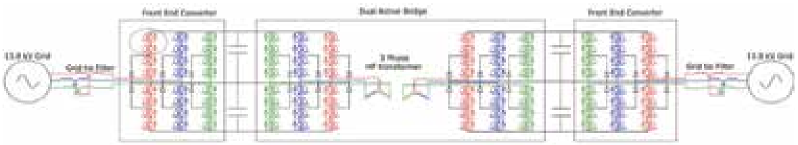
Technology has been adopted in the world's thinnest universal 45W PD adapter. Many other designs are in process with ODMs and OEM support.

Deliverables include 30 adapter ref designs with design, performance & manufacturing collateral.

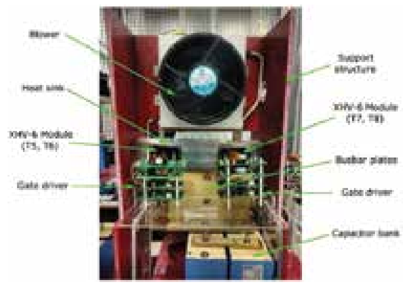
Impact/Benefits

Reduced labor costs with fully automated transformer; reduced manufacturing costs with improved manufacturing quality & consistency (yield); reduced re-work cost; significant US smartphone, game-station, and mobile computing OEM interest.

Asynchronous Microgrid Power Conditioning System (MicroGrid PCS) Connector to MicroGrid



Asynchronous Microgrid Power Conditioning System (AMPCS) connector to Microgrid.



Medium voltage three level neutral point clamped voltage source converter pole enabled by series connection of 10kV, 15A Gen-3 SiC MOSFETs.

Project Summary

Design, develop, validate and optimize the Asynchronous Medium Voltage Grid Connector. The tasks include in-depth analysis and simulation of the whole system under different operating conditions. DSP and FPGA-based controller boards will be used to code and test the controller responses. Full scale hardware, including the three-level Neutral Point Clamped (NPC)-based Front End Converters (FECs) and Dual Active Bridge (DAB), will be built and tested at grid-connected full load conditions.

Technology Gap/Market Need

The Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid is required today for all Microgrid PCS connections to the utility grid. In the era of advanced power electronics, this solution can easily be improved by a factor of 10-100. In other words, a quantum jump in power density is possible with HV SiC 10kV MOSFETs. This is exactly what this project demonstrates over a period of 3 years with a 13.8kV to 13.8kV Microgrid PCS connectors with SiC 10kV MOSFETs developed and enabled under PowerAmerica. This will then spur growth and adoption of MV power conversion systems in all areas.

The Microgrid PCS connectors have the potential to sell 1000+ units per year as the integration of renewable energy resources increases in the U.S. – with California mandating 50% renewables on the grid by 2030.

Accomplishments/Deliverables

- Medium voltage gate drivers for series connected 10kV, 15A Gen-3 SiC MOSFETs.
- Static and dynamic voltage balancing technique of series connected 10kV, 15A Gen-3 SiC MOSFETs.
- Avalanche ruggedness characterization of 10kV, 15A Gen-3 SiC MOSFETs.
- Continuous heat run test of latest XHV-6 power modules for 10kV SiC MOSFETs.
- Successful experimental demonstration of medium voltage, three-level neutral point clamped voltage source converter enabled by series connection of 10kV, 15A Gen-3 SiC MOSFETs.

Impact/Benefits

The inclusion of high voltage silicon carbide devices will lead to reduction in the volume and overall cost of the system in the long run as the SiC foundry model is successful. This aspect has created a lot of interest for this project in the industrial sector. The application of HV and demonstrating the series connection of WBG devices in the converter design is going to affect medium voltage drives, traction applications; Grid-tied PV and wind applications, and HVDC transmission.

Currently, Pareto Energy is the only viable supplier of the Microgrid Power conditioning connectors, which have a maximum efficiency of 88-92%, implemented with Si IGBTs and bulky 60Hz transformers on both MV sides, with high system cost of $1M/MW. A quantum jump in power density and reduction of footprint size, weight and volume is possible with HV SiC 10kV MOSFETs. Further, this can be enabled by forced air or heat-pipe based cooling rather that liquid cooling.

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- RAIL TRACTION
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES

Development of an Active Harmonic Filter using Interleaved SiC Inverter

NC STATE UNIVERSITY

North Carolina State University

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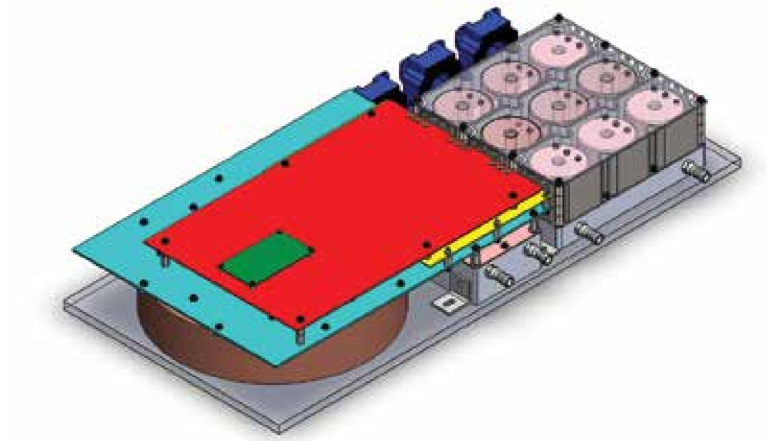
PowerAmerica Roadmap Targets

- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- RENEWABLE ENERGY
- POWER QUALITY
- UPS DATA CENTER
- ELECTRIC POWER GRID



150A SiC-based Active Harmonic Filter.

Project Summary

The goal of this project is to design, fabricate, and test a 150A Active Harmonic Filter (AHF) using an interleaved SiC-based inverter. The AHF is designed to have high efficiency (>98% peak) with high switching frequency (>50kHz) and high power density (>1kW/L). The design target is to achieve four-quadrant operation capability up to the 51st harmonic cancellation, along with significant reduction in grid current (<5% THD).

Technology Gap/Market Need

- Use of wide bandgap power devices allows operation at higher switching frequency and higher temperature, which results in a significant gain in efficiency, while reducing overall system size and weight. This provides significant advantages with regards to performance measures and reliability when compared to current Si-IGBT based systems.
- The switching speeds of the SiC systems are generally limited by the system parasitics. Accurate estimation of system parasitics and design optimization based on the parasitic elements can improve the overall system performance.

Accomplishments/Deliverables

- 150A SiC-based Active Harmonic Filter (AHF) has been designed and is currently being built utilizing interleaved topology for high-performance (<2% THD, elimination up to 51st harmonic), high power density (> 3kVA/L).
- FPGA-based controller platform has been developed utilizing grid-current sensing
- Low inductance modular PCB-based busbar has been designed.

Impact/Benefits

The high-performance and high-power density AHF can serve as a benchmark for industry application as it presents a SiC-based interleaved topology along with innovative FPGA-based control strategy utilizing gridcurrent sensing. Capitalizing on the high-risk/high-gain design approach of the academic research setting, compared to industry R&D, this project can serve as an example for future adoption of WBG power devices and advanced control and sensing techniques to enhance the capabilities of industrial AHFs.

Next Generation 350kW Three-Phase Medium Voltage, High-Efficiency EV Fast Charger

Single-phase 120-kW fast charger module.

Project Summary

North Carolina Sate University (NCSU) is building a medium voltage (MV) fast charger using 10kV SiC devices obtained from the PowerAmerica device bank. The system features a 12.47kV three-phase AC input, 350-1000V DC output, delivering 350kW output with over 98% peak efficiency. The project serves as a reference design for PowerAmerica. By demonstrating the SiC-based fast charger system, and quantifying the performance, power density, and efficiency gains, the project will help the industry build confidence in WBG-based MV power electronics and accelerate WBG adoption in power electronics applications. The project will continue helping to develop the WBG workforce by involving undergraduate and graduate students in various aspects of WBG technology.

Technology Gap/Market Need

The goal of this project was to demonstrate the advantages of using the 10kV SiC devices in a modular converter topology. As the 10kV technology and devices mature, the design and the lessons learned from this work will help the technology advance by providing proof of concept performance comparison to solutions using Si, and low voltage SiC solutions.

Accomplishments/Deliverables

The key accomplishment of this project is a working prototype of the MV fast charger using the 10kV devices. The team will deliver a detailed reference design document with all the details and performance described and made available on the PA web portal as well as the NCSU website.

Impact/Benefits

This project involved three graduate and three undergraduate students that will form the backbone of the future advanced manufacturing workforce.

NC STATE UNIVERSITY

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PowerAmerica Roadmap Targets

- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- UPS DATA CENTER
- ELECTRIC POWER GRID

SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration

Modular components of the PV inverter with SiC power devices

TOSHIBA
Leading Innovation

Toshiba International Corporation

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PowerAmerica Roadmap Targets

REDUCING COST

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Application

RENEWABLE ENERGY

Project Summary

This project aims to commercialize a SiC-based commercial hybrid PV inverter with Li-ion Battery integration in the U.S. Aligning with the overall strategy and roadmap of PowerAmerica, our next generation commercial hybrid PV inverter was designed and developed in 2017. By releasing and manufacturing the SiC-based PV product, our goal is to prove the merit of SiC devices for a fast-growing PV inverter market, and also foster the mass production of SiC devices to reduce their cost.

The deliverable of this project is the 50kW SiC device-based hybrid PV inverter. The most important critical to quality (CTQ) feature for a PV inverter is the inverter's efficiency, since a return on investment (ROI) of a PV inverter is directly proportional to the inverter's efficiency. The second important CTQ is the inverter's size and weight, which is particularly important for small commercial PV inverters. Costs of installation, transportation and inventory of small commercial inverters accounts for a large proportion of their life-cycle cost. By using a SiC MOSFET inside the PV inverter, 98.5% PV to grid efficiency, 97.5% PV to battery efficiency and 97% battery to grid efficiency have been achieved.

At the same time, power electronics engineers, supply chain engineers, industrial engineers and factory plane managers have been involved to support the design, fabrication and test of the new SiC device-based hybrid inverter.

Technology Gap/Market Need

The first technology gap is to optimize design of magnetic components, which aims to improve efficiency, reduce size and reduce weight. The requirements for magnetic components has changed dramatically with the adoption of SiC devices. Making a good design for magnetic components is crucial for a good product design and a solid supply chain.

The second technology gap is the learning curve for power electronics engineers, supply chain engineers and industrial engineers to understand new SiC devices and apply them to new product designs and manufacturing.

Accomplishments/Deliverables

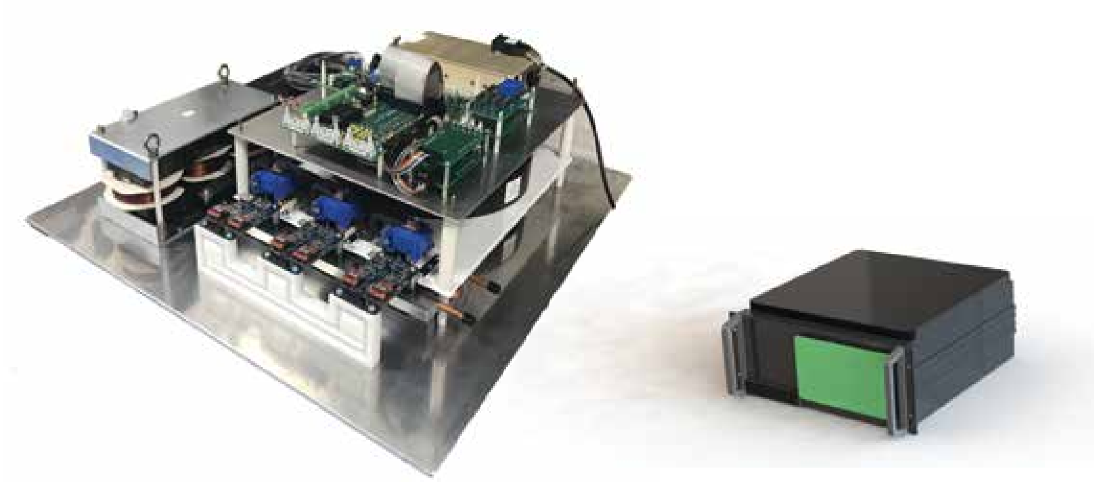
The SiC device-based 50kW Hybrid PV Inverter with Li-ion Battery Integration has been developed and tested. The hybrid inverter can achieve 98.5% PV to grid efficiency, 97.5% PV to battery efficiency and 97% battery to grid efficiency.

Impact/Benefits

One of the biggest trends in the renewable energy industry is more energy storage integration. Commercial and residential customers demonstrated great interest in battery integration for PV inverters.

The developed high-efficiency low-weight SiC device based hybrid PV inverter with Li-ion battery integration will play a key role in increasing market share. Moreover, it will contribute to boosting the share of U.S. -manufactured products in the global market.

SiC Active Harmonic Filter for Variable Frequency Drives



Silicon Carbide Active Harmonic Filter for Motor Drives Applications.

Project Summary

United Technologies Research Center (UTRC) developed an optimized 150A Silicon Carbide (SiC) Active Harmonic Filter (AHF) with minimal parasitic inductance that allows SiC devices to reach switching frequencies between 40 and 80kHz at full current, increasing the AHF power density by a factor of 2 with a projected lower system cost and high efficiency. UTRC demonstrated the technology in a relevant environment by applying the SiC AHF on a 450A drive variable speed chiller and achieving a THD lower than 5%.

The results of this effort will break the market barrier for AHF applications and will increase the adoption of this technology not only as a system level solution but also as a point of load solution where harmonics could be canceled at the terminals of the non-linear loads that produce them.

Technology Gap/Market Need

Nowadays, the semiconductor technology of choice for commercial AHF is silicon IGBTs. This technology imposes a limitation of the switching frequency due to its high switching losses. Therefore, most designs try to find a compromise between performance, cost and efficiency at around 10 to 20kHz. The SiC-based active harmonic filter developed under this program demonstrated for first time in a relevant environment a 150A SiC-based active harmonic filter optimized around a 40kHz switching frequency - achieving at the same time a higher power density, higher efficiency and better harmonic cancellation performance than a silicon- based AHF.

Accomplishments/Deliverables

High Power Density: The TRL 6 prototype achieved a power density of 2kW/liter, exceeding the initial target of 1kW/liter. It is expected that a TRL 8 prototype with a power density of 3kW/liter can be achieved by implementing a tighter package of the components.

High efficiency: The system achieved efficiencies higher than 97.6 % at full load.

Active Harmonic Filter Functionality Demonstration in Relevant Environment: The system was demonstrated at Carrier "Power electronics and Motors Laboratory" where the SiC AHF provided harmonic cancellation for a 450A variable speed screw compressor achieving a 3.8% Total Harmonic Distortion (THD) which is below the 5% THD target.

Impact/Benefits

Thanks to the collaboration with PowerAmerica the SiC Active harmonic filter technology advanced from a TRL 3 proof of concept to a full demonstration in a relevant environment TRL 6. Bringing this technology closer to a product development program, by reducing key technical risk and positioning this technology for further corporate investment.

In addition, in order to take full advantage of WBG devices for high power applications and achieve high levels of integration, is very important to have an ecosystem of components that support their high switching frequency capability i.e. (low inductance modules, capacitors, bus bars, inductors etc.). This project addressed this fundamental issue by bringing system level specifications and requirements to the various component manufacturers so they can provide components that support the unique capabilities of WBG devices, bringing up the US manufacturing industry.

United Technologies Research Center

United Technologies Research Center

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PowerAmerica Roadmap Targets

- ENHANCING PERFORMANCE CAPABILITIES
- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- POWER QUALITY
- ELECTRIC POWER GRID
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- UPS DATA CENTER

Multi-Functional, High-Efficiency, High-Density, Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module

THE UNIVERSITY OF TENNESSEE KNOXVILLE

The University of Tennessee, Knoxville (UTK), Southern Company Services (SCS), Chattanooga Electric Power Board (EPB), EPC Power.

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Application

ELECTRIC POWER GRID

25kV dc PCS phase-leg prototype with 35kW power rating using 10kV SiC MOSFET.

Project Summary

The overall objective is to develop a power conditioning system (PCS) module for the asynchronous microgrid employing high voltage (10kV) SiC power semiconductors with > 10kHz switching frequency to deliver more than 100kW power at required AC voltage level of 13.8kV. The PCS module should achieve the overall efficiency target of 98% and 95% with low/partial load (<30% loading), volumetric density of 4m^3/MW, footprint of 3m^2/MW, and specific power of 1kW/kg, and provide the bandwidth (voltage control bandwidth > 300Hz and current control bandwidth > 1kHz) needed for both the grid- and microgrid-support system-level functions. The current focus is a single phase-leg with 25kV DC link and 35kW power (capable of outputting 13.8kV AC and 100kW for three-phase) and grid function validation in a hardware testbed.

Accomplishments/Deliverables

The accomplishments include: 1) Specification and grid requirements determined for the PCS module with help of EPB and SCS; 2) Latest generation 10kV SiC MOSFET characterized including reliable gate driver design; 3) PCS phase-leg design including topology and PWM strategy, passives, thermal, isolated power supply, and mechanical structure; 4) PCS controller design including control and interface board, sensor board and control algorithm; 5) High voltage test platform building; 6) 25kVDC 35kVA phase-leg prototype building and testing; 7) PCS module controller demonstrated with grid-emulation hardware testbed.

The 25kV DC PCS phase-leg prototype with 35kW (capable of outputting 13.8kV AC and 100kW for three-phase) is completed as a deliverable.

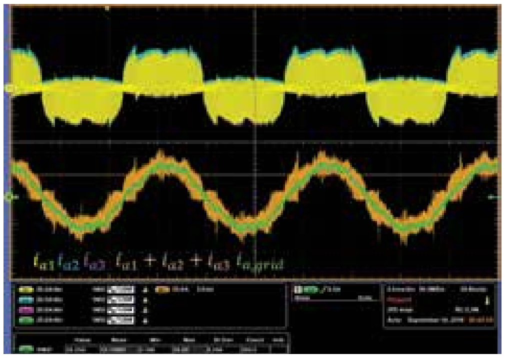
Technology Gap/Market Need

The project addresses challenges for application of high voltage SiC power semiconductors in medium voltage converters and grid-connected converters, accelerating the commercialization for medium voltage SiC-based converter and demand of high voltage SiC devices with growth of the microgrid.

Impact/Benefits

The project helps accelerate the proliferation of WBG devices in high voltage and distribution applications and microgrids that feature renewable energy sources; improves U.S. competitiveness on renewable energy integration and microgrid technologies with U.S. -based high voltage SiC device; and provided hands-on training for the next-generation power engineering workforce in WBG power electronics (3 graduate and 2 undergraduate students involved).

100kW PV Inverter with Efficiency > 99% Operating in Interleaved Triangular Conduction Mode (iTCM)



Waveforms of phase-A current for inverter 1, 2, and 3, the sum of three phase-A current, the grid-side current.

Interleaved three-level three-phase inverter operating in TCM

PV inverter undergoing tests in the CPES laboratory.

Project Summary

This project will develop a high efficiency 100kW, transformer-less, three-phase PV inverter featuring an average efficiency greater than 99%, per CEC regulations, a power density greater than 50W/in^3 , and a specific power greater than 10kW/kg, while limiting the ground-leakage current to be less than 300mA.

Technology Gap/Market Need

The use of transformers in commercial-scale PV inverters is a standard practice seeking to mitigate the ground-leakage current that PV inverters generate; however, it limits efficiency to the 94–97% range, and power density to values as low as 0.05–0.92kW/l. The use of Si IGBT semiconductors further limits efficiency and power density in these converters by their inherent performance and switching frequency limitations.

The use of SiC MOSFETs, although not commercially adopted, has already been shown to increase efficiency to near 99% in these applications. Nonetheless, this semiconductor device is better suited to operate in zero-voltage-switching (ZVS) mode at turn-on rather than in continuous forced-commutation mode. This is given that its turn-on switching energy is 4–6 times higher than its turn-off energy, with which nearly all switching losses can be eliminated if this operating mode is adopted allowing for a PV inverter to operate at much higher switching frequencies without sacrificing efficiency, while also gaining significantly in power density.

Lastly, to increase efficiency in the PV modules and DC distribution system, the operation at 900V DC is highly desirable, for which three-level topologies are better candidates than the industry workhorse, namely the 2-level voltage-source-converter topology. In addition, this topology reduces ground-leakage current emissions thanks to its split DC bus.

This program accordingly proposed the use of three-level SiC-based PV inverters operating in ZVS switching mode with enhanced switching sequences to further reduce the leakage current in the system eliminating the need for isolation power transformers.

Accomplishments/Deliverables

- Development of triangular conduction mode (TCM) modulation scheme for 3-level converter topologies achieving ZVS switching for all devices, featuring minimized common-mode voltage emissions and EMI, and quasi-constant switching frequency (< 3% variation)
- Developed of 3-channel interleaved TCM modulation scheme for 3-level converter topologies achieving ZVS switching for all devices, featuring minimized common-mode voltage emissions and EMI, and quasi-constant switching frequency (< 3% variation)
- Achieved a power density of 100W/in3, double the original target of 50W/in3 due to the use of a modular converter structure and a hybrid planar DC bus with aluminum electrolytic and film capacitors
- Complied with leakage current requirements (< 300mA for 100kW unit, < 120mA for 40kW unit) without the use of an isolation transformer.
- Developed closed-loop control implementation of iTCM scheme eliminating the need of lookup tables.
- Developed gate-driver with 3-level SiC MOSFET module with high dv/dt immunity (> 50V/ns)
- Developed EMI containment and mitigation strategy for multi-channel TCM PV inverter.

Impact/Benefits

A key contribution of this project was to develop the design and integration methodology to achieve high power density, including the design of the power converter modules and the planar DC bus with hybrid capacitor technology. The project also devised the EMI containment strategy for such SiC-based PV inverter in order to ensure its operational integrity.

VirginiaTech

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

RENEWABLE ENERGY

MOBILE CHARGER ADAPTER

INDUSTRIAL MOTOR DRIVES

POWER QUALITY

UPS DATA CENTER

ELECTRIC POWER GRID

MILITARY

AEROSPACE

HEAVY VEHICLES

Documentation of Design and Process of GaN Power Devices

Rensselaer

Rensselaer Polytechnic Institute

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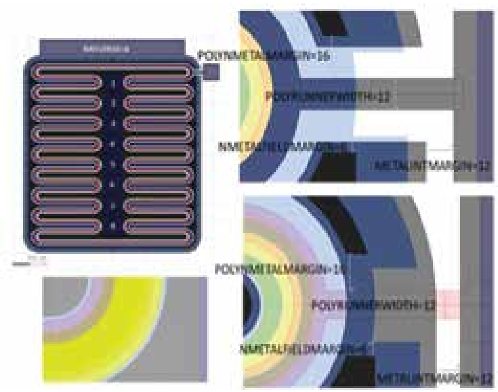
PowerAmerica Roadmap Targets

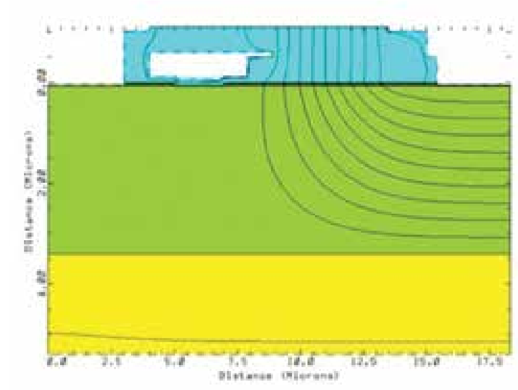
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- AEROSPACE



Autogenerated GaN MOS-HEMT device layout (overview and detail).



Geometry optimization using automated simulation.

Project Summary

Drawing on our research group's 15 years of experience designing and fabricating gallium nitride MOS-HEMTs, we selected the best-practice architecture and design for full documentation. In addition to comprehensive documentation we provide an automated layout tool to generate mask layouts from a concise set of design parameters. As our tool matures, higher level design parameters replace lower level geometric parameters; parameters obtained from integral simulation replace user input parameters; and more detailed device models are generated. Our project is undergraduate-driven with much of the design and documentation the result of undergraduate research projects.

Technology Gap/Market Need

Commercially available GaN FETs and most experimental university FET designs are pure HEMT designs based on a microwave device heritage. We document a MOS-HEMT process with a traditional power device heritage and a process architecture more compatible with silicon process technology.

Accomplishments/Deliverables

Full documentation of our process architecture has been submitted to PowerAmerica. We periodically submit updates to our layout tool incorporating program deliverables including simulation optimization, robustness modeling, and parameter extraction. Future deliverables include incorporating more design synthesis into our current layout tool with the aim of producing a fully turnkey design tool.

Impact/Benefits

Full documentation of our design along with the provision of an automated layout tool should spur more rapid adoption of our design and process architecture. Our documents and tool should be useful to both industrial practitioners and university researchers.

WHAT OUR MEMBERS ARE SAYING ABOUT POWERAMERICA:

"Through PowerAmerica's funding opportunities, HELLA has been able to accelerate its development of wide bandgap-based products for the automotive market."

Matt McAmmond, Advanced Engineering Manager,
HELLA Electronics Corporation

"PowerAmerica has been a great partner to Navitas in creating this next-generation high efficiency, high-density fast charger for mobile devices. This success would not have been possible without their financial support, vision for WBG devices and industrial and academic connections."

Gene Sheridan, CEO, Navitas

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industry visionaries and lead the revolution. Get access to groundbreaking research, proven processes, and an educated workforce to help **grow your business.**

PowerAmerica

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