ANNUAL REPORT 2020

ACCELERATING SiC AND GaN SEMICONDUCTOR MANUFACTURING FOR CLEAN ENERGY

PowerAmerica

THE POWERAMERICA TEAM

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"Membership in PowerAmerica provides Texas Instruments (TI) the opportunity to influence the important research being done in wide bandgap technology by the organization.

At TI, we are already experiencing the revolution in power density enabled by wide bandgap technology with our GaN portfolio and SiC isolated drivers, and we look forward to further opportunities enabled by the research and workforce people development happening at PowerAmerica."

Stephanie Watts Butler,
GaN Technology Innovation Architect,
Texas Instruments

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FROM THE EXECUTIVE DIRECTOR

TO OUR VALUED POWERAMERICA MEMBERS, PARTNERS, AND ASSOCIATES:

The year 2020 began normally for our organization, kicking off with the PowerAmerica Annual Meeting in February. Little did we know that would be the last in-person event we would hold for the foreseeable future. As the pandemic settled in this country in March, we quickly transitioned, along with everyone else, to a time of remote work, virtual events, and numerous changes to our professional and personal lives. I'm extremely proud of how well our organization and our members have weathered these challenges, and I firmly believe that we emerged from 2020 stronger than before.

2020 marked the end of our five years of Department of Energy funding and the start of the transition to a member-sustained enterprise. Since the institute began, we have completed almost 200 projects to advance the commercialization of silicon carbide and gallium nitride power semiconductor technologies. In 2020 alone, we finished 46 projects in our primary focus areas of foundry and device development, module manufacturing and reliability, commercialization applications, and education and workforce development. These projects address major application areas like automotive and rail, on board chargers, power supplies, industrial inverters/converters/rectifiers, portable power, aerospace electrification, renewable electric energy including photovoltaic and wind, microgrid and grid integration technologies, energy storage, wireless charging, motor drives, UPS, and data centers. These "seed" projects demonstrate the competitive advantages of wide bandgap power electronics, resulting in industry investment in clean energy technologies that create high tech manufacturing jobs and energy savings - both crucial to the U.S. economy and national security. Through this work, we are also investing in the future workforce, training 410 students to date in "hands-on" industry/university collaborative projects.

POWERAMERICA EXECUTIVE DIRECTOR/CHIEF TECHNOLOGY OFFICER VICTOR VELIADIS

Our ecosystem is now stronger and bigger than ever, with 60 members - including large corporations, small businesses, universities and government labs - representing all areas of the supply chain. We continued to connect with one another in 2020, hosting our first-ever virtual summer workshop and virtual short course. One benefit of this virtual approach is our new ability to reach a larger audience than ever before. Both of these events resulted in record attendance; a silver lining during an unprecedented time. While we miss networking face to face, we were pleased to have the tools to replicate some of that experience online.

The conclusion of the DOE funding phase of PowerAmerica's work is just the beginning for us. We've built an extremely solid foundation with a compelling membership value proposition on which to continue to grow. We launched a dozen member-initiated and open innovation fund projects this year, and will continue to award groundbreaking research and development initiatives that benefit all our members for years to come. It is a time of tremendous and sustained market growth for SiC and GaN power semiconductor technologies, and we are excited to continue accelerating these clean energy initiatives. I look forward to building on the great work we've done with our members, and continuing to make a strong impact in the future.

Sincerely,

Victor Veliadis, Ph.D., IEEE Fellow
Executive Director and CTO, PowerAmerica
Professor in Electrical and Computer Engineering, North Carolina State University

A record of accomplishm

As we conclude our fifth year as a Department of Energy-backed, Manufacturing USA institute, PowerAmerica takes great pride in our institute's accomplishments to date. Together with our members, we've built a strong network of technologists and manufacturers—moving wide bandgap semiconductor technology out of the lab and onto the assembly line. Member projects have created jobs and spurred innovation that has resulted in more powerful, more efficient devices across a range of applications. We look forward to continuing our mission as a self-sufficient, member-driven organization.

PowerAmerica funded

196 **projects from 2015-2020**

73 industry

112 academic

11 national labs

Applications

Harnessing the capabilities of wide bandgap semiconductors can lead to dramatic energy savings in industrial processes, data centers, and consumer devices; increase electric vehicle driving range; and help integrate renewable energy onto the electric grid.

KEY APPLICATION FOCUS AREAS OF THIS YEA

Electric/Hybrid Vehicles

WBG enables better range/less charging time

Example project: see University of Akron, pg. 46

Renewable Grid Integration

WBG enables an efficient, flexibl and reliable grid

Example project: see NC State University, pg. 34

nents, and the promise of more to come.

$58.1M

Foundry & Device Development

Enable low-cost, large volume device manufacturing in the U.S.

$14.4M

Module Manufacturing & Reliability

Bridge the gap between device readiness and commercial adoption

$49.2M

Commercialization Applications

Boost manufacturing by showcasing compelling wide bandgap system advantages

$4.6M

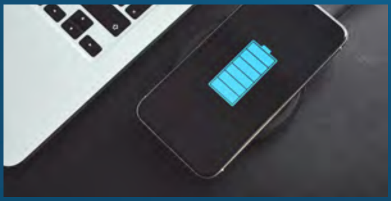
Education & Workforce Development

Educate the next generation of wide bandgap power engineers

145 million

in total WBG projects and member promotion

R'S POWERAMERICA PROJECTS INCLUDE:



Consumer Electronics Power Supply

SiC/GaN enables higher efficiency and smaller device size

Example project: see Fastwatt, pg. 41

Electric Motor Drives

SiC-based variable speed drives enables volume, weight and cost advantages

Example project: see Toshiba, pg. 32

Data Centers

SiC/GaN power electronics innovations enable efficient data center architectures

Example project: see ABB, pg. 31

Power in membership

PowerAmerica provides a forum for members to improve the performance of SiC and GaN power semiconductor technology and develop new, clean energy applications. Our membership network spans the wide bandgap technology ecosystem, from materials to device developers and foundries to module manufacturers to end users, as well as universities that educate and supply the future workforce. As we continue to grow, so does the diversity of our membership.

TOSHIBA

SYNDEM

Southern Company

SENSITRON SEMICONDUCTOR

Academic Institutions & Government Labs

The University of Akron

University of Arkansas

UNC Charlotte

University of Colorado Boulder

EPRI

the Institute for Advanced Learning and Research

Marquette

Miami University

UWM University of Wisconsin Milwaukee

NC State University

Rensselaer

The Ohio State University

The University of Tennessee Knoxville

Texas Tech

The University of Toledo

Virginia Tech

Naval Research Laboratory Washington, DC

Argonne National Laboratory

Naval Nuclear Laboratory

NREL National Renewable Energy Laboratory

60 MEMBERS

Wide Bandgap Systems
Devices, Circuits & Modules
Foundry & Materials
SiC
GaN
ABB
ATOM POWER
BAE SYSTEMS
APPLIED MATERIALS
BETA FLIGHT RECHARGED
COOLCAD ELECTRONICS
GeneSiC SEMICONDUCTOR
HESSE MECHATRONICS
FASTWATT
Infineon
MICROCHIP
ON Semiconductor
SemiQ POWER SEMICONDUCTORS
Sonrisa Research, Inc.
USCi United Silicon Carbide, Inc.
JOHN DEERE
WBGS WBGlobalSemi, Inc.
VISHAY
Wolfspeed
PALLIDUS
Heraeus
SICAMORE SEMI
soitec
X-FAB MIXED-SIGNAL FOUNDRY EXPERTS
TEXAS INSTRUMENTS
VisIC TECHNOLOGIES
Systems
MERSEN
LOCKHEED MARTIN
NIR GROUP Renewable Energy Solutions

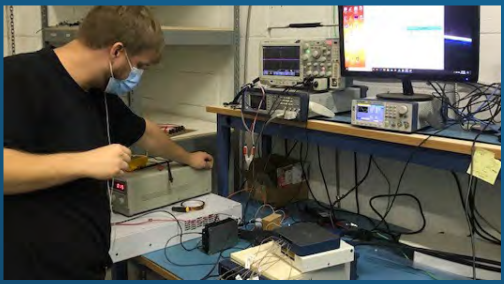
Education & workforce development

Over the past 5 years, PowerAmerica has developed programs to educate power electronics professionals, built networks with manufacturers, and created programs to match students with industry.

112 University Projects totaling more than

$34 million,

including the creation of undergraduate/graduate device and power electronics courses with WBG lab components.



410 students

trained in WBG technologies.

38+ University education projects that have generated WBG courses and labs, reference drawings and documentation.

WBG SEMICONDUCTOR TECHNOLOGY COURSE EXAMPLES

North Carolina State University *developed a WBG power device short course in its Nanofabrication Laboratory.*

University of North Carolina Charlotte *developed a power electronics teaching lab incorporating WBG semiconductor switches and circuits process flow for GaN lateral power devices.*

Helping industry recruit skilled employees

Our member portal matches specialized skills with member needs to expedite hires and internships.

3500+

power electronics professionals have attended PowerAmerica sponsored tutorials, short courses, and webinars to learn about WBG semiconductor technology. The exchange of knowledge accelerates technology adoption.

The value of membership

PowerAmerica provides value to its members through accelerating their concept-to-prototype cycle. Through the adoption of SiC and GaN semiconductors and their clean energy applications, industry members grow their U.S. manufacturing businesses, and university members benefit through collaboration with industry. Join us today!

- Comprehensive source of SiC and GaN semiconductor technical and business information
- Effortless customer/supplier introductions by PowerAmerica staff and focused networking at our semi-annual meetings with typical attendance of over 200 participants
- Access to PowerAmerica's members-only searchable talent recruitment portal featuring dozens of undergraduate and graduate students trained in wide bandgap technology
- Funding of member-initiated pre-competitive projects demonstrating the benefits of wide bandgap technology in power electronic systems with results and intellectual property shared by members
- Quick access to long lead-time SiC and GaN pre-production engineering devices and modules
- Access to the member-driven wide bandgap technology roadmap
- Discounted access to wide bandgap short courses and tutorials and participation in the 18-member university PowerAmerica ecosystem
- Promotion of PowerAmerica members through media and trade conferences
- Participation in quarterly members-only meetings where we deliver a collective, amplified voice on issues that affect the wide bandgap industry, influencing its direction and growth
- Referrals for SiC and GaN device and module designs, test and reliability services, manufacturing outlets, circuit integration reference drawings, and educational materials

2020 MEMBER REPORTS

Foundry and Device Development

Module Manufacturing & Reliability

Commercialization Applications

Education & Workforce Development

GeneSiC: 3.3kV SiC Power MOSFET and Diode Commercialization

GeneSiC Semiconductor Inc.

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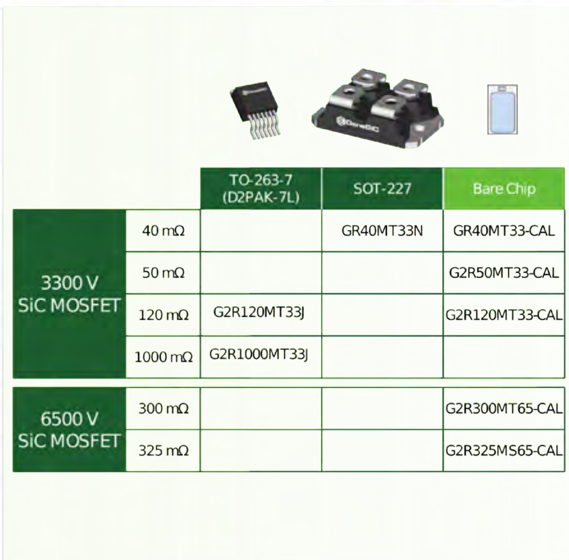
PowerAmerica Roadmap Targets

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



		TO-263-7 (D2PAK-7L)	SOT-227	Bare Chip
3300 V SiC MOSFET	40 mΩ		GR40MT33N	GR40MT33-CAL
	50 mΩ			G2R50MT33-CAL
	120 mΩ	G2R120MT33J		G2R120MT33-CAL
	1000 mΩ	G2R1000MT33J		
6500 V SiC MOSFET	300 mΩ			G2R300MT65-CAL
	325 mΩ			G2R325MS65-CAL

Sample of GeneSiC commercial products.

Project Summary

GeneSiC Semiconductor developed and commercialized multiple product lines of medium-voltage SiC MOSFETs and diodes, each targeted at a specific 3.3kV and 6.5kV market segment. The 3.3kV and 6.5kV SiC MOSFET and diode chips were manufactured at a 150mm foundry, X-Fab Texas, to lower the costs; standardize the supply chain, and increase the quality level of production. Multiple 3.3kV and 6.5kV MOSFET and diode products were commercially released. Samples of these first-of-a-kind products have been sent to multiple U.S. universities and also commercial entities for medium-voltage power module development and for demonstration in the next-generation of power conversion applications.

Technology Gap/Market Need

Commercializing 3.3kV and 6.5kV SiC power MOSFETs and rectifiers is essential for the next-generation of electric traction, grid-tied applications, and extreme fast charger infrastructure. There were no commercially available 3.3kV or 6.5kV SiC MOSFETs prior to this project.

Accomplishments/Deliverables

- Completed fabrication of 8 wafer lots of 3.3kV and 6.5kV SiC MOSFETs and rectifiers
- Commercially released multiple product lines of 3.3kV and 6.5kV SiC MOSFETs and rectifiers

Impact/Benefits

This project realized the first ever commercial release of 3.3kV and 6.5kV SiC MOSFETs manufactured on 150mm substrates in the USA. Commercializing 3.3kV and 6.5kV SiC power MOSFETs and rectifiers is essential for the next-generation of electric traction and extreme fast charger infrastructure. This in turn will save energy and create U.S. manufacturing jobs by accelerating the development and large-scale adoption of wide bandgap semiconductor technology made with silicon carbide in medium-voltage power electronics systems.

North Carolina State University: Development of 3.3kV-Capable, Open-Source, Low-Cost Packaging Solution for SiC Transistor and Diode Testing

Left: Advanced low-cost, full power, test substrate (FPTSs) package for developing 3.3kV WBG devices. The high thermally conductive, low modulus substrate allows for extreme effects characterization. Right: The CAD model for the Advanced low-cost full power test substrate (FPTSs). The fabrication files are open source at go.ncsu.edu/prees_open_source.

Project Summary

Today's WBG power devices operate at high frequencies and voltages. To develop such devices for large-scale manufacturing, advanced low-cost full power test substrates (FPTSs) are needed to support advanced testing approaches during device development. Further, to support the PowerAmerica mission, substrate design(s) are open source (https://go.ncsu.edu/prees_open_source). This ambitious project develops and demonstrates low-cost, full power, test substrates (FPTS) for mounting multiple 3.3kV WBG power MOSFETS of typical dimensions of ≤1cm X 1cm die.

Technology Gap/Market Need

This project proposes cost-effective 3.3kV/175˚C test packages for power IC design houses in the U.S. (e.g. Microchip Technology). Test packages will be designed with leakage currents ≤10μA at 25ºC and ≤100μA at 150ºC at 2.5kV, and terminal-to-terminal resistance ≤1V/50A measured through traceable instrumentation procedures. Test package design, fabrication flowchart and necessary equipment are documented.
To demonstrate feasibility, this project identifies at least one substrate volume manufacturer (e.g. TAIHONG CIRCUIT IND. Co., Ltd) for FPTSs, including assessment of manufacturing compatibility for the ERCD process with pricing projections for 1k, 10k, and 100k pcs. A cost analysis comparing metallic and organic substrates is reported.

Accomplishments/Deliverables

- Deliver 100 FPTSs to the PowerAmerica Device Bank to support 3.3kV DIODE testing.
- Deliver 150 FPTSs to the PowerAmerica Device Bank to support 3.3kV MOSFET testing, and document open source designs for high volume manufacturing.

Impact/Benefits

- Open source test package designs are now available for advanced device testing.
- Developed full documentation of design processes and equipment that enable in-house production for very rapid packaging for developmental testing.
- Developed package characterizations to benchmark traditional metal-clad ceramic approaches and advanced organic-based approaches.

NC STATE UNIVERSITY

North Carolina State University

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PowerAmerica Roadmap Targets

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

Commercial Applications

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

Microchip Technology Incorporated: Productization of 3.3kV & 700V Silicon Carbide (SiC) MOSFETs

MICROCHIP

Microchip Technology Incorporated

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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

SP6LI Power Module (2.9nH stray inductance.)

Project Summary

The objectives of this project are two-fold:

1. Design and commercialization of class-leading 700V SiC FETs to compete with and displace Si superjunction devices.
2. Productization of 3.3kV class SiC MOSFETs by completing reliability studies and fabricating large area devices to compete with 3.3kV IGBTs.

Technology Gap/Market Need

The introduction of 3.3kV devices into the market completes the opening of a new voltage node for the WBG industry, allowing continued innovation in the high-power traction and grid markets. Development of 700V SiC MOSFETs with reduced cost and enhanced performance allows the WBG industry to gain entry to the large markets currently served by Si superjunction devices with higher performance and competitive pricing.

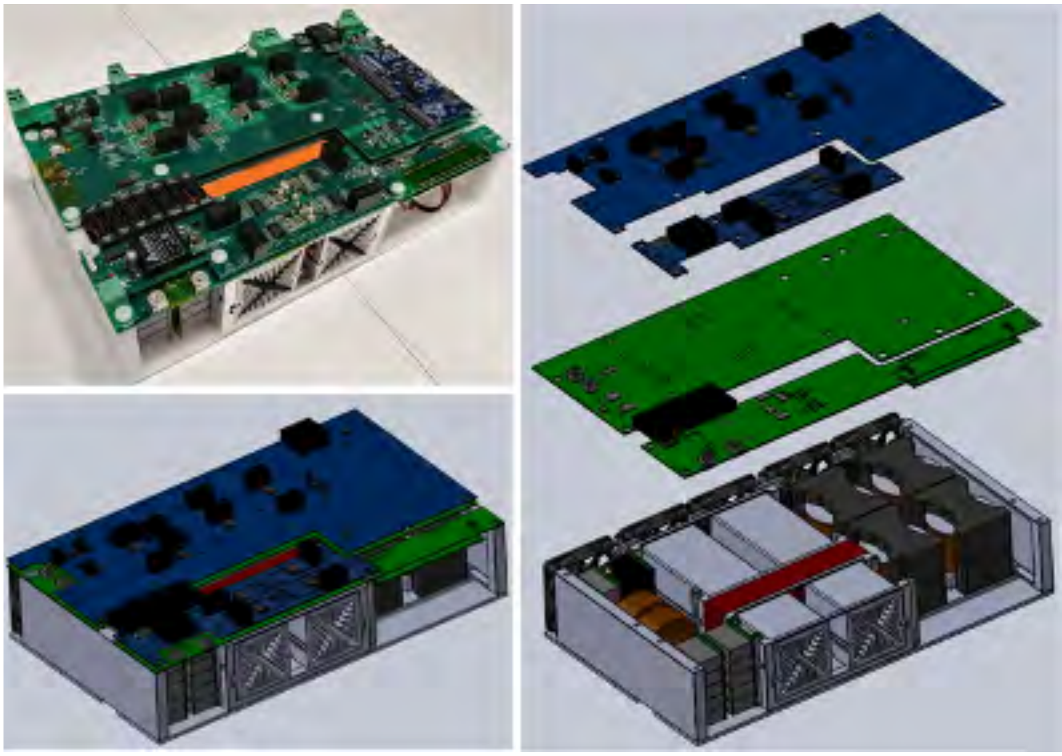
Accomplishments/Deliverables

- Completed design and manufacturing of targeted commercial 3.3kV MOSFETs, demonstrating excellent die sort yield. Completed characterization, datasheets, ruggedness and reliability assessment of 3.3kV MOSFETs and initiated commercial qualification.
- Completed design matrix, wafer fabrication, test, and characterization of 700V MOSFET designs to meet targeted market requirements. Completed ruggedness and reliability assessment of initial designs, and completed new design based on best outcomes. Launched lead lot of the optimized design.

Impact/Benefits

Through this project, both design and manufacturing of SiC devices are being performed in the U.S., keeping high-tech manufacturing and jobs onshore. Expansion of medium to high volume markets for Microchip SiC power devices increases the share of WBG markets served by our domestic product design and wafer manufacturing.

North Carolina State University: Development of a SiC-Based Resonant Converter for an EV Charger Using 3.3kV & 700V SiC MOSFETs



30kW isolated DC-DC converter with 97.9% peak efficiency and 6kW/L power density at 210kHz switching frequency and 2kV bus voltage.

Project Summary

This project aimed to develop a SiC-based resonant converter for an EV charger using 3.3kV & 700V SiC MOSFETs. A high efficiency (97.9% peak) and cost-effective 30kW SiC solution was developed with fully functional hardware and software. It supports both unidirectional and bidirectional implementations of 30kW resonant isolated DC-DC converters for EV chargers. Given the significant demands from the automotive and industrial markets to provide such reference designs, the combination of class-leading device technology and NCSU's expertise in building state-of-the-art power electronic systems would clearly help launch SiC-based systems in cost-sensitive market segments.

Technology Gap/Market Need

The technology gaps and market needs that this project addresses are: 1) to prove the system level advantages of using 3.3kV SiC devices, 2) to provide a rapid prototyping platform to automotive and industrial customers desiring to move to WBG technology, and 3) to demonstrate the relative strengths and weaknesses of using unidirectional or bidirectional resonant converters for EV charger infrastructure.

Accomplishments/Deliverables

3.3kV SiC MOSFETs operating at 200kHz enable a 16X reduction of transformer volume over the 3.3kV silicon IGBT solution. System robustness is ensured and verified by the full range of soft-switching of 3.3kV SiC devices, even under no load. The resonant isolated DC-DC rapid prototyping platform has been designed, tested and demonstrated with 30kW power for an EV charger using 4-pin TO 247 cost-effective SiC semiconductors and high-performance AlN thermal interface material. The full-power prototype validated the 97.9% peak efficiency and 6kW/L power density at 210kHz switching frequency and 2kV bus voltage.

Impact/Benefits

High voltage SiC devices enable the emerging markets of next generation efficient fast EV chargers, data center, solid state transformer, grid-forming MV converters, and high-power inverters for renewables applications. The project provides the system level advantages of using 3.3kV SiC devices with high frequency and high efficiency operation. The detailed reference design, including schematics, PCB layout, Bill of Materials, and testing results have established the starting point for commercialization of new product lines. The project has also advanced the skilled workforce for high-power WBG converters and high-bandwidth digital controls.

NC STATE UNIVERSITY

North Carolina State University

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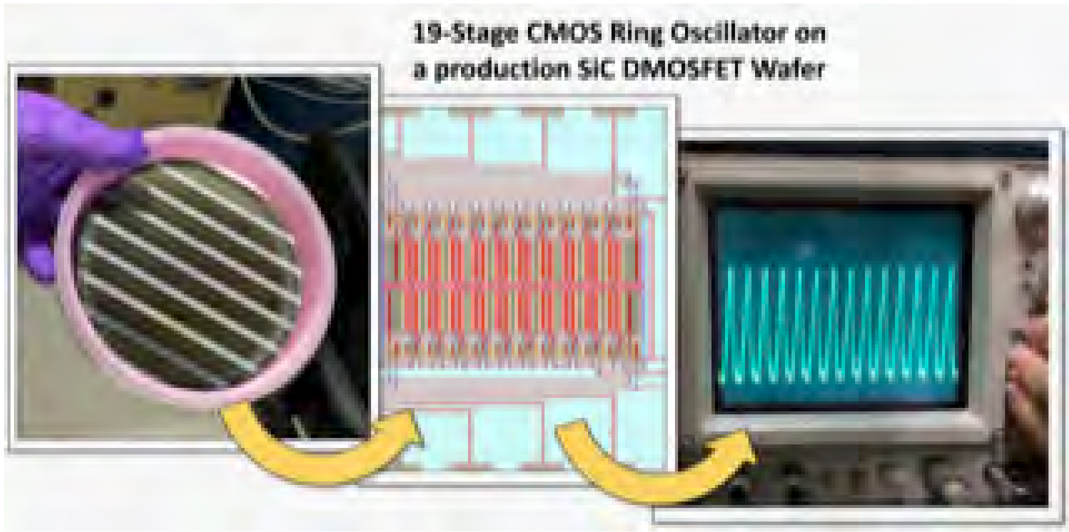
PowerAmerica Roadmap Targets

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

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- MOBILE CHARGER ADAPTER
- RAIL TRACTION
- UPS DATA CENTER
- ELECTRIC POWER GRID
- HEAVY VEHICLES

Sonrisa Research: SiC Planar DMOSFETs and Power ICs with Enhanced Short-Circuit Withstand Time



Left: 150mm SiC wafer with XFAB DMOSFETs and CMOS ICs. The CMOS ICs are fully isolated from the high voltage on the substrate. Middle: Layout of a 19-stage CMOS ring oscillator using our polycell library. Right: SiC CMOS ring oscillator operating on a 10V power supply.

Sonrisa Research, Inc.

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

Sonrisa Research, Inc. and X-FAB, Texas

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PowerAmerica Roadmap Targets

- 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
- HIGH VOLTAGE DC/DC CONVERTERS

Project Summary

This project impacts SiC power devices in two areas: (1) increased ruggedness and reliability, and (2) increased functionality. To increase ruggedness, we introduce the concept of constant-gate-charge scaling. In this approach, we scale the gate oxide thickness and gate drive voltage proportionally, keeping the oxide field and gate charge constant. This reduces the MOSFET saturation current and increases the short-circuit withstand time without increasing on-resistance or switching energy. Measurements on 1,200V production DMOSFETs from the 150mm foundry at X-FAB confirm a 2.5x increase in short-circuit withstand time at 600V and 3.5x increase at 960V, with no increase in on-resistance. To increase functionality, we developed technology for integrating SiC CMOS ICs on the same die as power DMOSFETs. Our process adds one implant to the standard DMOS process, and provides full isolation of the CMOS IC from the high voltage on the substrate. Operation of digital CMOS ICs on a 10V power supply has been verified at X-FAB and development is continuing, with the goal of integrating over-current and over temperature sensors directly on the DMOSFET die.

Technology Gap/Market Need

Commercial SiC power MOSFETs typically have short-circuit withstand times in the range 3–5μs, whereas silicon IGBTs have withstand-time specifications >10μs. This discrepancy acts as a barrier to the adoption of SiC MOSFETs in commercial power systems. We address this issue on two fronts: (1) we increase short-circuit withstand time using gate-charge-scaling without impacting on-state or blocking performance, switching performance, or oxide reliability; and (2) we have demonstrated a simple technology for incorporating CMOS sensing and protection circuits directly on the power DMOSFET die.

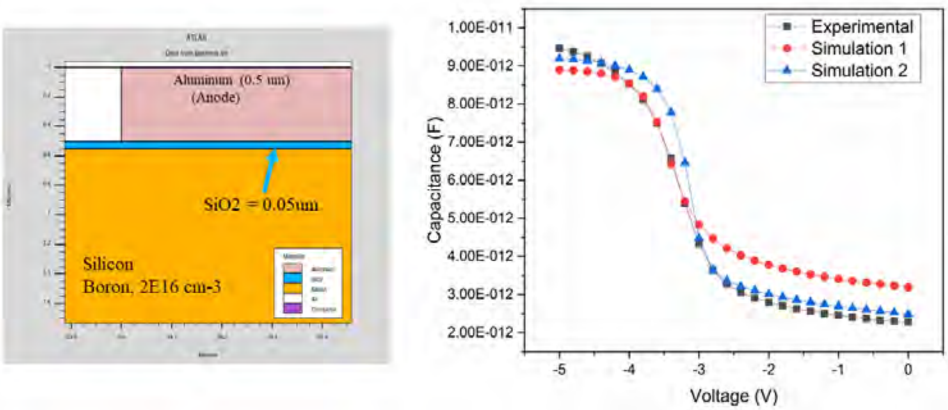
Accomplishments/Deliverables

(1) We have demonstrated a 2.5–3.5x increase in short-circuit withstand times in SiC production DMOSFETs by gate-charge scaling, with no increase in specific on-resistance or reduction in blocking voltage. A technical paper is in preparation.
(2) We have demonstrated CMOS ICs monolithically integrated on production DMOSFETs at the 150mm X-FAB foundry. The process is being refined to center the noise margins, and a technical paper will be published on the resulting technology.

Impact/Benefits

We demonstrated a zero-cost approach to increasing the short-circuit ruggedness of SiC power MOSFETs with no impact on their on-state, blocking, or switching performance. In addition, we developed a process and a digital polycell library for integrating CMOS control, sensing, and protection circuitry on a power DMOSFET die, with the added cost of one implant step over the standard DMOSFET process.

NC State University: Implementation of SiC Block Process Steps to Aid Transition of SiC Technology Developments



Comparison of modeled and experimental CV results from gate oxide.

Project Summary

NC State University and X-Fab Texas are working to establish a development fab for SiC device fabrication in the NC State Nanofabrication Facility (NNF). This project enabled the first steps in this process by supporting the development of a set of standard SiC process blocks in the NNF. The successful demonstration of these process blocks in a flexible, dynamic university fab provides a development opportunity for next generation process/material for SiC devices.

Technology Gap/Market Need

Due to its capital-intensive cost, most SiC fabrication is currently done by large industrial fabs, such as X-Fab Texas. However, due to economies of scale, such fabs do not work with single-wafer or small lots. On the other hand, University fabs – who will work with single-wafer or small lots – lack the capital for the necessary equipment. However, University fabs do have the flexibility to work with small and/or single-wafer lots where the disruptive advancements are made. By transferring large-fab process blocks to a University fab setting, it allows for innovative research ideas to be explored in a faster, more efficient way.

Accomplishments/Deliverables

The NNF was able to demonstrate the following SiC process blocks:

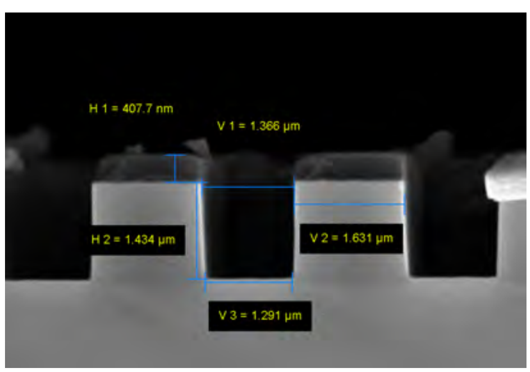
- Deposition, patterning, and etching of silicon-dioxide hard mask to implant-blocking hard mask
- High temperature gate oxide formation of n-type SiC, along with the doping, patterning, and etching of a phosphorus-doped polysilicon gate electrode. Modeling of oxide behavior was also carried out, and compared well with experimental results.
- Deposition of a interlayer dielectric, followed by an innovative patterning and etch technique which led to the desired sloped sidewall profile
- Deposition, patterning and annealing of ohmic contacts to both n-type and p-type SiC.

These process blocks will be available to all current and future NNF users, including those from industry, academia, and government labs. Moreover, NNF employed undergraduate students, graduate students, and post-docs for this project. They all played significant roles in its completion, and gained valuable experience in the area of SiC power device fabrication.

Impact/Benefits

Through this project, NNF was able to further PowerAmerica's strategy of providing U.S. companies access to SiC technology to accelerate innovation and adoption of SiC power devices in mainstream applications.

Furthermore, NNF used this project as an opportunity to teach its undergraduate and graduate student staff, as well as its team of post-docs, how to fabricate leading-edge SiC-based power devices, and thus train the next generation of experts, in fab-realistic conditions, in this critical and rapidly-growing field.



SEM image of patterned and etched silicon dioxide hard mask.

NC State University
X-Fab, Texas

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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
- MOBILE CHARGER ADAPTER
- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES

Microchip Technology Incorporated: SiC Production in a High-Volume, Low-Cost 150mm Wafer Fab

Microchip Technology Incorporated

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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

SiC high temperature implant annealer.

150mm wafer fab in Colorado Springs, CO.

Project Summary

This project aims to establish volume manufacturing of SiC power devices within our low cost 150mm wafer fab located in Colorado Springs, CO. Power devices included are Schottky Barrier Diodes (SBDs) and MOSFETs with voltage ratings between 600V and 3300V, to be extended to higher voltages as market needs dictate.

Technology Gap/Market Need

Establishment of internal, low-cost manufacturing capability will enable Microchip to better meet the rapidly increasing market demand for SiC power devices, particularly for automotive applications. In addition, the increased R&D flexibility enabled by internal SiC device fabrication will allow Microchip to rapidly respond to commercial technology and product needs.

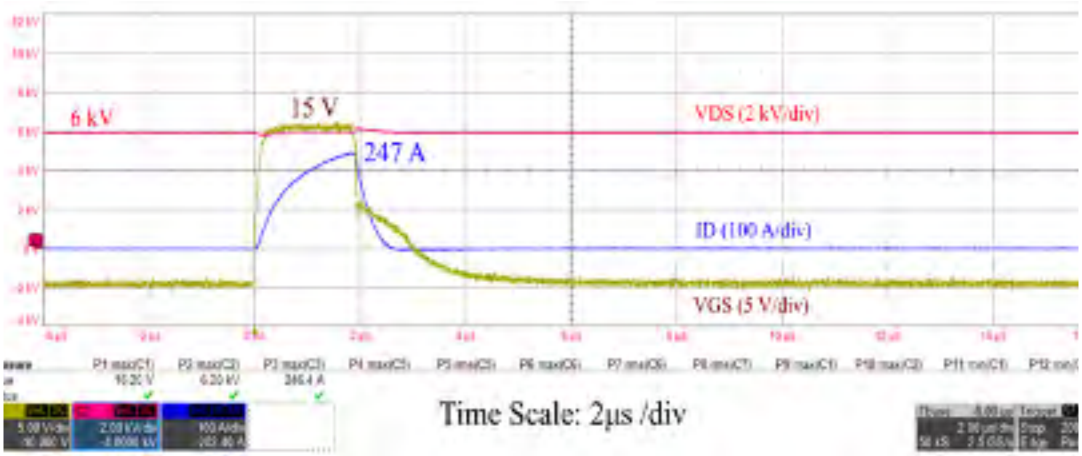
Accomplishments/Deliverables

SiC power device manufacturing was set up in our low-cost 150mm wafer fab. 700V, 1200V, and 1700V 50A SBDs were successfully fabricated with good yield and performance. 1200V 40mOhm MOSFETs were successfully fabricated with sufficient yield and performance to confirm process setups and design. SBDs are now moving into the automotive qualification stage. Deliverables: 50 units each of 700V and 1200V SBD, 50 units each of 700V and 1200V MOSFETs

Impact/Benefits

Utilization of our internal 6" wafer fab for SiC manufacturing along with our external foundry partner provides significant potential capacity expansion to better serve the growing markets for these devices. In addition, utilization of the internal fab for product and technology development will accelerate product-to-market timelines and provide reduced R&D cycle times.

North Carolina State University: Switching and Dynamic Ruggedness Characterization of Gen3 10kV/300mOhm SiC MOSFETs



Experimental waveform of the 10kV/300mOhm SiC MOSFET during the HSF short circuit fault at 6kV dc bus under a limited SC fault duration of 2 μs. Gate drive voltage: +15V/ -5V.

Project Summary

Wolfspeed/Cree-RTP has developed a manufactural and reliable Gen3 10kV/300mOhm SiC MOSFET device technology fabricated on 150mm 4HN-SiC wafers. In this project proposed by NCSU, the switching and dynamic ruggedness characteristics (short circuit and avalanche) is established for these 10kV MOSFETs developed by Wolfspeed/Cree-RTP.

Technology Gap/Market Need

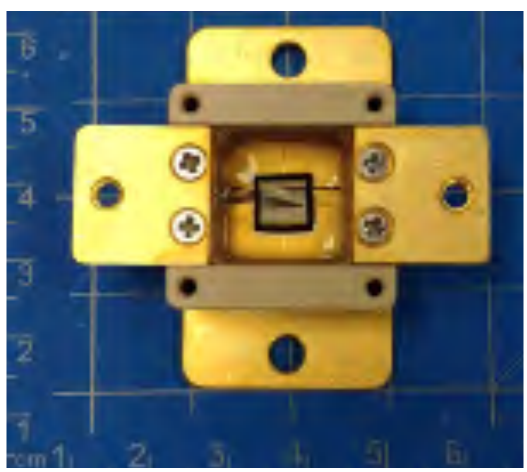
The switching characterization of a power MOSFET is an essential requirement to estimate the power converter's overall power losses. The power converter is designed for an optimal size, volume, and efficiency based on these characteristics. The power converter's reliability is measured by short-circuit ruggedness and the avalanche ruggedness of the power MOSFET during the fault conditions. The power density, efficiency, and ruggedness are important criteria for successfully commercializing the power converter made of these 10kV SiC MOSFETs. The project outcomes will help in the commercialization of the medium voltage power converters enabled by these 10kV SiC MOSFETs.

Accomplishments/Deliverables

- Medium voltage gate drivers for the latest Gen-3 10kV SiC MOSFETs have been designed, fabricated, and qualified.
- A medium voltage test bench has been developed for switching and ruggedness characterization of 10kV SiC MOSFETs.
- Hard-switching, soft-switching, short-circuit and single-shot avalanche ruggedness of 10kV/300mOhm SiC MOSFETs have been evaluated at the rated operating conditions.

Impact/Benefits

The hard-switching and soft-switching characteristics of the 10kV SiC MOSFETs will be required for the optimal design of the cooling system of the medium voltage power converters enabled by these 10kV MOSFETs. The short-circuit characteristics will be necessary to design a compatible short-circuit protection circuit for the 10kV MOSFETs to improve the MV power converters' reliability. The avalanche ruggedness limits the maximum inductive energy connected to the 10kV MOSFET in case of the avalanche fault. Overall, all these characterization results will help design more efficient and high power density MV converters using these 10kV MOSFETs.



The 10kV/300mOhm SiC MOSFET developed by Wolfspeed.

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

- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
- ELECTRIC POWER GRID
- HIGH VOLTAGE DC/DC CONVERTERS

SICAMORE SEMI

NC STATE UNIVERSITY

SiCamore Semiconductor and North Carolina State University

Contact:
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Prof. Jay Baliga, North Carolina State University

PowerAmerica Roadmap Targets

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

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- RAIL TRACTION
- UPS DATA CENTER
- ELECTRIC POWER GRID
- MILITARY
- AEROSPACE
- HEAVY VEHICLES

SiCamore Semiconductor: 3.3kV SiC Planar-Gate Power JBSFETs

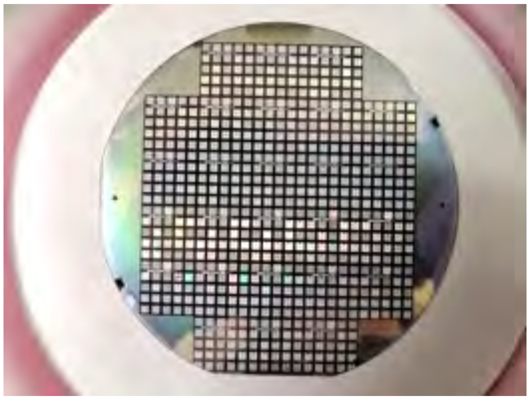
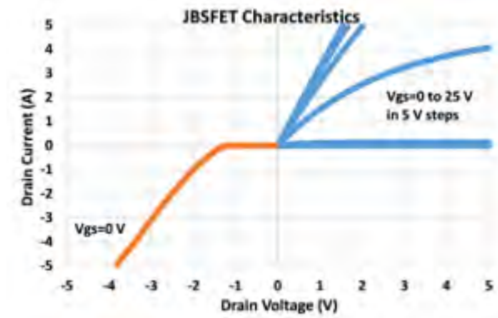


Image of 4 inch SiC Wafer fabricated at SiCamore Semiconductor with 3.3kV JBSFETs, MOSFETs, and JBS Diodes designed by NCSU.



First and Third Quadrant Electrical Characteristics of the 3.3 kV JBSFETs designed by NCSU and fabricated on a 4 inch 4H-SiC Wafer by SiCamore Semiconductor.

Project Summary

Create a Gen 5 PRESiCE™ chip design and process technology for manufacturing 3.3kV rated SiC planar-gate power JBSFETs in a new, second-source, 4-inch Commercial Foundry at SiCamore Semiconductor, Bend, OR. The chip design created by NCSU included planar-gate power JBSFETs, planar-gate power MOSFETs, and JBS rectifiers. A hybrid-JTE edge termination was designed to be capable of achieving > 3.3kV blocking voltage and use around all the devices. A Gen 5 PRESiCETM process was defined by NCSU and provided to SiCamore. The ion-implant profiles specified by NCSU were verified by SiCamore using SIMS analysis. Two lots of 6 wafers with 3.3kV epitaxial layers were manufactured by SiCamore. Lithography tools at SiCamore were optimized to allow fabrication of the NCSU chip designs. The Ni and Ti Schottky contact formation was optimized to achieve the expected barrier height. Measurements of the chips with linear cell designs for the planar-gate power JBSFETs demonstrated breakdown voltages above 3.3kV, specific on-resistances of less than 20mΩ-cm2, threshold voltage of 3V, and third quadrant diode voltage drop of 2.65V. These values met the project goals. The linear cell designs for the planar-gate power MOSFETs had measured breakdown voltages above 3.3kV, specific on-resistances of less than 20mΩ-cm2, threshold voltage of 2.5 , and third quadrant diode voltage drop of 3.8V. These results confirm that the JBS diode integrated in the JBSFET designs has a sufficiently low voltage drop to by-pass the power MOSFET P-N junction body diode. The JBS diodes with Ti Schottky contact had good blocking voltages above 3.3kV with a low on-state voltage drop of 1.55V at a current density of 50A/cm2. In contrast, the JBS diodes with Ni Schottky contact had blocking voltages below 2.0kV with a larger on-state voltage drop of 2.00V at a current density of 50A/cm2.

Technology Gap/Market Need

Until this project, only one SiC commercial foundry operation existed in the United States. This project was successful in implementing the Gen-5 PRESiCE™ process technology to fabricate planar-gate SiC power MOSFETs, planar-gate SiC power JBSFETs, and JBS diodes at a second commercial foundry operation in the United States. This is a second source foundry for SiC power devices for utilization by the SiC power device manufacturers and academic research groups. Although the project focused on 3.3kV rated devices, the basic technology can be used for other (650V, 900V, 1200V, and 1700V) SiC power device products.

Accomplishments/Deliverables

A new Gen-5 PRESiCE™ process technology was successfully developed by NCSU and transferred to SiCamore Semiconductor for manufacturing SiC power devices. Planar-gate 3.3kV power JBSFETs, power MOSFETs, and JBS diodes were manufactured with excellent electrical characteristics. A combination of 50 dies of these devices were delivered to the PowerAmerica device bank.

Impact/Benefits

A second source SiC commercial foundry in the United States was created by this project at SiCamore Semiconductor, Bend, OR. This capability allows SiC power device manufacturers to utilize this new resource to back-up their production of commercial devices. This capability can also be used by universities to enhance academic research on SiC power devices.

Wolfspeed: Removing Customer Concerns to Support Industry Adoption of Medium Voltage SiC Power Modules

Project Summary

During this project, Wolfspeed was responsible for removing customer concerns and perceived barriers to support industry adoption of medium-voltage (MV) SiC power modules through:

- Ruggedizing 1.7 – 10kV SiC modules for voltage isolation and partial discharge;
- Developing and validating a reference design for paralleling MV modules in high-current applications;
- Investigating higher levels of module / driver protections (Integrated drivers, use of Rogowski coils, temperature measurements, snubbers, & multi-level turn-on/turn-off schemes) with the U. of Alabama (UA);
- Exploring performance degradation from extended burn-in testing of MV SiC modules

Technology Gap/Market Need

This project filled a technology gap where there was no US made 3.3kV all-SiC power module available in a low-inductance (< 10nH), high-current (800A @ TC = 25°C & 600A @ TC = 90°C) package. This project enables the following future derivative products:

- 1.7kV all-SiC power module available in a low-inductance (< 10nH), high-current (> 1600A @ TC = 25°C) package
- 3.3kV all-SiC diode bridge power module available in a low inductance (< 10nH), high-current package
- 3.3kV all-SiC buck and boost chopper power module availability in a low inductance (< 10nH), high-current package
- Power module materials knowledge as a function of temperature for baseplate isolation and partial discharge standard conformance

Accomplishments/Deliverables

- Developed a parametric test plan and executed vertical
- Developed a parametric test plan and executed vertical voltage isolation test experiments leading to AC breakdown data, which was used to codify internal power module design rules.
- Developed a parametric test plan and executed lateral/horizontal voltage isolation test experiments leading to AC breakdown data between top-side patterned metal pads (i.e., HS drain, HS source/LS drain/Midpoint, and LS source pads) which was used to codify internal power module design rules.
- Completed testing to demonstrate unequal current sharing for an arrangement of three (3) parallel XHV-7 modules with unequal output inductance utilizing Wolfspeed's commercially-available gate driver. The measured current sharing results were documented.
- Completed FEA simulations and summary showing the current balance in three (3) parallel XHV-7 modules. Completed design of an optimized output busbar structure with variation of inductances from module to module of less than ± 10%.
- The optimized bus structure designed was implemented and tested along with the most common gate driver schemes: 1) single driver for N modules, and 2) N isolated drivers for N modules.
- The University of Alabama integrated a CT snubber into a gate driver. The CT snubber was tested in a double-pulse test and compared to an industry standard RC snubber to validate its performance. A report was completed describing measured results for all relevant datasheet parameters such as drive strength, propagation delay, protections timing, rise/fall times, etc.
- The University of Alabama completed a report that compares a CT snubber to existing snubber techniques (e.g., such as an RC snubber and RCD snubber) to determine trade-off of complexity, performance, and cost.
- A gate driver prototype was completed with the necessary refinements to meet the following key metrics defined by the industry survey: 1) output drive strength, 2) maximum switching frequency, 3) propagation delay, 4) jitter, and 5) protections requirements.
- Completed a report describing statistical correlation of burn-in acceleration test to the physical destructive analysis results of the devices under test for indication of package degradation.

Impact/Benefits

This project aligns with the high-level goals of PowerAmerica by:

1. Enabling a U.S.-based, all-SiC power module commercialization pathway.
2. Enabling a U.S.-based, all-SiC medium & high voltage power module production manufacturing capability.
3. Exploiting the positive attributes of 1.7kV to 10kV WBG devices with low thermal impedance, low inductance, and high temperature capability power modules.
4. Developing a module evaluation kit (including busbar assemblies and gate drivers with fast short circuit and/or dV/dt protection.
5. Promoting insertion of newly developed high voltage modules in MV applications through critical EMI/EMC work with the University of Alabama.

Wolfspeed A CREE COMPANY

THE UNIVERSITY OF ALABAMA

Wolfspeed, Inc.
University of Alabama

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PowerAmerica Roadmap Targets

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U.S. NAVAL RESEARCH LABORATORY

Wolfspeed. A CREE COMPANY

GeneSiC SEMICONDUCTOR

SemiQ

X-FAB

U.S. Naval Research Laboratory

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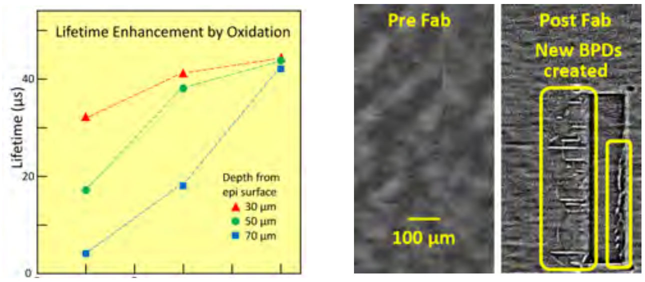
U. S. Naval Research Laboratory: SiC Device Reliability, Yield, and Control of Enhanced Carrier Lifetime



Left: 1-3-5 hour lifetime.
Right: Pre and post-fab images.

Project Summary

NRL continues using its advanced non-destructive ultraviolet photoluminescence (UVPL) wafer mapping capability to assist member companies in identifying and counting basal plane dislocations (BPDs) and other extended defects that adversely affect device yield and reliability. In the past year this includes X-FAB Texas, GeneSiC and SemiQ. In previous years, NRL initiated a collaboration with X-FAB Texas to investigate the introduction of BPDs due to Al implantation. This work showed that BPDs introduced by implantation of Al required the combination of room temperature implantation and activation anneal. It also showed a strong dose dependence: the dose used for p-wells did not introduce BPDs, whereas the higher dose for p+-contacts consistently introduced BPDs. These findings led to the creation of another DOE program, "Improving SiC Wafers and Processing for Lower Costs and Higher Reliability." For this program, NRL is working with five federal, industry and academic PowerAmerica partners to determine the feasibility of using room temperature (RT) Al implantation to manufacture reliable SiC MOSFETs. The attraction of RT Al implantation is that the overall cost to fabricate SiC MOSFETs is lower. MOSFET fabrication is being done at X-FAB and another SiC foundry. Another issue that PowerAmerica has addressed is the development of commercial SiC devices such as IGBTs, which can operate at higher voltages than is feasible with MOSFETs. SiC IGBTs have the innate potential to outperform Si devices in the higher voltage range, >15kV, such as would be needed for microgrid systems. They require thick epitaxial drift layers, >150µm, and in order to optimize the trade-off between on-state and switching losses, it will be necessary to enhance and to control the carrier lifetime through the total drift layer thickness. Techniques presently used to monitor lifetime are limited to measuring the top 50µm. Working with Wolfspeed, NRL demonstrated the capability of this non-destructive technique developed by NRL to measure the lifetime depth profile through thick epitaxial layers.

Technology Gap/Market Need

To sustain the market growth of SiC power devices, both their reliability and yield must continue to improve, so that they become comparable to the Si-based power devices they compete with. The suppression of BPDs and other extended defects in SiC wafers is an important factor in producing devices with high yield and reliability and this becomes more challenging as the voltage rating of the SiC devices increases. Also, in the future, to fabricate SiC devices with breakdown voltages higher than 10kV, MOSFETs will have to be replaced with IGBT or similar devices to enhance and control the drift layer carrier lifetime. While research has developed methods to enhance the carrier lifetime in the thick drift layers of high voltage devices, methods to non-destructively measure this lifetime through the full drift layer thickness are very limited. Working with commercial partners, both of these issues have been addressed.

Accomplishments/Deliverables

Investigations conducted by NRL and X-Fab into BPD formation by room temperature aluminum implantation resulted in a new DOE program that started in BP5. In this new program, NRL worked with five other institutions to determine the feasibility of using room temperature Al implantation to manufacture reliable, low-cost SiC MOSFETs. MOSFET fabrication is being done at X-FAB and another SiC foundry.

Using a two-photon absorption technique, NRL, in collaboration with Wolfspeed, have shown the feasibility of measuring the depth profile of the carrier lifetime in the thick epitaxial layers that will be needed in the next generation of high-voltage SiC devices such as >15kV IGBTs. It is non-destructive and can be used to monitor the lifetime during device fabrication.

Impact/Benefits

The potential of SiC devices to make higher efficiency power electronics systems with new capabilities has been known for a while. Within the last few years there has been significant progress in realizing that potential and SiC devices have captured a small but steadily growing portion of the power electronics market. NRL's accomplishments have addressed two important factors that will contribute to the expansion of SiC's importance in the power electronics market. The first has been working with PowerAmerica partners to reduce BPDs and other extended defects that degrade device reliability and yield. The second has been working with Wolfspeed to demonstrate the feasibility of non-destructively measuring the carrier lifetime in the thick epitaxial layer of high-voltage IGBTs.

GE Aviation Systems: Design and Manufacture of Advanced Reliable WBG Power Modules

1200V, 150A Six Pack.

1200V, 400A SR Full Bridge.

Project Summary

GE Aviation's project provides two additional module types to the five types of Wide Bandgap (WBG) Power Modules provided in the prior budget year. Seven modules of popular topologies will satisfy a need for advanced reliable, SiC and GaN power modules in WBG complementary packaging. This project addresses the PowerAmerica roadmap elements that include FA 3.1a High Performance Power Module Packaging and FA 3.2 90-8 Reliability and Testing where GE has included the National Renewable Energy Laboratory (NREL) to support life modeling / analysis of module internal structures and interconnects as well as reliability testing and evaluation. Gate Drivers and low inductance DC Link Busbar assemblies with capacitors will be provided to facilitate module evaluation. A team from N.C. State's FREEDM Systems Center has joined our team to provide a high-performance gate driver for GaN power modules. The modules provided under the project are higher current density than commercially available modules with low stray inductance due to the implementation of GE's Power Overlay interconnect technology (POL). Power Overlay eliminates traditional wire bonds which are a well-documented failure item in today's power modules used in traction applications. All SiC MOSFET based modules will include GE's 200°C SiC MOSFET die, will utilize high temperature materials and accommodate advanced cooling to achieve low Rth, to enable cooling via engine cooling loops; typically 105°C to 115°C.

Technology Gap/Market Need

GE recognized that traditional wire bond interconnects needed to be eliminated to reach the high frequency environment of WBG devices. GE also recognized that traction modules which experience repetitive power cycling could see failures in the wire bonds, an issue that is well documented. Small chip size is also limiting higher current power modules. With these weaknesses in mind, GE developed the Power Overlay interconnect technology shown above which replaces wire bonds with a planar copper interconnect layer.

Accomplishments/Deliverables

- Completed design, build, and testing of a 100V, 150A GaN on POL full bridge module utilizing GaN Systems top side cooled devices, mounted on Si3N4 substrate and interconnected with POL interconnect and mounted on AlSiC baseplate. Two modules were delivered to the PowerAmerica Device Bank. NCSU developed a gate driver and bias supply and supported testing and improvements to module design.
- Completed design, build, and testing of a 1200V, 400A full bridge module for Switched Reluctance machine applications. Two modules were delivered to the device bank.
- Completed design, build, and testing of a 1200V, 150A three phase module. Two modules were delivered to Device Bank.
- Completed design, build, and testing of 650V SiC full bridge rectifier module. Die from three PowerAmerica members were evaluated. Five modules were delivered to the Device Bank.
- Gate drivers for the 1200V/1700V, 400A three phase, 1200V, 475A 1/2 bridge were designed, built, and tested.
- NREL developed thermal/structural models and analyzed the packaging technologies. NREL completed thermal analysis, reliability analysis and structural analysis and testing, and determined that GE Power Overlay interconnect technology is more robust than traditional wire bond packaging.

Impact/Benefits

- Project will standardize module internals; driving up quantities and driving down cost.
- With limited module manufacturers in the U.S., the project's contribution to next generation technologies through a simplified manufacturing process will encourage new players to enter the market through licensing agreements, potentially creating more U.S. jobs in the module space.
- Project will deliver WBG modules to the PowerAmerica Device Bank, enabling academia to experiment and develop the next wave of advanced power electronics.
- Improved U.S. competitiveness through early adoption of delivered WBG modules and product support provided by the team.

GE Aviation Systems, LLC; GE Global Research, National Renewable Energy Laboratory, North Carolina State University

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- AEROSPACE
- HEAVY VEHICLES

TEXAS TECH UNIVERSITY

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PowerAmerica Roadmap Targets

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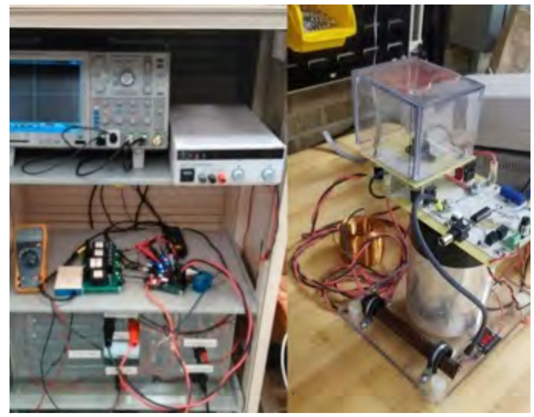
Texas Tech University: Establish an Independent Testing Facility to Perform Reliability Analysis of Wide Bandgap Semiconductor Devices



Left: High temperature testbeds. Right: Examples of testbeds to be implemented at the independent test facility.

Project Summary

The goal of this project is to establish an Independent Testing Facility that provides a full range of standard characterization and evaluation services for power semiconductor devices and modules, with a special focus on wide bandgap devices. The standard services that will be offered are: high temperature reverse bias (HTRB), high temperature gate bias (HTGB), high temperature operating life (HTOL), temperature humidity bias test (THBT), intermittent operating life (IOL), time dependent dielectric breakdown (TDDB), avalanche (for MOSFETs and diodes), surge, short circuit, di/dt, dv/dt, and continuous switching. The equipment installed in the testing facility is designed to test devices with blocking voltages up to 15kV. In addition, high-temperature testing can be conducted up to 200°C, and humidity testing can be completed at a humidity level ranging from 30% to 90% RH. In addition to the standard services, custom device testing may be provided. Test services can be provided to both device manufacturers and end-users. For example, manufacturers may use the independent test facility to complement gaps in their own in-house test capabilities, or to verify or corroborate their own test results. Device end-users may use the services to aid in determining the suitability of devices for specific applications. This project is intended to help increase overall confidence in the long-term reliability performance of wide bandgap devices and modules by providing independent services for device characterization, testing, and failure analysis.

Technology Gap/Market Need

There is not an independent power semiconductor device testing center available in the U.S. that specializes in wide bandgap technology. This project aims to fill that gap.

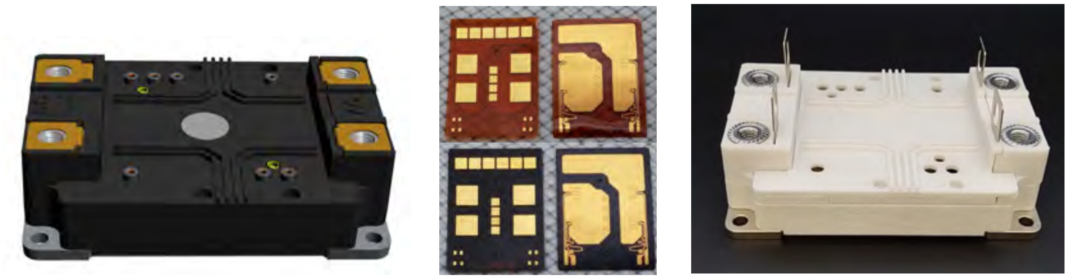
Accomplishments/Deliverables

At the end of BP4, significant progress was made at the testing facility on the high-temperature testbeds, as well as the short circuit, surge, and avalanche test boards. The remainder of the project was completed in BP5. In addition, device testing was completed on various 1.2kV and 3.3kV SiC MOSFETs and JBS diodes. Some of the tests that were completed are short circuit, avalanche, dv/dt, and surge.

Impact/Benefits

Reliability data can be invaluable to a manufacturer, in order to improve future generations of products and manufacturing techniques.

GE Aviation Systems: Design of High Performance HV Module



Left: 6.5kV ½ Bridge CAD model. Center: 5mil, 10mil Power Overlays. Right: 6.5kV ½ Bridge Packaging.

Project Summary

GE Aviation will develop a high performance 6.5kV ½ Bridge Silicon Carbide (SiC) power module. The design effort will establish a platform for low inductance packaging of multiple die complementary to wide bandgap (WBG) devices. This 6.5kV SiC MOSFET module development will serve to fill a “gap” in the PowerAmerica portfolio of funded projects which is very time-sensitive and required for all MV power conversion systems for grid tied systems, MV motor drives, naval and future aerospace systems.

This project addresses the PowerAmerica roadmap element FA 3.1a High Performance Power Module Packaging. GE will include our Power Overlay (POL) interconnect technology and advanced insulation materials which combined with suitable ceramic substrate and busbars will enable a high current density, low inductance module package suitable for high voltage applications.

Electric field analysis will be performed on the busbar structure and POL to substrate assembly early in the development. Partial discharge testing will be performed on mechanical samples of the module design to inform the final design. Partial discharge testing of the final module design will be performed with the objective outcome being a “PD free” module assembly. The HV module design will be similar to industry standard formats to allow direct comparison of switching performance. The module design provided under the project is scalable to higher currents and the ½ Bridge POL topology will enable the realization of ½ Bridge, Full Bridge and 3 Phase module designs within the same high voltage module package.

A team from NC State’s FREEDM Systems Center will provide gate drive hardware, double pulse and inverter level testing.

Technology Gap/Market Need

GE recognized that traditional wire bond interconnects need to be eliminated to reach the high frequency environment of WBG devices. GE also recognized that power modules that experience repetitive power cycling could see failures in the wire bonds, an issue that is well documented. Small chip size is also limiting higher current power modules. With these weaknesses in mind, GE has adopted Power Overlay interconnect technology shown above which replaces wire bonds with a planar copper interconnect layer. Through extensive qualification and 3rd Party analysis, the Power Overlay structure has shown to have an order of magnitude lower stresses in the Die Source/Gate metallization interconnect, therefore higher reliability than traditional wire bond modules.

Accomplishments/Deliverables

- Electrical design of the 6.5kV ½ Bridge module is complete.
- Completed the mechanical design based on industry standard package.
- E-Field and Q3D analysis for Power Overlay interconnect, MOSFET Die, AMB substrate, and busbar stacking is complete.
- Q3D analysis for Power Overlay interconnect, MOSFET Die, AMB substrate, and busbar stacking complete.
- Power Overlay design for 5mil and 10mil PI films is complete
- Power Overlay split fabrication with 5mil and 10mil PI films is complete.
- Gate Interconnect circuit board designed, and fabricated.
- 6.5kV ½ Bridge module assembly started.

Impact/Benefits

- Project will standardize module internals driving up quantities and driving down cost.
- With limited high voltage module manufacturers in the U.S., the project’s contribution to next gen technologies through a simplified manufacturing process will encourage new players to enter the market through licensing agreements potentially creating more U.S. jobs in the module space.
- Project will deliver high voltage WBG modules to the PowerAmerica Device Bank, enabling academia to experiment and develop the next wave of advanced power electronics.
- Improved US Competitiveness through early adoption of delivered WBG Modules and product support provided by the team.

GE Aviation Systems, LLC; GE Global Research, National Renewable Energy Laboratory, North Carolina State University

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PowerAmerica Roadmap Targets

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

Commercial Applications

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

The Ohio State University: Artificial Intelligence-Based Current Sharing for Parallel Operation of 3.3kV Silicon Carbide MOSFET Chips in Power Module

THE OHIO STATE UNIVERSITY

Center for High Performance Power Electronics at The Ohio State University

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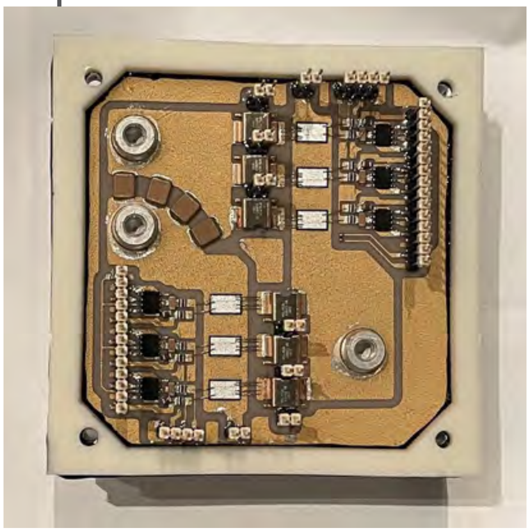
PowerAmerica Roadmap Targets

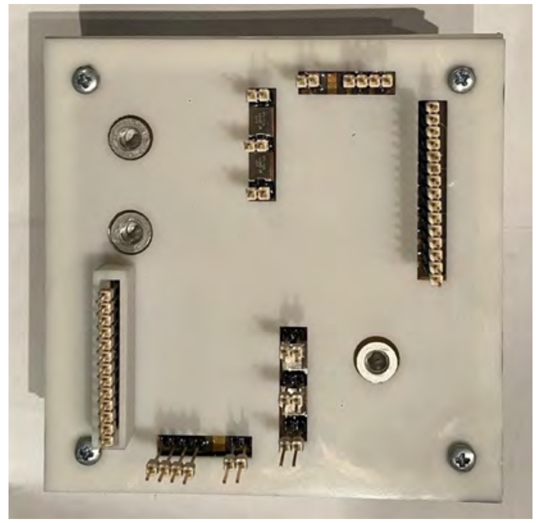
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

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



3.3kV SiC MOSFET module with current/voltage/temperature measurement for individual parallel chips integrated.



Finished power module with case installed.

Project Summary

The objective of this research is to apply artificial intelligence techniques on the next generation of wide band gap (WBG) power electronic devices to achieve even current sharing of parallel chips. The purpose is to achieve higher reliability, longer operational lifetime of the power semiconductors, and system efficiency optimization. This research focuses on high power application. Therefore, we will use SiC-based WBG semiconductors in our analysis, design, prototypes and controls. This PowerAmerica Open Innovation project uses 3.3kV SiC bare die to design and build power modules, which are a better representation of high power SiC modules. The design of the power module integrates current and temperature measurement and adjustable gate drive voltage for individual parallel chips.

Technology Gap/Market Need

The uneven distribution of important device parameters, from the same or different vendors, present unique challenges in module design when many devices are combined in parallel. These parameters may include short circuit times, threshold voltage and body diode degradation across SiC devices, as well as different temporal behavior based on device history. Initially devices are matched with respect to threshold voltage and on-resistance to promote current sharing. However, depending on the stress history of each device, these parameters drift with time, resulting in uneven current sharing. As one device carries more current than the others, it will heat up, which further reduces the threshold voltage and on-resistance due to an increase in inversion layer electron mobility with increase in temperature. This is generally a runaway situation which needs to be checked appropriately. This project explores advanced packaging technology for SiC MOSFET power modules and controls to achieve even current sharing between parallel chips.
This project uses individual gate control for each device in a module to maintain current sharing. AI algorithms can be integrated in the future to account for the asymmetric characteristics of individual chips and different stress histories of individual chips.

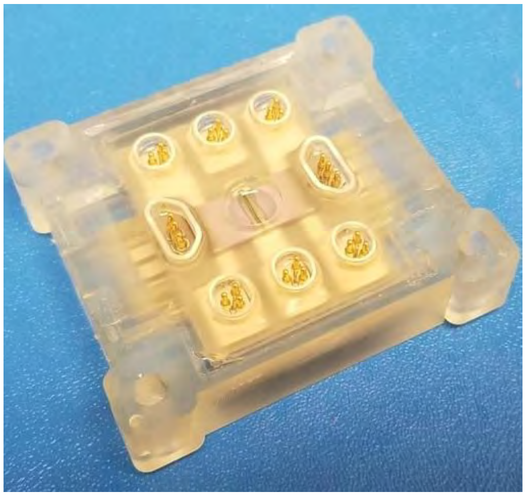
Accomplishments/Deliverables

- Designed a 3.3kV SiC MOSFET power module that has multiple chips in parallel. The power module integrated the current, voltage, temperature measurement for individual chips inside.
- Appropriate current, voltage and temperature sensors were selected.
- Power module parasitic parameters were simulated using a finite element analysis tool to guide the power module design.
- The gate drive design for this power module enables various levels of gate drive output voltages for individual parallel chips.
- Power module packaging has been completed.

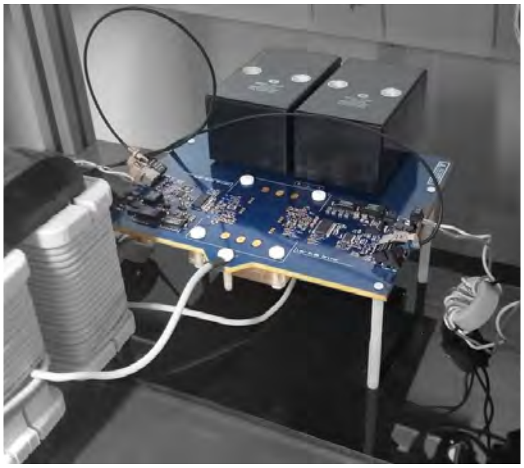
Impact/Benefits

This project helps enhance the performance of power modules by actively balancing the current and thermal stress of individual parallel power semiconductor chips, and improving the reliability and lifetime of power modules. If successful, this will help accelerate the adoption of next generation wide bandgap power electronics in commercial power electronic converter products.

Virginia Tech: Prototyping and Evaluation of High-Speed 10kV SiC MOSFET Power Modules with High Scalability and System-Integration Solutions



10kV SiC MOSFET half-bridge power module (69mm x 62mm x 16mm).



PCB-integrated bus bar and gate driver for 10kV SiC MOSFET half-bridge module, with high-speed short circuit and overload protection.

Project Summary

A high-density package for 10kV silicon carbide (SiC) power MOSFETs has been proposed that achieves low and balanced parasitic inductances, resulting in a high switching speed of 140V/ns at 6kV with negligible voltage overshoot. The scalability, system integration, and reliability of the proposed 10kV SiC power module is evaluated and verified. A system-module interface is proposed to reduce the inherent trade-off between high voltage and high density. The interface utilizes PCB embedded guard rings around enclosed spring-pin terminals to achieve a voltage scalable, compact interface between the module, the gate driver, and the bus bar. Partial discharge testing is conducted to verify insulation performance, and switching tests are used to verify module operation. Thermal cycling is performed on the module multi-layer substrates, which are bonded using low-pressure silver sintering.

Technology Gap/Market Need

Wide bandgap (WBG) power devices with voltage ratings exceeding 10kV have the potential to revolutionize medium- and high-voltage systems due to their high-speed switching and lower on-state losses. However, present power module packages are limiting the performance of these unique switches. Asymmetric device layout and bulky system interfaces cause high commutation inductance, limiting switching speed and increasing state loss. Conventional manufacturing techniques and materials limit operating temperatures and have high thermal resistance, throttling current ratings. The proposed package seeks to mitigate these issues by employing silver sintering processes and package topologies, married with a laminate bus bar and integrated gate driver to achieve higher operating temperatures, improved reliability, higher power density, and streamlined integration.

Accomplishments/Deliverables

A 2-die SiC MOSFET half-bridge power module was constructed which demonstrated a reverse leakage current of 30nA at 9.5kV Vds. Thermal cycling tests from -40°C to 200°C were carried out on Ag sintered multilayer DBA substrates. Cross-sections were cut and imaged after 300, 400, and 500 cycles to monitor the sintered silver bond. No failures were observed after 500 thermal cycles. A laminated PCB bus bar with integrated gate drivers and embedded field grading structures was designed and experimentally demonstrated a partial discharge inception voltage of 11.6kV rms under 60Hz sinusoidal excitation.

Impact/Benefits

This work seeks to reduce the tradeoff between power density and high voltage. The compact interface, large-area silver sintering, and wire-bond-less and current-scalable module layout provide high voltage operation and high density formfactor without compromising long term reliability, isolation strength, or device performance. The proposed system is scalable for both voltage and current rating, and demonstrates techniques that are viable for reducing module and converter footprints – a need which is present in a wide range of aerospace, military, and consumer applications.

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The National Renewable Energy Lab (NREL)
Wolfspeed

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PowerAmerica Roadmap Targets

- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

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

Virginia Tech: Surge Energy Robustness of GaN Power Devices and Modules: Application-Driven Evaluation and Physics-of-Failure Modeling

Virginia Tech
Lockheed Martin

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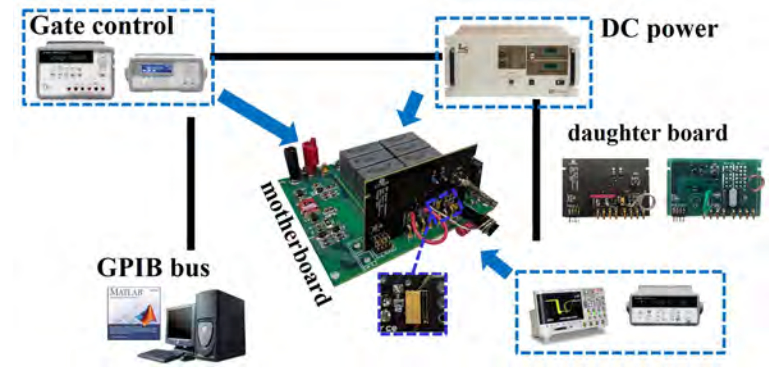
PowerAmerica Roadmap Targets

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

Commercial Applications

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



Surge-energy robustness characterization platform for multiple types of GaN power devices.

Project Summary

This project aims to evaluate the surge energy robustness of commercial GaN power transistors and modules, through a combination of experimental characterization, failure analysis, and physics-based modeling. The outcomes of this project include: (a) understanding how the GaN power transistor, a device without avalanche capability, withstands the surge energy, as well as the key determining factors for the withstand capability under single event and repetitive stress tests; (b) unbiased evaluation of surge-energy robustness of commercial GaN devices based on different enhancement-mode (E-mode) technologies; (c) evaluation of surge energy robustness of GaN devices under surge energy switching events based on an aerospace application-specific mission profile; (d) evaluation of surge energy robustness of GaN modules comprising GaN devices, integrated gate drivers and protection circuitry. The test platform developed in this project will be made available to all PowerAmerica members.

Technology Gap/Market Need

A key challenge for the market insertion of GaN power devices has been their reliability and robustness. The qualification of GaN transistors cannot solely rely on established reliability procedures for Si devices but must take into consideration the device withstand capability of abnormal events out of SOA (safe operating area) conditions. An essential withstand capability for power devices is the ruggedness to safely dissipate/withstand surge energy, which is desired in many power electronics applications, including aerospace, vehicle electrification, power grids, etc.

The surge energy withstand capability of Si and SiC MOSFET relies on their intrinsic avalanche capability. However, the surge-energy withstand mechanisms of GaN HEMTs remains unclear, as they don't have avalanche capabilities and the withstand mechanisms may vary among different device types.

The results from this project are expected to provide key understanding and momentum for the market adoption of GaN power devices and modules and pave the way to develop intelligent control and condition monitoring for GaN devices in applications that demand stressful operating conditions.

Accomplishments/Deliverables

The first deliverable of this project is a unified test platform to characterize the surge energy robustness (single event, and repetitive) for various GaN power devices. The set-up comprises a universal motherboard with multiple daughter boards that accommodate at least three mainstream commercial enhancement-mode GaN devices. The test platform allows the surge energy robustness tests at different temperatures.

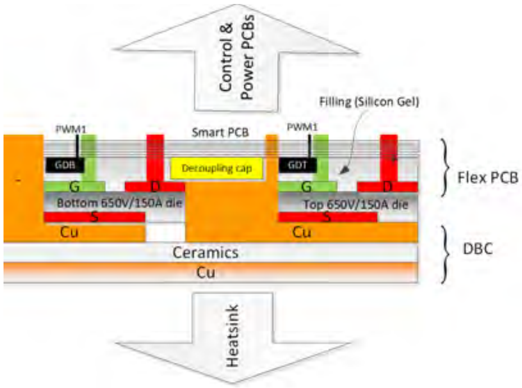
The second deliverable of this project includes comprehensive reports on the surge-energy withstand capabilities of various commercial GaN devices and modules under single-event, repetitive-event, and mission-profile tests. Physics of degradation and failure models will be developed and reported for each type of GaN device.

Developed models will be incorporated into technical reports, and all design files for the universal test platform will be made available for all PowerAmerica members.

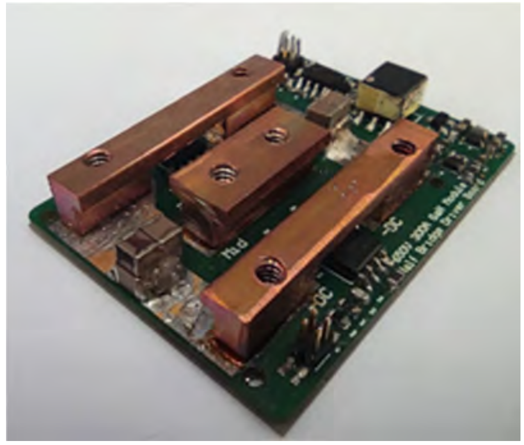
Impact/Benefits

The above deliverables will bring significant value to advance PowerAmerica's technical roadmaps. Besides providing a GaN device robustness characterization platform for all PowerAmerica members, the results from this project are expected to provide key understanding for the application of GaN power devices and pave the way to develop intelligent control and condition monitoring for GaN devices in aerospace, vehicle electrification, and other applications. The knowledge gained from this project would not only be important for power electronics application members, but also for device manufacturers to optimize the design of GaN transistors and modules to boost their surge-energy robustness.

University of Tennessee: Packaging A Top-cooled 650V/>150A GaN Power Module with Insulated Thermal Pads and Gate-Drive Circuit



Conceptual design of the GaN power module.



The finalized GaN power module.

Project Summary

The proposing team designed a 650V/>150A GaN power module using dies from GaN Systems. Direct Bonded Copper (DBC) is employed for the thermal pad insulation and the smart PCB is adopted for the flux cancellation and gate-drive-circuit integration. The project provides the highest current rated GaN half-bridge power modules by the project completion date, with high compactness (45*33*9.6mm3) and low thermal impedance (~0.4°C/W per die). It is the first known attempt to package the gate driver, auxiliary power supply, GaN die and DBC together to reach high voltage and high current capability. The proposed module can be implemented for immediate use in the 22kW EV on-board charger with Hella and 100kW six-phase inverter.

Technology Gap/Market Need

Present GaN devices, though showing superior switching performance over Si devices, have much lower current ratings, e.g., ~60A. High current applications then require multiple GaN HEMTs in parallel, which creates challenges for circuit layout aimed at current balancing. Meanwhile GaN HEMTs face more thermal challenges due to their much smaller footprint than Si/SiC MOSFETs, which becomes even worse when a thermal interface material is inserted between the heatsink and device.

With the proposed fully integrated GaN power module, >150A current capability and low thermal impedance are both achieved, without an extra gate-drive board needed and securing both high power density and high reliability. This facilitates the usage of GaN and opens the door for the high-power applications, for instance, 22kW EV on-board charger and 100kW EV inverter.

Accomplishments/Deliverables

The project deliverables include: 1) Mechanical design of packaged GaN modules; 2) Schematics and layout of the smart and flex PCB; 3) Test waveform and report for the packaged module; and 4) A graduate-level packaging course. Throughout the project, the UTK team also generated two papers and disclosed one potential patent to UT Tech Transfer.

Impact/Benefits

By the project completion date, the 650V/>150A power module is the highest power rated design with bus bars, decoupling caps, gate-drive circuit, dies and DBC integrated together. It expedites the applications of GaN HEMTs in the electric vehicle industry, particularly in EV chargers and motor drive inverters. The project engages industrial members (GaN Systems, HELLA and GM), three UTK graduates and two undergraduates, enhancing the power electronics pipeline for EV manufacturers and leveraging the DOE WBG Traineeship at UTK.

THE UNIVERSITY OF TENNESSEE KNOXVILLE

GM

HELLA

GaN Systems

University of Tennessee, Knoxville;
General Motors,
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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

Commercial Applications

HYBRID/ELECTRIC VEHICLES

INDUSTRIAL MOTOR DRIVES

ELECTRIC POWER GRID

John Deere: 200kW 1050V DC Bus SiC Inverter/Converter and 5kW 350VDC/56VDC SiC/GaN DC/DC Converter System for Heavy-Duty Electric Vehicles

JOHN DEERE

John Deere Electronic Solutions, Inc.
National Renewable Energy Laboratory

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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 Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- POWER QUALITY
- ELECTRIC POWER GRID
- MILITARY
- HEAVY VEHICLES

Project Summary

This project resulted in the design, development, fabrication, vehicular deployment and testing of WBG power electronics systems for all-electric vehicles. During BP1-BP4, JDES and DOE-National Renewable Energy Laboratory (NREL) have teamed-up in the successful development, manufacturing, and in-vehicle (JD 644K WBG Loader) demonstration of a power-dense high-temperature energy-efficient 200 kW 1050V DC bus SiC inverter. In BP5, JDES has exploited the expertise gained and facilities developed during the past four years to execute key technology and manufacturing innovations. This effort resulted in three enabling WBG technologies for all-electric vehicles. These technologies are:

(a) SiC MOSFET-based three-phase inverter to drive permanent-magnet-alternating-current (PMAC) traction motor,

(b) SiC MOSFET-based three-phase buck-boost non-isolated DC/DC converter to interface the battery-pack with the three-phase SiC inverter, and

(c) three-phase dual-active-bridge (DAB)-based isolated DC/DC converter to supplement electronic/electrical loads otherwise supplied by the vehicle alternator when the vehicle uses the inefficient diesel engine.

These three technologies will eventually be utilized in the system-level integration and demonstration of a prototype test platform of an all-electric vehicle.

Alternator replacement and near-maximum-temperature (with power devices' junction close to 175°C and coolant close to 105°C) operation of energy-efficient SiC/GaN converters resulted in a vehicle platform which can use a downsized cooling-pack. Therefore, the resulting vehicle platform will offer the necessary value proposition for WBG power electronics. Despite significant design, development, and vehicle testing since Feb 2015, JDES's SiC inverter technology continues to miss the commercialization cost target. However, adding key features could allow JDES to achieve commercialization-cost-targets in a unique and early adopter application that is only possible with and enabled by the WBG power electronics. Some of the future applications of the WBG power electronics include all-electric vehicles required in underground mining, poultry-farming and agricultural operations.

Technology Gap/Market Need

First, the project was a direct application demonstration of potential WBG system cost advantages. This includes the downsizing of a cooling-pack in battery power vehicles utilizing the increased efficiency of WBG power converters. Second, the project supports training and workforce development of WBG technologies and applications. Finally, the project supports U.S.-based design and manufacturing of WBG systems.

Accomplishments/Deliverables

The key accomplishment achieved during the project was the simulation, manufacture, and hardware demonstration in the JDES laboratory of an energy-storage assisted heavy-duty load profile and testing of 200kW 1050V SiC inverter under 55°C ambient with 115°C water-ethylene glycol (WEG) coolant without the need to de-rate the inverter for continuous operation at 150kW.

A 350V to 500V-1100V non-isolated DC/DC SiC converter was fabricated and tested at 100kW bidirectional power flow between 350V energy storage device and 1050V nominal DC bus of 200kW SiC inverter.

A 350V to 56V isolated three-phase SiC/GaN bidirectional DC/DC converter was designed, fabricated, and tested up to 3kW power flow at 350V (high-voltage side) to 50V (touch-safe isolated side).

NREL has provided engineering support in thermomechanical stress simulation of a 1700V 250A six-pack SiC power module sourced from GE Aviation Systems.

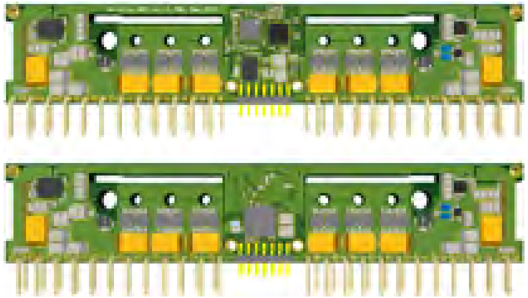
Impact/Benefits

Three WBG technologies developed and converter fabricated. These will be used by John Deere in product development programs:

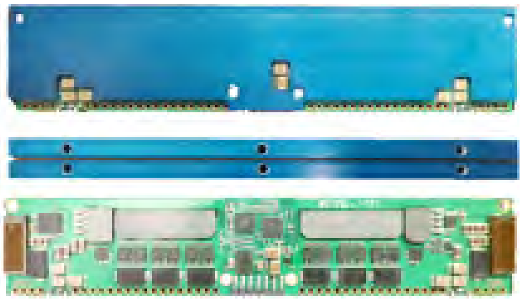
- 200kW, 1050V SiC inverter
- 200kW, 350V to 500V-1100V non-isolated bidirectional SiC DC/DC converter
- 15kW rated 350V to 56V isolated SiC/GaN DC/DC converter

The know-how produced on converter design, 1 MHz BW current sensor (used in isolated SiC/GaN DC/DC converter), and magnetics design (packaging, thermal management and integration in both DC/DC converters) will greatly support the John Deere electrification program underway for vehicles that may go into production in a few years. Therefore, this PowerAmerica project significantly helped John Deere with its technology advancement.

ABB: High Power Density, High Efficiency, and Wide Range GaN-based 48V-1V, 300A Single-Stage LLC Converter



3D sketch.



Prototype.

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Virginia Tech University

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

UPS
DATA CENTER

Project Summary

The project is to develop and demonstrate an efficient GaN-based single-stage 48-1V point of load (POL) converter that occupies less than half the board space occupied by equivalent solutions today. The POL input voltage ranges from 40-60V and output ranges from 1.5-2V with 200A /400pk output current. The target peak efficiency is 95%, the max power density is 1kW/in3, and it provides 1kA/us fast transient response.

Technology Gap/Market Need

The project demonstrates the single-stage 48-1V POL architecture enabled by the Sigma topology and GaN devices. The single-stage solution addresses the continuous demand of higher efficiency and higher power density for POL. The project will deliver the knowledge of circuit design and implementation with GaN devices. This will give a jump-start for the silicon device user to shift to GaN devices. Therefore, these measures will promote and expedite the adoption of GaN devices in data center applications.

Accomplishments/Deliverables

In this project, we have achieved

- GaN device selection was completed, and EPC2002 100V GaN HEMTs are used
- Vertical mounting POL hardware has been developed and verified with closed loop control up to full power testing
- Peak efficiency of 92.2% and power density of 340W/in3 was achieved
- Thermal system design was completed and verified

Impact/Benefits

- Economic impact – if successful, this technology will lead to a multi-million annual dollar business for the GaN device manufacturers alone
- Potential for job creation – through increased investments in data center infrastructure and equipment manufacturers
- Workforce Development and Education – VA Tech helped develop the magnetics design in this project, and we have weekly discussions on the project results and technical issues
- Improved US Competitiveness – Use of GaN devices made by PowerAmerica members; concept will have deep impact on POLs for super computers and data centers.

TOSHIBA

THE OHIO STATE UNIVERSITY

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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

- INDUSTRIAL MOTOR DRIVES

Toshiba: Commercialization of 1MW SiC-Device Based High Speed Medium Voltage Motor Drive with Redundant Operation

Project Summary

The objective of the project is to solve three major technical challenges that are very critical for commercialization and industrialization of the wide bandgap semiconductor-based 1MW SiC Medium Voltage Drive (MVD) with the Modular Multi-level Converter (MMC) topology:

1) Fault-tolerant Operation. There are 72 submodules in a 1MW SiC-based MVD. Fault-tolerant operation means if one or more of the 72 submodules experience a failure during operation, the SiC-based MVD system is capable of isolating the malfunctioning submodule and continuing operation with a reduced number of submodules within 1.5 seconds. This is a dramatic improvement in reliability and will also reduce maintenance costs.

2) High-Speed Operation. The SiC-based MVD system is capable of operating with more than 800Hz output frequency, which is higher than any commercial MVD system in the market.

3) Filter-less long-cable operation. In oil and gas applications, the cable that connects a MVD with a motor can be longer than one mile. This project aims to create a filter-less long-cable operation system capable of operating a medium voltage motor with a one mile cable without an additional filter. The benefit of this feature will be in a tremendous reduction in the cost of a MVD system for long-cable application.

Technology Gap/Market Need

Conventional MVD systems in the market have three drawbacks: 1) failure of a power module usually means days of operational gap while it is replaced, which leads to economic losses and risks in critical applications; 2) the output frequency of conventional MVD usually is 50/60Hz. But potential customers are driving the high-speed (>300Hz) requirement in the applications of electrical submersible pumps; 3) conventional MVD systems need additional filters for mitigating the voltage spark problem in long-cable applications. And the high dv/dt of switching devices also brings challenges in the insulation of both cables and motor windings.

The SiC-based Medium Voltage Drive (MVD) designed and built in this project solved the above three critical challenges: 1) the redundancy control allows isolating malfunctioning power modules and continuing operation with reduced number of power modules within 1.5 seconds, which would dramatically increase the reliability of the MVD system and reduce the cost and risk on operations and maintenance; 2) the output frequency can be more than 800Hz, which is sufficient to meet any high speed requirements in the market; 3) the SiC MVD system doesn't need additional filters for long-cable applications, which reduced the cost of MVD system.

The 1MW SiC-Device Based High Speed MV Motor Drive.

Accomplishments/Deliverables

At the end of this project, the accomplishments include: The first commercial level 1 megawatt full wide bandgap semiconductor-based active-front-end 4.16kV Medium Voltage Motor Drive (MVD) System in the United States with three critical functions: 1) Fault-tolerance operation, 2) High-speed operation, 3) filter-less long-cable operation. The efficiency of this wide-bandgap semiconductor based MVD system is more than 99%, and the weight has been reduced almost 50% compared with conventional MVD systems.

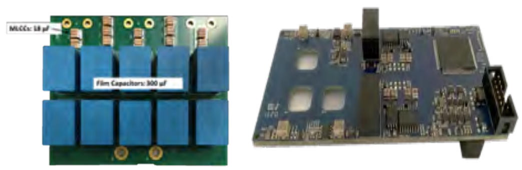
Impact/Benefits

The wide bandgap semiconductor-based Medium Voltage Drive (MVD) designed and built in this project brings together multiple facets of the wide bandgap supply chain and plays a key role in the U.S. advanced manufacturing workforce. It is the world's first 1 megawatt 4.16kV active-front-end MVD utilizing full wide bandgap power semiconductor. The output frequency can be more than 800Hz, which is higher than any other commercial 4.16kV MVD systems in the market. The fault-tolerant operation and filter-less long-cable operation function dramatically increased reliability and reduced cost. The technology and product in this project enhance the leading position of the United States in the power and energy industry, and serves as a milestone for future generations of wide bandgap semiconductor-based power electronics products and systems in U.S. industry.

Toshiba International Corporation is committed to manufacturing and increasing employment in the U.S. The new SiC MVD products with the proposed revolutionary new technology, manufactured in U.S., will ensure a bright future for our suppliers, our customers and the United States. The mass production of the new SiC MVD product will contribute to the boosting of the United States economy and the boosting of the share of U.S.-manufactured products in the global market.

Virginia Tech: 100kW SiC-based Generator Rectifier Unit for Variable Frequency Airborne Applications

View of the 100kW 600 V GRU: (left) GRU enclosure; (right) internal view depicting cold-plate, SiC modules, gate-drive, PCB-based DC-bus.



Left: View of the high-current PCB-based distributed capacitor array DC-bus. Right: Enhanced gate-driver for 1.2kV SiC MOSFET module with integrated Rogowski-coil based current

Project Summary

This project was formulated to develop a full SiC-based Generator Rectifier Unit (GRU) rated at 100kW, 600V DC, 200V rms line-to-neutral, and 400–900Hz, achieving a peak efficiency of 99%, a power density of 120W/in^3, operating at a junction temperature of 200°C, qualified for altitudes of up to 50,000 ft, with the intent of comparing the design against a state-of-the-art IGBT-based 85kW GRU.

Technology Gap/Market Need

Commercial GRUs are presently implemented with Si devices, typically 1.2kV IGBT power modules, that limit efficiency to 96–97% and power density to 50–80 W/in3. The switching frequency used in commercial GRUs is accordingly in the 10–20kHz range due to the inherent limitation of IGBT devices, imposing a hard limit on the generator rotational speed as well as on the energy storage requirements on the DC bus. The regulation bandwidth of the latter, and hence the GRU output impedance, are likewise limited. Lastly, Si IGBTs operate typically with junction temperatures (Tj) of 125°C (Tj max = 150 °C), imposing another critical barrier for aircraft applications where the refrigerants used for power electronics cooling systems vary from 70–90°C leaving a narrow operational margin. In consequence, GRUs rated at >50 kW must parallel Si IGBT modules in achievable power density.
Further, although third-generation SiC MOSFET devices inherently solve many of the limitations imposed by Si IGBTs, there are no commercial SiC MOSFET modules that can change the design paradigm. GE Aviation's devices have such capability, as they are the only SiC MOSFETs rated for operation with Tj = 200°C, featuring ultra-low parasitic loop inductance and compact packages, which have also been recently qualified to operate at altitudes of up to 50,000 ft (air pressure = 86 Torr). These modules have been used in the development of the SiC-based GRU fully utilizing the capability of these semiconductors, enabling the operation at 100kW with peak efficiency exceeding 99%, and simplifying the circuit topology of the GRU to be a simple two-level inverter without the need to force-parallel or interleaved multiple power modules.

Accomplishments/Deliverables

- Developed a gate-drive for 1.2kV SiC MOSFET module with integrated Rogowski-coil current sensor qualified for an altitude of 50,000 ft
- Qualified a 1.2kV SiC MOSFET module for an altitude of 50,000 ft
- Developed a PCB-based common-mode (CM) choke qualified for an altitude of 50,000 ft
- Demonstrated a 100kW, 540V DC, three-phase GRU using a single two-level voltage-source inverter bridge achieving efficiency of 99 %

Impact/Benefits

A key contribution of this project has been the development of power electronics components qualified to operate at 50,000 ft, including the SiC MOSFET power module, gate-drivers, PCB-based planar DC-bus, and CM EMI filter. This was accomplished by carrying out an electric field-oriented design of all components, relying on finite-element analysis to predict their field distribution within and without their bodies. In addition, partial-discharge and breakdown tests conducted in a high-altitude chamber were used to verify this capability.

Another advancement has been the utilization of the first SiC MOSFET devices rated for a junction temperature of 200 °C, which in addition, profit from the SiC-optimized package from GE Aviation using their power-overlay technology. The use of these devices allowed for the designers to opt for the simplest possible three-phase converter topology, i.e., a two-level voltage-source inverter, eliminating the need to force-parallel or interleave multiple SiC modules to achieve the target 100 kW rating. This feature improves reliability, which is crucial for aerospace applications, as well as power density, and specific power. In all, it demonstrate and embodies the substantial advantages of adopting wide bandgap semiconductor technology for these types of applications.

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PowerAmerica Roadmap Targets

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

Commercial Applications

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

North Carolina State University: Shore-to-Ship MV SiC Converter System: Application of Medium Voltage Asynchronous Micro-grid Power Conditioning System

North Carolina State University

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PowerAmerica Roadmap Targets

- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

Commercial Applications

- POWER QUALITY
- ELECTRIC POWER GRID
- OTHER (HIGH VOLTAGE DC/DC CONVERTERS)

Project Summary

A 3.3kV SiC MOSFET based Shore-to-Ship power system topology has been evaluated for achieving improved efficiency and power density compared to similarly rated commercially available Shore-to-Ship system solutions. A 100kVA three-phase two-level voltage source converter laboratory prototype enabled by three series-connected 3.3kV SiC MOSFETs per switch has been designed and fabricated. This is a building block of the back to back converter-based Shore-to-Ship system. A methodology for design of medium voltage gate drivers for successful series connection of 3.3kV SiC MOSFETs has been explored.

Technology Gap/Market Need

This project addresses the white space of 2-7MVA shore-to-ship power conditioning systems with a 3.3kV SiC MOSFET based air-cooled system with asynchronous high voltage shore connection capability. In this white space of 2-7MVA, parallel connection of 2MVA Si-IGBT PCS will require bulky/custom transformers; and downscaling & operating higher power (>7.5 MVA) Si-IGCT PCS is inefficient. Demonstration of a series connection of 3.3kV SiC MOSFETs will open the possibility for operation with higher DC voltages and, therefore, transformer-less solutions from 4.16-11kV AC output.

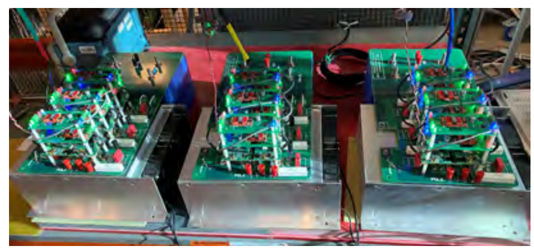
Accomplishments/Deliverables

- Medium voltage gate drivers for series connection of 3.3kV SiC MOSFETs have been designed and validated in the converter
- Static and dynamic voltage balancing of series-connected 3.3kV SiC MOSFETs has been analyzed on SaberRD® and validated experimentally
- A 100kVA Three-phase Two-level Voltage source converter laboratory prototype enabled by three series-connected 3.3kV SiC MOSFETs per switch has been designed and fabricated

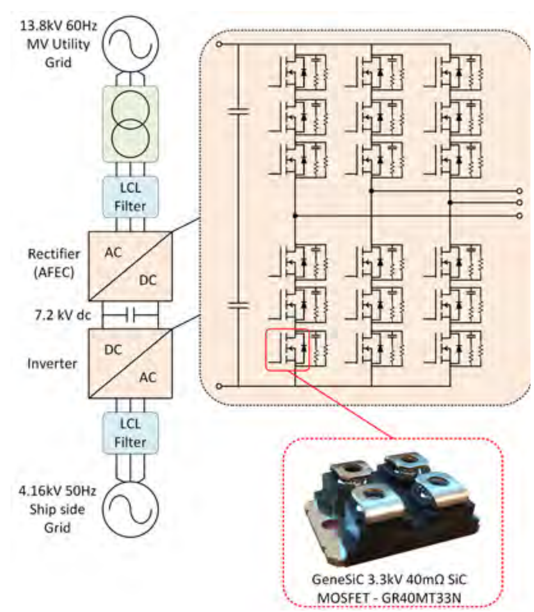
Impact/Benefits

The utilization of high efficiency, high power density MV SiC series-connected converters tapping directly to the MV feeders will bring significant benefits to ports around the world for real estate utilization and total cost of ownership (TCO). This electrification approach will also significantly reduce global greenhouse gases and noise pollution due to diesel engines and generators at ports worldwide.

The MV SiC solution is a more cost-effective approach, even considering the higher cost of SiC converter units. Although SiC devices are more expensive, the semiconductor devices typically represent less than 15% of the cost of the overall MV power converter system.



Proposed 3.3kV SiC MOSFET based Shore-to-Ship power system.



3-phase 2-Level Converter with Three series connected 3.3kV SiC MOSFETs per switch.

Raytheon: High Efficiency Multiport Power Conversion for a Hybrid-Electric Propulsion System

Project Summary

This project focused on accelerating wide bandgap (WBG) adoption in state-of-the-art aerospace applications. The project developed a high efficiency WBG-based modular multiport converter unit to interface simultaneously with a 15kW 350V variable frequency aircraft generator emulator, a 7kW 350V Auxiliary Power Unit (APU) emulator, and a 15kW 270V Lithium-Ion battery, and create a 540 DC output port with a midpoint grounded terminal. This highly efficient and flexible design provides self-starting features for generators and back up and peak power from the battery during sudden load changes.

Technology Gap/Market Need

This project is strongly focused on aerospace applications - More Electric Aircraft (MEA) and All Electric Aircraft (AEA) with broad usage of electric equipment in the place of hydraulic systems for actuation, motion and energy transfer. There is a technology gap in the aerospace power distribution space in interconnecting and managing power flow between variable frequency AC sources, DC loads and DC energy storage elements. This project aims to fill that gap by developing a power dense architecture based on WBG devices. The project also has power density and cooling requirements much higher than the current aerospace industry standard to push the state of the art.

Accomplishments/Deliverables

The team designed a Modular Multi-Port Converter (MPC) built around a three phase three level T-type AC/DC converter as a Basic Building Block (BBB). The BBB hardware (Figure 1) has 122W/in3 of power density, and the BBB converter can be software reconfigured to function as an AC-DC converter or a DC-DC converter. The MPC in this project consists of three BBB converters, two interfacing AC Generators at 15kW and 7.5kW and the third connected to a DC supply at 15kW emulating a battery or a supercapacitor.

Each BBB converter consists of a power board, gate drive board and control board. The power board consists of a single side insulated metallic substrate (IMS) printed circuit board (PCB) to enhance heat dissipation and increase power density. Four copper layers were printed on the PCBs rather than the conventional one or two layers to help minimize parasitic inductances of commutation paths during fast switching transients of the WBG MOSFET devices. Simulation and parameter extraction of commutation loops show loop inductance between 3 nH – 6 nH. The gate driver board includes the MOSFET gate-source drive logic along with AC, DC voltage sense and AC current sense logic. The AC voltage sense logic was based on high impedance grounding which introduced common mode noise, predominantly the third harmonic in line voltages. To eliminate distortion in the AC voltage sense, external voltage sensors with true galvanic isolation were added and AC-DC converter performance was verified with DC bus voltage control and closed loop AC current control. The control board was built around the Texas Instruments (TI) TMDSCNCD28379D controlCARD which includes the TI F28379D microcontroller. The control board includes high speed analog and digital signal logic to convert signal levels between the TI controlCARD and the gate driver board.
The BBB converter was operated as a bidirectional AC-DC converter and was tested with 60Hz grid and a programmable AC power supply. The BBB converter was also operated as a bidirectional buck-boost DC-DC three phase interleaved converter with a software configuration. The DC-DC converter operation was tested by interfacing the low voltage DC source with the high voltage resistive load. The BBB converter met the target volumetric, weight and power density requirements. Total Harmonic distortion (THD) in the AC current in AC-DC mode was around 3%. The converter also met efficiency requirements and thermal/loading requirements. Reduced level system testing was also done with one DC-DC converter and AC-DC converter.

Impact/Benefits

The MPC developed in this project is an enabling technology for More Electric Aircraft (MEA) and All Electric Aircraft (AEA). It will also meet converter specifications for next generation aircraft with a DC bus voltage of ±270V (540V on the DC link). The developed technology is broadly applicable for a wide range of industrial applications particularly for power below 20kW. The converter power structure is built with surface mount devices directly on printed circuit boards for simple packaging, manufacturing reasons and reduced cost.

Basic building block (BBB) of the multiport power converter (MPC). From top: Control board, Gate driver board, Power board.

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

RENEWABLE ENERGY

POWER QUALITY

UPS DATA CENTER

ELECTRIC POWER GRID

AEROSPACE

Virginia Tech: High Density Bidirectional SiC/GaN based Soft-switched DC-DC Charger for Hybrid Electric Propulsion System

Virginia Tech
United Technologies Research Center

Virginia Tech
United Technologies
Research Center

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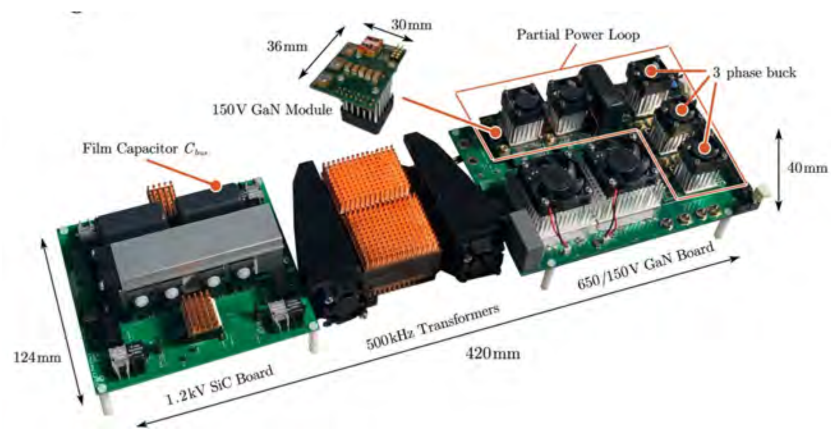
PowerAmerica Roadmap Targets

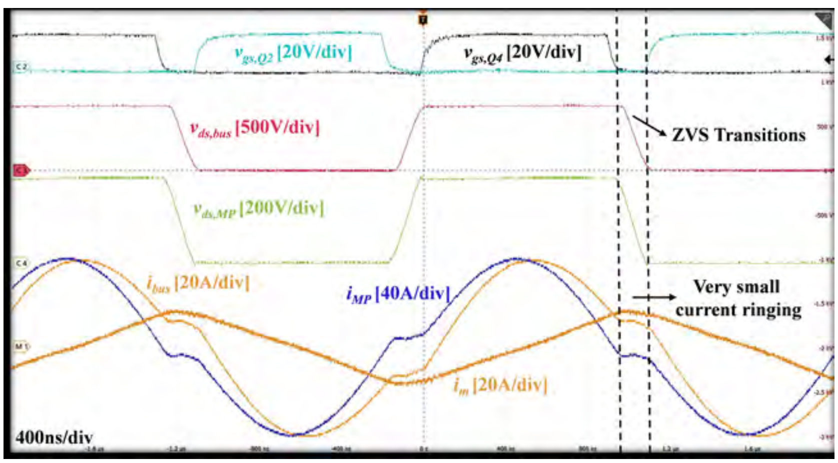
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- AEROSPACE



18kW (23kW peak) bi-directional battery charger prototype with 500kHz planar transformer.



Steady-state waveforms of the transformer current at 18kW.

Project Summary

The project demonstrated a high-density (150 kW/in3 peak power density), high-efficiency (98.8% peak efficiency) and high performance isolated bi-directional charger system with 23kW peak power. The innovative technologies demonstrated include partial power processing solution and 500kHz transformer with intra-winding configurations. The project not only demonstrated the circuit function but also passed the rigorous thermal evaluations. The technology can be applied to multiple applications, including onboard battery charger, stationary energy storage interface, solar DC optimizer, and DC distribution transformers.

Technology Gap/Market Need

The high-efficiency and small footprint solution is always desired for onboard and offboard energy storage applications. The bulkiest component is the galvanic transformer. Pushing for higher operational frequency of the transformer is always desired. However, the existing high-frequency planar type transformer is still very large and there is no commercial 500kHz high power transformer yet. The existing bi-directional charger system needs a two-stage solution to regulate battery voltage, which, however, leads to larger size, lower efficiency, and higher EMI emissions.

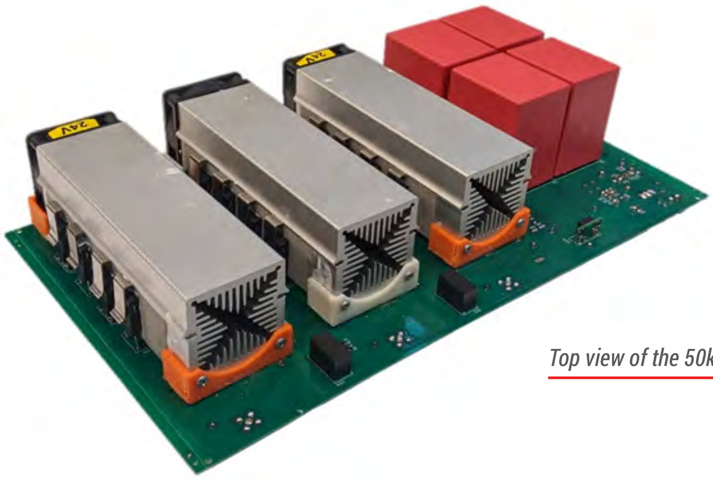
Accomplishments/Deliverables

500 kHz 18 kW planar transformer and its design solutions.
Modeling and design guidelines of the bi-directional CLLC resonant converter for best efficiency.
Full converter prototype that delivers 23 kW peak power.

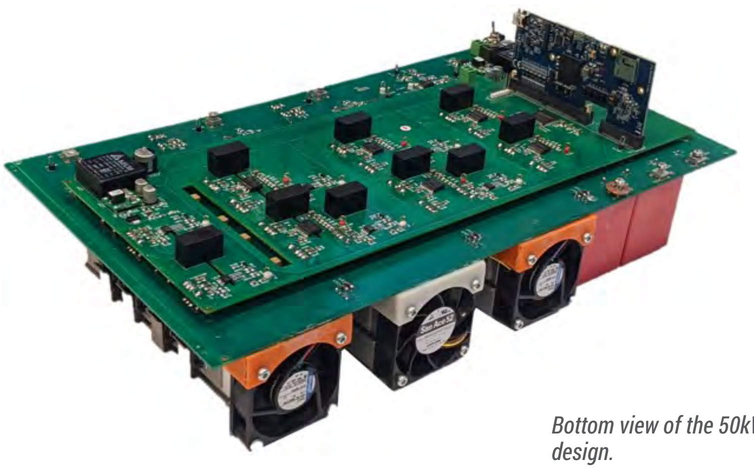
Impact/Benefits

The latest 1.2kV, 650V, and 150V rated SiC and GaN devices are utilized in the solution to achieve the best efficiency and power density. The solution will accelerate the adoption of WBG devices in transportation and energy storage applications.

North Carolina State University: High Efficiency Multiport Power Conversion for Aerospace Application: Integrated Converter-Generator Design



Top view of the 50kW air-cooled T-type inverter design.



Bottom view of the 50kW air-cooled T-type inverter design.

Project Summary

NCSU developed an integrated converter-generator for aerospace applications. The team designed and virtually prototyped a custom integrated converter-generator; designed and built a prototype of the SiC converter; and designed an integrated SiC converter-generator system based on a modified off-the-shelf machine.

Technology Gap/Market Need

By delivering both a low-risk solution, based on a modified off-the-shelf machine design, and a higher investment (but better performing) solution for longer-term development, this project will enable industry partner UTRC/Raytheon to quickly bring a WBG-based product into the market at low risk and low cost, while exploring ways to manufacture more advanced, customized solutions.

Accomplishments/Deliverables

- Designed a 230VAC, custom 50 kW permanent magnet and induction electric machine that meets the application performance targets.
- Performed a comprehensive inverter topology trade-off study and settled on the T-type inverter design using readily available discrete SiC devices.
- Completed the design of the air-cooled inverter rated at 50kW.
- Manufactured the 50kW inverter with a power density of ≥10kW/L and efficiency ≥ 98%. The inverter uses a 10layer PCB bus-bar and achieves very good current sharing between paralleled discrete SiC devices.

Impact/Benefits

Reduction in system size and weight; improvement in efficiency; lower cost through system integration and elimination of connectors and harnesses.

NC STATE UNIVERSITY

United Technologies Research Center

Raytheon

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PowerAmerica Roadmap Targets

- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

Commercial Applications

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

University of Tennessee, Knoxville
Southern Company

University of Tennessee, Knoxville
Southern Company
EPB

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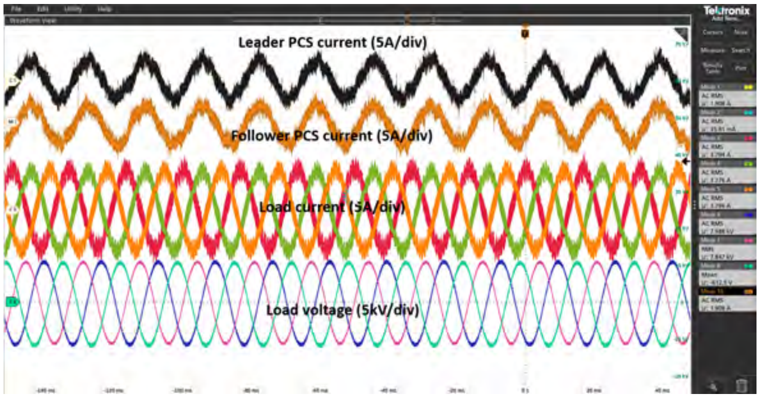
PowerAmerica Roadmap Targets

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

Commercial Applications

- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- ELECTRIC POWER GRID

University of Tennessee, Knoxville: Multi-Functional High-efficiency High-Density Medium Voltage SiC-Based Asynchronous Microgrid Power Conditioning System Module



Left: Current and voltage waveforms of two paralleled PCS operating at 25kV DC.

Bottom Left: Developed three-phase four-wire PCS converter with 13.8kV AC, 25kV DC and 100kVA power rating using 10kV SiC MOSFET.

Bottom Right: Developed back-to-back three-phase PCS converter with 13.8kV AC, 25kV DC, and 100kVA 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. A full modular-multi-level converter (MMC) topology based back-to-back PCS module interfacing a distribution grid and an asynchronous microgrid has been developed and successfully tested at rated voltage and power. Grid support functions were successfully demonstrated with the developed PCS module. A scalable PCS was also demonstrated by paralleling two 100kW PCS modules.

Technology Gap/Market Need

The success of this project has bridged the technology gaps including: 1) MV power converter design that enables high dv/dt noise immunity, fast protection, reinforced insulation, and robust operation required by 10 kV SiC devices and MV grid applications; 2) MV PCS that enables unbalanced load supporting, power quality improvements, grid stability enhancement, and other grid benefits; 3) Scalable MV PCS to support MW-level MV microgrids. The technologies developed in this project can be promoted to utility customers such as manufacturing plants, renewable energy industries, and combined heat and power (CHP) customers, helping to accelerate the commercialization of HV WBG devices and MV converters.

Accomplishments/Deliverables

The accomplishments include: 1) Three phase four-wire PCS converter designed considering grid requirements; 2) Controller of the full back-to-back PCS module developed and tested; 3) Full back-to-back PCS module prototype built and tested at rated voltage and power; 4) Scalable PCS module demonstrated. The three-phase four-wire AC/DC/AC back to back PCS module prototype with 13.8 kVAC and 100 kVA power rating was completed as a deliverable.

Impact/Benefits

This project has successfully demonstrated grid benefits enabled by the developed MV PCS modules. The developed technologies contribute to MV power electronics research communities as well as renewable energy and microgrid related industries. Commercialization of the proposed technologies helps to: 1) accelerate the proliferation of HV WBG devices and microgrids that feature renewable energy sources; 2) improve U.S. competitiveness in renewable energy integration and microgrid technologies; 3) provides hands-on training of the next-generation power engineering workforce in WBG power electronics.

University of North Carolina at Charlotte: Introduction of WBG Devices for Solid-State Circuit Breaking at the Medium Voltage Level

Double pulse test switching waveforms of AC phase leg at 4.3kV and 50A.

Project Summary

With SiC technology poised to break into the protection field by bringing down cost and efficiency barriers to adopting semiconductor devices for breaker design, this project aims to implement a proof of concept build of a solid-state circuit breaker at the medium voltage level of 4.16kV (MV SSCB). The transition in the protection field from electromechanical breakers towards solid-state started with low voltage SiC devices is emerging industry (for example: Atom Power Inc., UNC Charlotte's partner in this project), and will continue as higher voltage options hit the market.

Technology Gap/Market Need

The need for a solid-state circuit breaker arises due to the sluggish response time of traditional mechanical circuit breakers. This delayed response allows large fault currents to build up on the network before protective action is taken, which increases the number of dangerous and destructive arc flash events. Until the advent of WBG, Si-based breaker designs were complex and not cost competitive. SiC devices filled that need and allowed for reasonably sized and cost-effective implementations to become feasible.

Accomplishments/Deliverables

A comprehensive review of prior art in the design and application of WBG-based solid state breakers was carried out. This review led to detailed design and simulation studies on the application of emergent medium voltage SiC devices from Cree to the breaker space. For the hardware build, a JFET-based supercascode was selected and constructed utilizing 1.7kV SiC JFETs from UnitedSiC. Detailed modeling of said cascode has been carried out, and simulation studies led to identification of various destructive oscillatory modes inherit in this design, and validation of design tweaks to mitigate those events. PCB build and assembly required for a 3-Phase AC breaker realization using this circuit was carried out and experimentally tested up to the rated voltage and current (4.3kVA/50A).

Impact/Benefits

Demonstrating a medium voltage circuit breaker will de-risk future adoption by industry thus advancing PowerAmerica's mission. Also, this project provides a path to commercialization of MV SSCBs through partnership with WBG industry (eg: UnitedSiC, Wolfspeed) for provision of SiC hardware, combined with leveraging Atom Power's experience in building and validating SSCBs. Other likely partners are mainstream circuit breaker manufacturers such as Eaton, ABB, Siemens, Schneider Electric, S&C Electric etc. The 4160V prototype is the entry point into the medium voltage space, so as higher voltage SiC Mosfet offerings become available, opportunities for prototyping higher rated MVSSCBs will arise.

UNC CHARLOTTE EPIC

ATOM POWER

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PowerAmerica Roadmap Targets

BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN

ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

Commercial Applications

ELECTRIC POWER GRID

University of North Carolina at Charlotte: Modular Hybrid SiC and Si based Battery Inverter for Energy Storage Integration

UNC CHARLOTTE
EPIC

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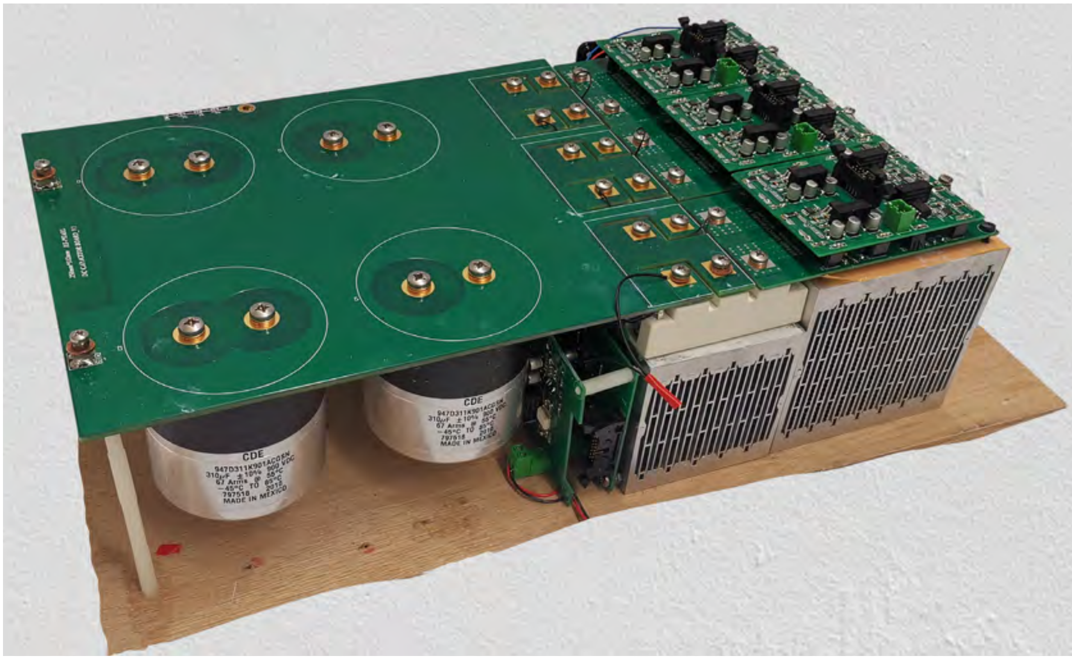
PowerAmerica Roadmap Targets

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

Commercial Applications

- RENEWABLE ENERGY
- ELECTRIC POWER GRID



UNC Charlotte 30kW hybrid SiC and Si based A-NPC inverter

Project Summary

The objective of the project is to develop, test, and demonstrate a modular hybrid SiC and Si-based battery inverter for energy storage integration. The proposed solution is based on an optimized approach with SiC MOSFETs in parallel with Si IGBTs for energy storage applications. The project developed and demonstrated a 30kW hybrid SiC and Si-based Active Neutral-Point-Clamped (A-NPC) inverter with dynamic gate driving and optimized switch patterns. The inverter demonstrated 98.7% CEC efficiency and 27W/in3 power density (3X of current product power density). This approach introduces SiC benefits to the battery inverter at a significantly lower cost and provides high efficiency and high power density for energy storage integration.

Technology Gap/Market Need

The project addresses the need to develop a modular 1500V battery inverter with high efficiency at wide load ranges with a smaller form factor, while still maintaining cost-competitiveness as a building block for large utility energy storage projects. The technology developed in the project provides a benchmark design and optimization for the A-NPC inverter using hybrid SiC and Si technology. The team proposes device die size optimization, dynamic gate driving and optimized switching patterns to fully utilize the hybrid SiC and Si device and achieve high efficiency and high power density.

Accomplishments/Deliverables

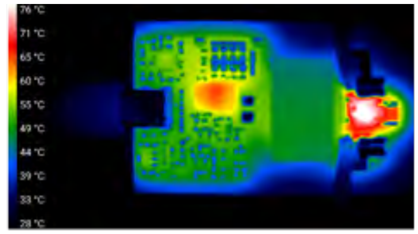
- Developed, tested and demonstrated a 30kW modular hybrid SiC and Si-based A-NPC inverter for energy storage integration. The test demonstrated 98.7% CEC efficiency and 27 W/in3 power density (3X of current product power density).
- Developed a benchmark inverter design of using hybrid SiC and Si technology to introduce SiC benefits to the battery inverter market at a lower cost.
- Proposed hybrid SiC and Si-based A-NPC inverter design optimization, including die size optimization, dynamic gate driving, and switching patterns.
- Education and training. The project trained two undergraduate students and two graduate students on design, simulation, and hands-on testing for WBG power converters.

Impact/Benefits

The developed hybrid SiC and Si solution fully utilizes commercially available SiC MOSFET and Si IGBT devices to extract the potential of both SiC and silicon devices in one. The hybrid SiC and Si-based A-NPC inverter offers significant cost savings on semiconductor devices, but delivers the same high impact on energy savings and reduced form factor. The proposed A-NPC inverter also significantly improves partial load performance and increases reliability with natural device redundancy. The results of the project will promote the large adoption of SiC devices in the grid tie inverter application.

Fastwatt: Compact and Efficient GaN-Based Back-Up or Portable Power for Electronics

(a)



(b)

(c)

(d)

100W GaN-based backup power supply with USB-C-PD input and 120V output
(a) PCB layout
(b) Thermal image of board under test
(c) Prototype unit
(d) Prototype unit feeding 120V desk lamp from a USB battery pack

Project Summary

A GaN-based backup power supply has been developed that can be used to run 120V electronic appliances such as TVs or modems from USB or power tool battery packs during power outages. GaN devices, operating at high switching frequencies with low losses, enable the backup power supply to be compact and efficient.

Technology Gap/Market Need

Lithium-ion battery packs are widely used in consumer applications such as phone backup chargers, power tools, etc. Although some battery packs and UPSs are available with 120V outputs, they are expensive, bulky and inefficient. This project addresses a market need for a portable 120V backup supply that can be fed from power tool/ phone charger batteries and is inexpensive, compact and efficient.

Accomplishments/Deliverables

A 100 Watt GaN-based backup power supply operating at ~1 MHz switching frequency, with a size of <3 cubic inches, and efficiency of 92% has been designed, built and tested. Several prototypes were assembled and successfully demonstrated to power electronic loads such as TVs and modems from power tool/ USB-C battery packs. Packaging and thermal design is being refined and this will be followed by commercialization efforts. PCT application for IP has been filed with the USPTO.

Impact/Benefits

The project uses GaN power devices supplied by Texas Instruments/ EPC. GaN devices can operate efficiently at high frequencies allowing a fully surface-mount compact PCB design. This in turn can allow automated manufacturing in the U.S. at reduced costs. Concepts developed can be used for backup power in data centers and other facilities/ buildings with the benefits of lowered equipment cost and higher efficiency.

FASTWATT

Fastwatt LLC

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

MOBILE CHARGER ADAPTER

UPS DATA CENTER

Miami University: Wide Bandgap-Based Low-Voltage / High-Current DC/DC Converter for Electrified Transit Buses

Miami University,
Vanner Incorporated,
United Silicon Carbide, Inc.

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

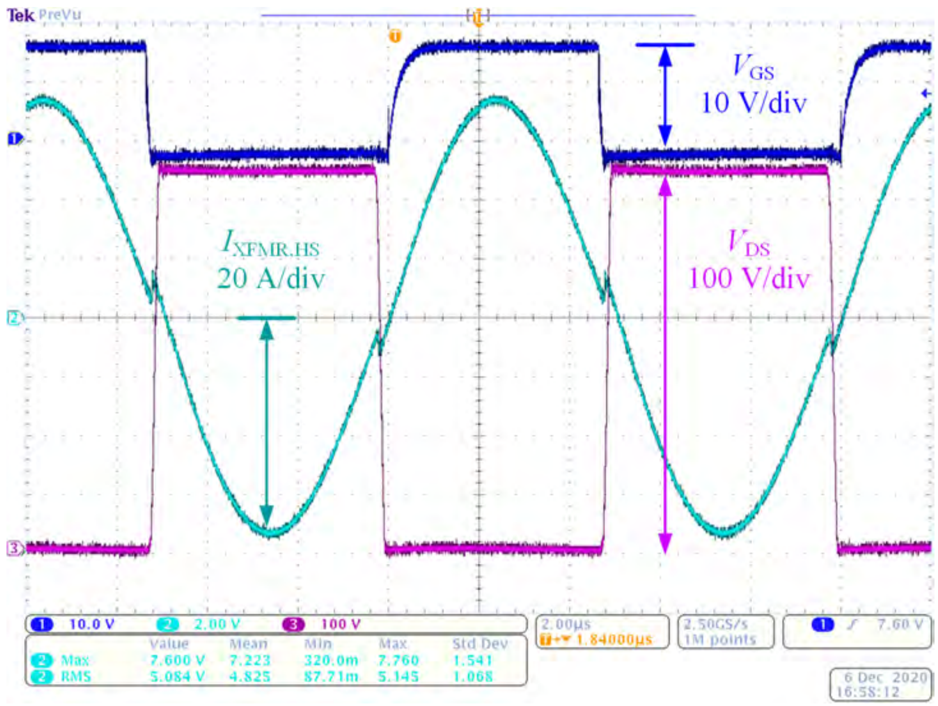
Commercial Applications

HYBRID/ELECTRIC VEHICLES

MILITARY

AEROSPACE

HEAVY VEHICLES



The DC/DC converter operating at 13.2kW with a switching frequency of 100kHz. The waveforms are the gate voltage (V_{GS}), drain-source voltage (V_{DS}), and the current ($I_{XFMR,HS}$) on the high-voltage side of the transformer.

Project Summary

This project incorporated silicon carbide (SiC) components into power electronics for hybrid electric transit buses. We retrofitted a DC/DC converter from Vanner, Inc. with SiC transistors from United Silicon Carbide, Inc. We also designed, built, and installed a new high-frequency, high-current transformer. This transformer went through three iterations to maximize the benefits from SiC's faster switching speeds and lower output capacitance. Our final product enjoyed higher output current, greater efficiency, increased power density, lower cost, and reduced weight. We realized these benefits by modifying the existing printed circuit boards (PCBs) for the high-voltage and low-voltage power stages including the gate drive. The bus-bars, control hardware and software, and EMI filtering were not changed.

Technology Gap/Market Need

Hybrid electric transit vehicles require DC/DC power conversion from the high-voltage battery (550V to 800V) to the 28-V auxiliary power bus. The low-voltage bus powers the engine's starter, headlights, and other auxiliary loads. Bus manufacturers and transit authorities have requested higher output current capabilities in the same footprint. his project demonstrates how to use SiC components to satisfy this demand.

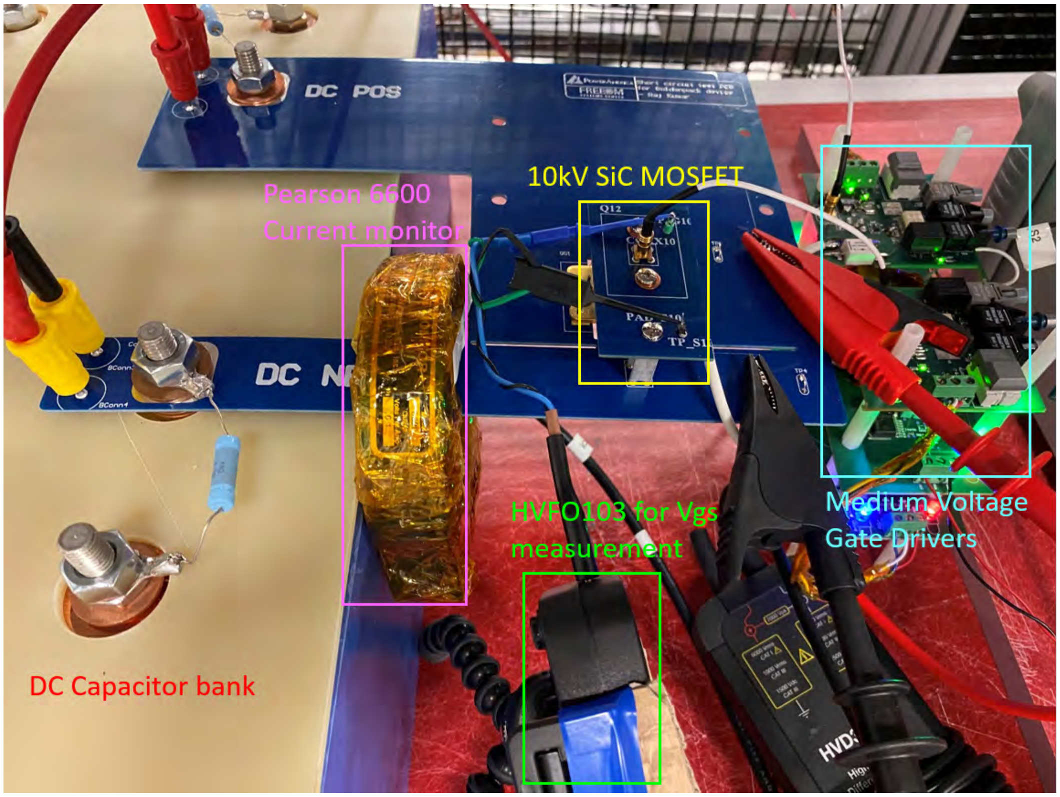
Accomplishments/Deliverables

The performance of Vanner's DC/DC converters improved significantly thanks to this project. The maximum output current increased from 300A to 450A. For step-down operation, the efficiency increased from 92% at 9kW and 80kHz to 94.4% at 13.2kW and 100kHz. We also created a single, high-frequency transformer that provides 558ARMS (836A_{PEAK}) current while operating at 100kHz. The new transformer's efficiency is 99% versus 98.5% for the existing one. Additionally, the cost of the semiconductors and magnetics used in the power stages decreased from $440.60 ($0.049/W) to $397.60 ($0.03/W). We eliminated the existing transformer's heatsink and shielding, which reduces weight and system cost. With new PCBs, bus-bars, and connectors, an output power up to 17kW is achievable.

Impact/Benefits

SiC transistors have lower on-resistances and smaller parasitic capacitances as well as faster switching speed. Our project showed how to apply these strengths with refined magnetics to enhance isolated DC/DC converters' performance. We demonstrated it is possible to increase the efficiency and power density while lowering the cost and reducing the weight of power electronics. The benefits can increase profits for companies that sell high-power, high-current DC/DC converters.

North Carolina State University: Establishment of WBG Power Electronics Testing Facility for Education and Workforce Training Engaging PowerAmerica Industry Members



Short Circuit test bench.

Project Summary

This project aims to establish a comprehensive WBG power electronics testing facility which will facilitate conducting four main characterization tests: Electro-Magnetic Interference (EMI), high power double pulse (DPT), Partial Discharge (PD), and reliability tests. The table below shows the key metrics of the proposed testing facility. The equipment ratings are based on addressing the needs for the high voltage WBG power electronics applications including automotive industry.

Technology Gap/Market Need

The test facility will be developed especially for the new generation of WBG devices with higher voltage and power ratings. The testing facility will be used for both education and research purposes. The facility will also allow PowerAmerica to offer these testing services to industry, and thus it will be an important resource for its sustainability.

Accomplishments/Deliverables

Double Pulse Testing capability for 650V – 10kV SiC devices was completed and demonstrated, as well as short circuit and avalanche energy characterization testbed. The established high power SiC EMI tester is capable of obtaining conductive common-mode and differential-mode EMI data with existing three-phase inverter (DUT) for 200A/800V device under test. The partial discharge testing is tested for the existing 40kV isolated 166 kW transformer. The established reliability testing facility is capable of avalanche and short circuit testing for SiC devices from 650V to 10kV. The deliverables are the established high-power SiC double pulse tester, EMI tester, partial discharge tester, and reliability tester. A laboratory manual for each of these tests has also been delivered.

Impact/Benefits

A comprehensive WBG power electronics testing facility is established and capable of conducting the main characterization tests: Electro-Magnetic Interference (EMI), high power double pulse, Partial Discharge (PD), and reliability tests. The test facility is especially for the new generation WBG devices with higher voltage and power ratings. It will be used for both education and research purposes. The WBG system testing facility is capable of characterizing devices up to 10kV blocking voltage, EMI testing up to 200kW, and partial discharge testing up to 40kV applied voltage.

NC STATE UNIVERSITY

North Carolina State University

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PowerAmerica Roadmap Targets

- IMPROVING RELIABILITY
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

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

North Carolina State University: 6.78-MHz, 200-W GaN-Based Class E and EF Inverters for Wireless Power Mats with Enhanced Load and Reactance Range Employing a Nonlinear Shunt Capacitor

North Carolina State University

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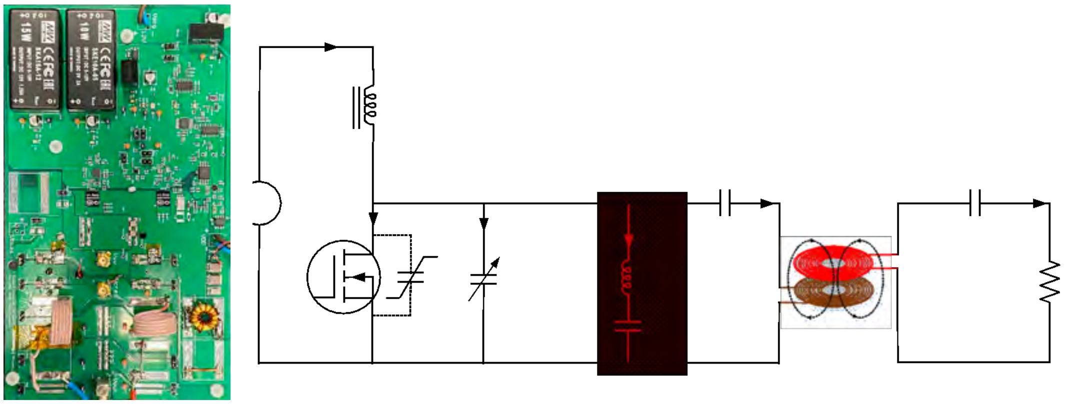
PowerAmerica Roadmap Targets

- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

Commercial Applications

- MOBILE CHARGER ADAPTER
- MILITARY
- OTHER (HIGH VOLTAGE DC/DC CONVERTERS)



Left: Prototype Board with GS66508B GaN switch and variable capacitive network. Right: Class E/EF$_2$-inverters applied in a wireless charging system.

Project Summary

This project is intended to create enabling technology for high-efficiency GaN-based mobile wireless chargers by improving the charger operation with variable loads and extending the spatial freedom of receiver positioning. The combination of fast and efficient GaN switches and the proposed tuning method will enable efficient charger operation (efficiency >90%, 200W) for a wide range of spatial positions of the receiver unit and a wide range of loads. The concept is based on the use of a nonlinear capacitor network to accommodate new load conditions automatically. This improvement will open new and broaden existing GaN employment areas, contributing to the wide adoption of GaN-based WBG semiconductor technology.

Technology Gap/Market Need

Potential adopters of the technology are in the areas of consumer electronics and mobile communication (mobile phones, tablets, notebook PCs, wearables, PC and home peripherals, small appliances, and power tools), and micromobility (power wheelchairs, electric scooters, segways, etc.). The Class E family of resonant converters are predominantly used for powering constant-load systems. They are typically considered premature for wireless charging applications where the effective load at the inverter side varies due to misalignment between transmitter and receiver, load variation, or the mistuning of the transmitter and/or receiver resonant circuits. Currently, there are no high-frequency wireless chargers on the market capable of supporting all these modes of operations simultaneously.

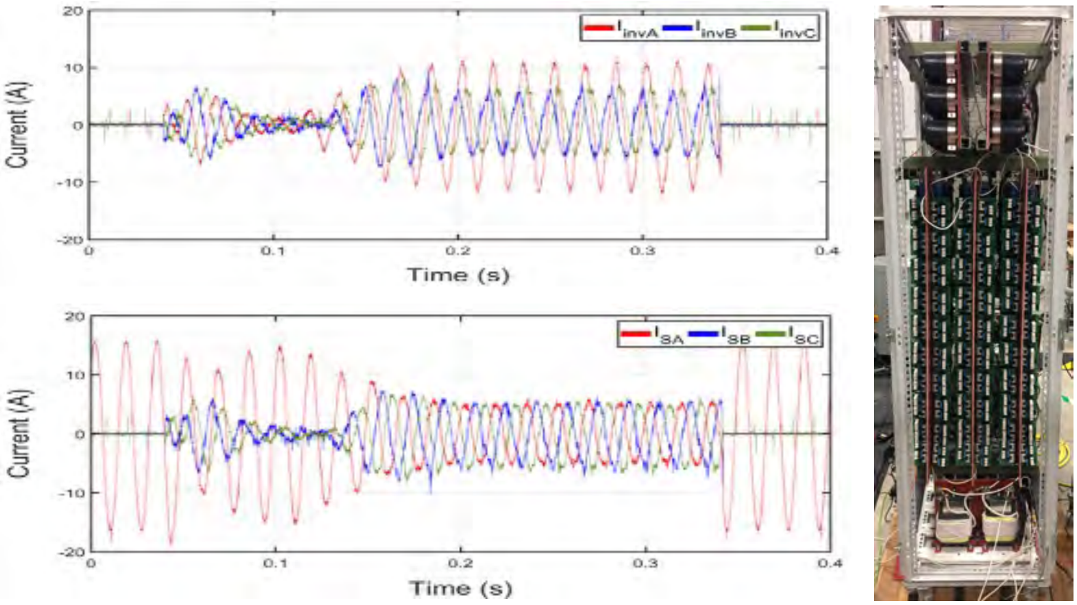
Accomplishments/Deliverables

a) The mathematical loss model of Class E and Class EF2 inverter with a variable capacitive network is derived. The model includes nonlinear output capacitance of GaN switch C_{oss}. The model will be utilized in an optimization procedure to derive an optimum inverter design with minimum power variation for a wide range of load impedance variations.
b) Software tool based on Particle Swarm Optimization (PSO) algorithm capable of determining the optimum structure of the nonlinear capacitor network to minimize the GaN losses for variable load impedance
c) Wireless power transfer testbed supplied by GaN-based evaluation boards with optimum nonlinear capacitor network to demonstrate robust operation for variable load and coupling.

Impact/Benefits

Considering PowerAmerica's Strategic Roadmap for Next Generation Wide Bandgap Power Electronics, one can identify the following outcomes and impacts of the project tasks if completed successfully:
a) The project outcomes will significantly Improve the Reliability of the broad family of GaN-based Class E and EF2 inverters intended for wireless chargers. The new design procedure for GaN-based Class E and EF2 inverters incorporating a variable nonlinear capacitor network should provide better efficiency for a wide load range and misalignment tolerance for the charger receiving unit. By reducing losses and switch stress, chargers can be reduced in size, and the operating life will be extended due to reduced thermal stress. With these improvements, manufacturers and customers can gain confidence in Class E and EF wireless chargers to replace less efficient Class D and DE converters slowly.
b) Enhanced Performance Capability for the specific category of ISM band wireless chargers. A new design optimization procedure will be devised that considers the GaN device, resonant circuit elements, and circuit parasitics. It will allow for the charger's robust and efficient operation with more spatial freedom. Spatial freedom will allow the receiver to move inside the range of 5 cm (2 inches) laterally and 1.25 cm (0.5 inches) vertically with respect to the nominal position.

Electric Power Research Institute : Medium-Voltage SiC-Based Compensators for Distribution Systems



MV-UCSC (top) and substation (bottom) currents: (a) Unbalanced currents (only one phase conducts), (b) Flying capacitors pre-charge, (c) Compensating action, (d) No compensation (like part (a)).

Project Summary

Current imbalances and power factor correction in distribution systems are compensated by a medium-voltage static compensator for unbalanced currents (MV-UCSC). An eleven-level flying-capacitor converter (FCC) was the chosen topology due to volume advantages (because level capacitance is inversely proportional to switching frequency) when placing the MV-UCSC at any place within a distribution system.

Technology Gap/Market Need

Distribution-Flexible AC Transmission System (FACTS) equipment based on SiC devices are in their early R&D stages; they are not currently commercialized. Pilot programs could produce results within 2 years and the commercialization time horizon is estimated to be 5 years.

Accomplishments/Deliverables

This research project accomplished the following:
(1) 3.3-kV switching positions consisting of two series connected 1.7kV SiC MOSFETs were designed and used in the MV-UCSC prototype. Gate drivers were self-powered using switch voltage in the off state.
(2) An eleven-level medium-voltage unbalanced-current static compensator (MV-UCSC) rated 13.8kV and using 3.3kV SiC MOSFET-based switching positions was designed and prototyped.
(3) A seven-level MV-UCSC rated 25kV and 2 MVA using 10-kV SiC MOSFET power modules was designed.
(4) Experimental testing of the eleven-level 13.8kV MV-UCSC was carried out at the NCREPT test facility in the University of Arkansas – Fayetteville (UAF).

Impact/Benefits

This research project addressed research work towards developing distribution-FACTS equipment (D-FACTS) based on SiC MOSFETs and connected directly to medium voltages. D-FACTS will become necessary components in future energy systems characterized by current imbalances among phases and bidirectional power flows. In this particular application, SiC MOSFETs enable higher switching frequencies than silicon IGBTs yielding volume reductions in addition to greater efficiencies.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

UNIVERSITY OF ARKANSAS

Electric Power Research Institute
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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

Commercial Applications

RENEWABLE ENERGY

ELECTRIC POWER GRID

The University of Akron: SiC Based Power Electronic Driver for Electric Vehicle Traction

The University of Akron
BorgWarner Inc

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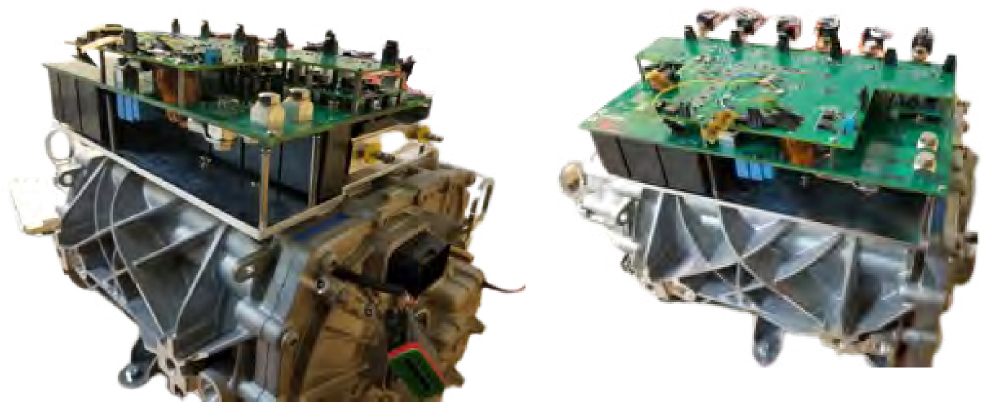
PowerAmerica Roadmap Targets

- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOP-MENT OF AN ADVANCED MAN-UFACTURING WORKFORCE

Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- INDUSTRIAL MOTOR DRIVES
- HEAVY VEHICLES



Integrated motor (left) and inverter assembly (right).

Project Summary

Environmentally-friendly electric vehicles (EVs) reduce tailpipe air pollutants and greenhouse gas emissions while contributing to energy security through a reduction in fossil fuel usage. For motor drive development for EV traction, it is challenging to achieve higher volumetric and gravimetric power density, at a reduced system cost. Alternative drive technologies are needed to achieve these targets. When the power electronics inverter and multiphase electric machine are integrated into a single unit, the design provides reduced cabling, better thermal design, and a compact motor drive system.

A SiC-based high power (210kW) multiphase integrated motor driver is proposed for the EV traction application. SiC devices have significant size, efficiency, and thermal performance advantages which enable a 210kW inverter to fit into the housing of the compact 6 phase motor for EV traction.

The high bandwidth capability of the power electronics inverter reduces the size of the filtering elements and improves the electric motor performance to reduce torque ripple and acoustic noise.

The dynamic interleaving between the two three-phase sets developed during the projects reduced the DC link current ripple and the DC bus capacitor requirement significantly. The final integrated motor and inverter assembly achieved 25.84 kW/l volumetric power density. The system has been tested successfully at reduced power. Full power dynamometer testing is underway. The inverter efficiency is expected to be 98% at the rated power.

Technology Gap/Market Need

Power electronics inverter and electric machine integrated into a single unit to achieve high volumetric and gravimetric power densities is desirable and can enable high penetration of EVs.

The project offers new control algorithms and innovative packaging with the use of multiphysics simulation to improve the performance and the volumetric power density.

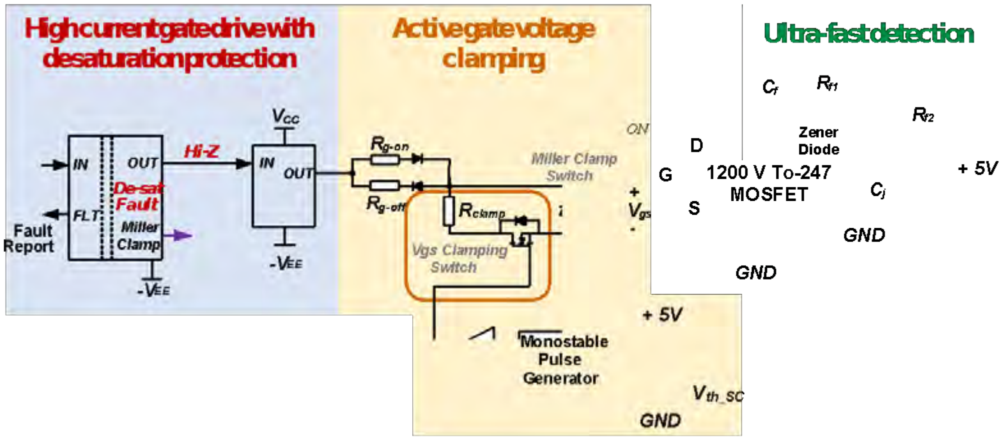
Accomplishments/Deliverables

- Complete analysis and design of the 210 kW 6-phase inverter including schematic capture, PCB layout, EMI filter, thermal analysis, mechanical packaging.
- Dynamic interleaving, and adaptive current regulation algorithms development for 6-phase motor drive.
- Complete inverter assembly and functionality testing
- Six-phase IPM electric machine is designed, built, and delivered for testing at UA dynamometer by BorgWarner Inc.
- Six-phase inverter and IPM motor are integrated.
- The system has been tested successfully at low power.
- Full power dynamometer testing is underway. The final test report will be generated once the tests are completed.

Impact/Benefits

The project demonstrates the performance improvement on the traction drives using a 6-phase configuration with SiC-based integrated design approach. High-performance Traction motor drive system would improve the mileage, cost, and reliability of the EVs. This integrated drive would be used in future Electric Drive Systems offered to OEM customers.

The Ohio State University: Short-Circuit Behavior and Protection of Next Generation 1.2kV SiC Modules and Devices

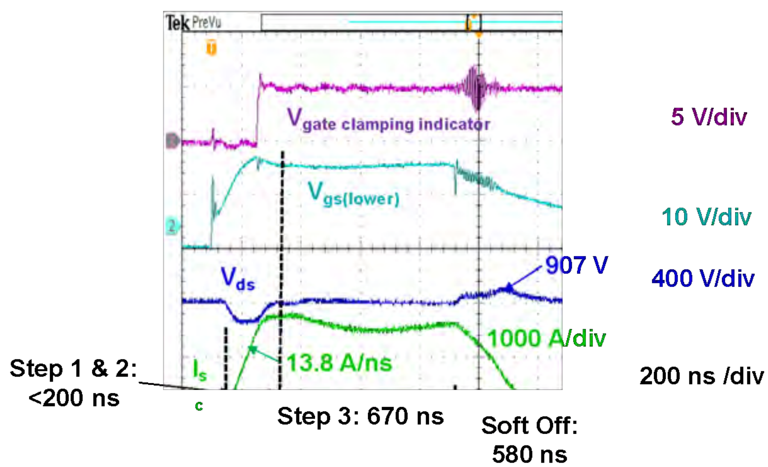


Three-step protection method:

Step 1: Ultra-fast detection: fast respond to detection signal on the dc bus

Step 2: Active gate voltage clamping: enhance short circuit capability of SiC MOSFET

Step 3: Confirmation based on desaturation detection: eliminate mis-trigger condition



Top: The three-step ultra-fast and reliable short circuit protection method (patent pending).

Left: Power Module SC Test with 3-step Protection.

Project Summary

The project aims to test SiC modules and TO-247 SiC devices from all leading U.S. manufacturers and validate a three-step ultra-fast and reliable short circuit protection method.

Technology Gap/Market Need

The project will lead to better understanding of short circuit capabilities of the new generation of 1200V SiC power modules and discrete devices and enable more reliable implementation of these devices with fast and reliable short circuit detection and protection.

Accomplishments/Deliverables

The team has designed and validated the three-step protection for 1200V rated SiC discrete devices and power modules. The short circuit capability evaluation of discrete devices from four device makers at five different temperatures was performed. Short-circuit withstand time of power module was measured. And accelerated short-circuit degradation tests were carried out for SiC discrete devices.

Impact/Benefits

- Understand the short circuit capabilities of the new generation of 1200V SiC power modules and discrete devices
- Enable more reliable implementation of these devices with fast and reliable short circuit detection and protection
- Improve the reliability of SiC-based circuits, thus reducing operation cost
- Help U.S. heavy duty vehicle manufacturers with future product design, thus maintaining competitive edge
- Train a group of students in gate drive designs and testing of SiC devices
- Help U.S. SiC manufacturers to maintain competitiveness

THE OHIO STATE UNIVERSITY
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PowerAmerica Roadmap Targets

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

Commercial Applications

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

North Carolina State University: High Bandwidth, Flexible SiC Testbed for Education and EV Industry Workforce Training

NC STATE UNIVERSITY

North Carolina State University

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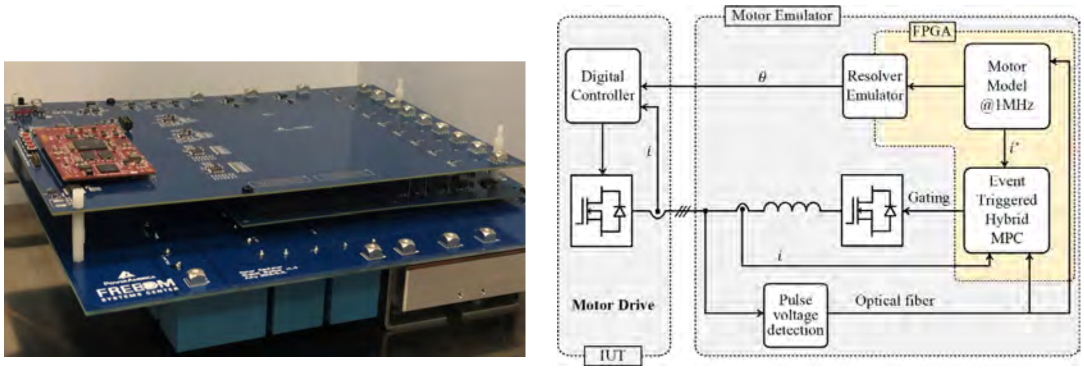
PowerAmerica Roadmap Targets

- 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
- INDUSTRIAL MOTOR DRIVES
- HEAVY VEHICLES



Left: 50kW SiC motor emulator hardware. Right: Function blocks of the motor drive and emulator system.

Project Summary

A modular, flexible, high bandwidth (>20kHz), and high efficiency (>97% peak) 50 kW SiC inverter with reconfigurable software was designed and built to meet the emerging needs of EV traction inverter testing and workforce training. Adoption of SiC building blocks will result in high volume production, reduced cost and losses, weight, size, and engineering effort for the large-scale SiC applications. In this project, a SiC power module, gate drives, thermal management, digital control and protection were holistically designed to meet the requirements of control bandwidth, efficiency, power density, and system cost. The power level and the cost of the bench-scale power supply were reduced more than 20 times by adopting SiC power-in-loop motor emulator.

Technology Gap/Market Need

Utilization of wide bandgap power devices allows operation at higher switching frequency, which results in a significant gain in control bandwidth and efficiency. This enables cost savings in passive components and performance improvements over the Si-based system. The high-performance field programmable gate array (FPGA)-based controller platform can fully utilize the high switching frequency of the SiC power devices and translate it into high control bandwidth. The combination of wide bandgap power devices and the FPGA platform greatly advanced the emulation accuracy and bandwidth for the motor emulator.

Accomplishments/Deliverables

The design of a 50kW SiC motor emulator hardware was completed using cost-effective 6-pack SiC modules and a PCB-based busbar. A low-profile, high-performance SiC gate driver has been tested and validated with isolated power supply operating at 1MHz.
The FPGA software and 50 kW SiC motor emulator hardware for high bandwidth current regulation and high-fidelity online motor model was developed, tested and demonstrated with current reference step response.
A lab handout of the motor emulator was developed for use in a graduate course; ECE 732 Control of AC Electric Machines.

Impact/Benefits

This project developed a commercializable motor emulator for university and other training courses. The evaluation kits will be used in the curriculum for motor control courses for laboratory experiments at both the graduate and undergraduate level for both components and systems. The project targeting commercialization is to develop the software reconfigurable 50kW SiC motor emulator platform that enables industry to flexibly test the efficiency and performance of the drivetrain system in prototype stage before manufacturing it in larger volumes.

University of North Carolina at Charlotte: Extending the "Power Electronics Teaching Lab Incorporating WBG Semiconductors Switches and Circuits" for Wide-Scale Availability: Preparing Manufacturing-Ready Hardware and High-Quality Online Course Contents

Project Summary

This project aims to develop resources needed for wide dissemination of "Power Electronics Teaching Lab Incorporating WBG Semiconductor Switches and Circuits" developed by the PIs at UNC Charlotte. The developed lab model has been innovatively designed to improve students' hands-on learning experiences by providing:

- Flexibility and reconfigurability of power electronics hardware with "Plug-and-Play" type modular architecture, which allows inserting different semiconductor daughterboards into the main power board.
- Learn-by-doing experiments with the developed lab manuals.
- Lab workshops at UNC Charlotte.

The main objectives of this project are:

- Design of a ruggedized plug-and-play power electronics education console.
- Creation of an online repository of lab resources containing manufacturing-ready hardware design packet, lab experiment manuals, and their supporting materials.
- Finally, wide-scale accessibility of the developed hands-on lab model throughout the U.S.

Technology Gap/Market Need

Hands-on experience is one of the most important qualifications for engineers who design, manufacture, and use real semiconductor devices and power electronics converter hardware. In particular, it is important for advancing new technology like WBG power electronics. To achieve the full hands-on education experience, a lab program/training is one of the most effective technical skill builders. However, many hands-on power electronics labs offered by academic/private institutions have accessibility issues: location, time, expense, prebuilt hardware, and offered curriculum. As a result, many individuals/groups experience difficulties finding a hands-on lab suitable for their needs and circumstances. In addition, online/remote education has become an important next-generation education trend due to its flexibility for students to take their learning outside of the classroom and in response to unpredicted and unavoidable emergency circumstances such as the COVID-19 pandemic. To address this issue, the project developed online hands-on power electronics lab resources that can be accessible to broad audiences and expandable for various education/ training objectives.

Accomplishments/Deliverables

Accomplishments

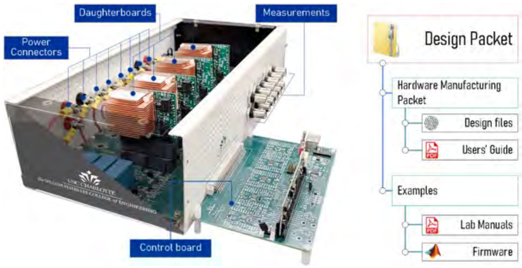
- Developed Plug-and-Play modular system achieving reconfigurability of various power electronics converter topologies and different semiconductor device types
- Developed ruggedized hardware design with comprehensive PCB layout and enclosure
- Developed learn-by-doing instructions for lab experiments from constructing basic power electronics converters to comparing devices' switching characteristics
- Provided wide accessibility with online shareable contents

Deliverable

- Design Packet of Power Electronics Educational Lab incorporating WBG semiconductors including
- Hardware design resources of Power Electronics Education Console
- Lab Manuals and User Guides
- Examples of Design Script, Simulation, and Digital Control Interface

Impact/Benefits

The ruggedized plug-and-play power electronics education console and its design packet can make the wide dissemination of advanced WBG technologies available throughout the United States. The manufacturing-ready hardware design packet and example lab resources will be accessible online. This wide-scale accessibility will contribute to increasing the number of hands-on, experienced WBG power electronics engineers, and, as a result, it will accelerate the pace of growth of WBG power electronics expertise in the U.S. Besides, the flexibility and the reconfigurability of the plug-and-play structure meets various types of learning objectives from different users. The education console can be further customized by users building their own semiconductor daughterboards. This flexibility can contribute to advancing WBG technologies in different fields and areas.



Ruggedized Plug-and-Play Power Electronics Education Console and its Manufacturing-Ready Design Packet.

UNC CHARLOTTE
EPIC

University of North Carolina at Charlotte

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PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

North Carolina State University: Development of Short Course for Wide Bandgap Power Devices in NCSU Core Facilities

NC STATE UNIVERSITY

North Carolina State University

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PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

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

Short course participants get a hands-on demonstration of atomic layer deposition in NNF (Note: photo taken before the onset of Covid-19 pandemic).

Prof. Victor Veliadis gives keynote at the live session of the short course (Note: photo taken before the onset of Covid-19 pandemic).

Project Summary

The NC State Nanofabrication Facility (NNF) and the Analytical Instrumentation Facility (AIF) held two separate multi-day short courses –one live, and one virtual – focused on wide bandgap power device technology. The courses featured lectures, demos of fabrication and microscopy equipment, and keynotes/panel discussions from world-class experts. The lectures and lab demonstrations covered the background science of wide bandgap power devices, as well as the manufacturing and commercialization aspects of this technology. The participants in this course ranged from professional engineers and technicians to students and postdocs.

Technology Gap/Market Need

The objective of these short courses was to increase the technical capabilities of the U.S. wide bandgap semiconductor workforce. Because NNF and AIF are university-affiliated centers, education and workforce development are critical components of their missions.

Accomplishments/Deliverables

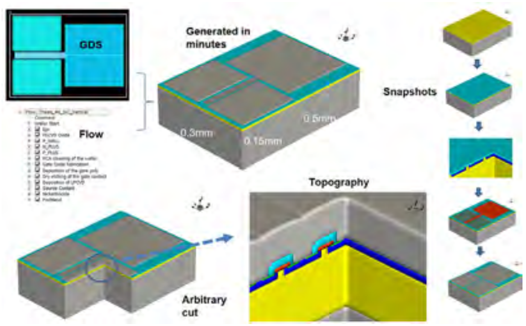
There were over 200 registrants combined for both short courses. These registrants were able to hear lectures from NC State faculty and staff, covering everything from fundamental physics and electrical properties of wide bandgap materials to packaging and testing of power devices. There were also lab sessions, both live and virtual, which focused on fabrication, microscopy, and electrical testing. In the virtual conference, the short course participants joined two virtual panel discussions with experts from academia (NC State, Stanford, Virginia Tech), government (ARPA-E, ORNL, Sandia), and industry (Wolfspeed).

Impact/Benefits

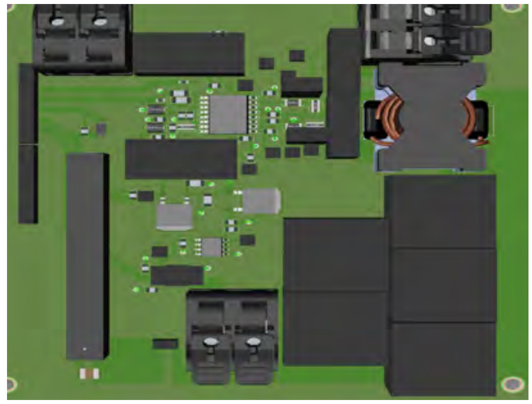
This project was able to contribute to PowerAmerica's goal of creating a pipeline of trained professionals to support the growing wide bandgap power device industry.

San Jose State University: Development of Low-Cost Graduate Course with Virtual Fab and Hands-on Circuit Lab Experience to Prepare Students to Work in the SiC Industry in Silicon Valley

San José State UNIVERSITY



Rapid Prototyping of SiC Device.



Designed PCB for a SiC Converter.

Project Summary

The purpose of this project is to develop low-cost and low-risk course modules from a SiC virtual fab to SiC converter prototyping to train WBG engineers in order to accelerate the development and deployment of WBG electronics by training WBG engineers. The training materials are kept at low cost, so that it can be an affordable model for other universities and companies to follow to educate their students/engineers on the use of SiC devices for power electronic applications. A virtual SiC fab is constructed using the Technology Computer Aided Design (TCAD) process simulation and emulation tools for students to understand SiC fabrication process. A virtual testbench using TCAD device simulation allows students to perform risk-free device testing and characterization. Students can then design SiC power converters through schematics design, simulation and PCB verification/optimization. Eventually, the students will do prototyping and experimental verification of their designs.

Technology Gap/Market Need

Compared to silicon technology that has well-established courses and laboratories from fabrication to device physics to circuit design, SiC technologies training materials are still insufficient and disconnected. Additionally, students/engineers familiar with silicon technology cannot find concise and insightful materials to help them appreciate the know-how of SiC technology in a reasonably short time interval. Moreover, SiC device fabrication is still much more expensive and less accessible to university students and engineers compared to silicon devices. In order to accelerate the adoption of SiC technology in power electronics, the availability of a low-cost but insightful course is crucial to prepare graduate students and to support silicon technology engineers with the rapid transition from silicon-based power electronics to SiC-based power electronics. The deliverables in this project are expected to bridge these gaps in the SiC industry.

Accomplishments/Deliverables

One undergraduate student was trained on SiC TCAD simulation and three undergraduate students were trained on SiC converter design.

Five graduate course modules have been developed and created

1. SiC Virtual Fab: 150 training slides for process simulation, 1 video for process emulation and simulation deck
2. SiC Virtual Testbench: 55 training slides and simulation deck
3. Circuit simulation with OrCAD PSPICE
4. Printed circuit Board (PCB) Level Design
5. PCB Verification and optimization.

Impact/Benefits

Four undergraduate students were trained on SiC technologies. The class modules developed can be used to train new engineers to enter the wide bandgap power electronics industry and transform Si power engineers rapidly into WBG experts in the industry, thus accelerating the manufacturing development of WBG products in the industry in the United States.

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PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

HYBRID/ELECTRIC VEHICLES

RENEWABLE ENERGY

ELECTRIC POWER GRID

Texas Tech University: Texas Tech and X-Fab Educational Partnership

TEXAS TECH UNIVERSITY

XFAB MIXED-SIGNAL FOUNDRY EXPERTS

Texas Tech
X-Fab

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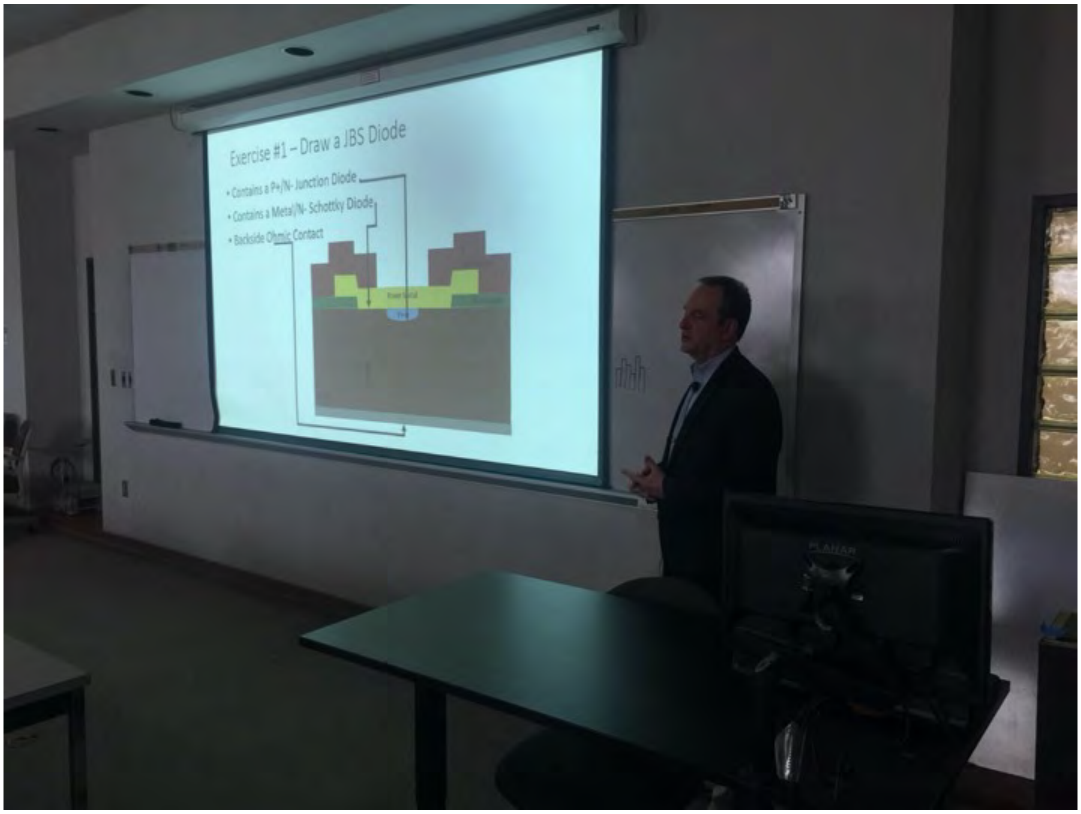
PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE



X-Fab engineer John Ransom lectures to a class.

Project Summary

Texas Tech University partnered with X-Fab Texas to develop and teach courses in the area of SiC power device design and processing. The two new courses that were developed and taught are “SiC Power Device Manufacturing Processes, Fabrication and Simulation,” and “Power Semiconductor Design and Layout.”

- A total of 22 students took the two classes
- Students were offered internships to work at X-FAB Texas and TTU.

Technology Gap/Market Need

This project addressed the need to train future engineers in the area of SiC power device design and process.

Accomplishments/Deliverables

- Developed two new courses in the areas of power device design and fabrication
- Taught two new courses in the areas of power device design and fabrication
- Offered internships to graduate and undergraduate students

Impact/Benefits

This project trained a new generation of students in the area of design and fabrication of SiC power devices.

Real impact

"PowerAmerica was integral in demonstrating our silicon carbide technology at the X-FAB foundry. Without their help in coordinating the fabrication and securing thick epi-wafers, this technology would not have been realized."

Woongje Sung
SUNY Polytechnic Institute

"PowerAmerica accelerates our vision for democratizing Power Electronics education through technology and innovation. PowerAmerica annual meetings have engaged key stakeholders with our program and soon we will see its impact specially on online education."

Babak Parkideh
UNCC

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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.**

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