ANNUAL REPORT 2019

INNOVATION + COLLABORATION

POWERAMERICA EMPOWERS THE THRIVING SILICON CARBIDE AND GALLIUM NITRIDE POWER ELECTRONICS ECOSYSTEM

PowerAmerica

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"PowerAmerica does a fantastic job in getting the engagement of some of the greatest minds within the wide bandgap semi-conductor industries, both from the producers and users of the technologies."

– Ryan Kennedy,
CEO, Atom Power

Acknowledgment: The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Number DE-EE0006521.

TO OUR VALUED POWERAMERICA MEMBERS, PARTNERS, AND ASSOCIATES:

Silicon carbide and gallium nitride semiconductor technologies are making significant commercialization strides, creating jobs and building the U.S. manufacturing base in diverse industries. These include electric vehicles, renewable energy, more efficient power distribution on small and large scales, and supporting U.S. defense and aerospace systems. In 2019, PowerAmerica managed more than 30 industrial, university, and national laboratory power electronics projects aimed at strengthening the ecosystem that supports these wide bandgap (WBG) technologies. Foundry projects fabricated microelectronic components and supported integrated manufacturers and fabless companies with a view toward streamlining processing and increasing production volumes. Other projects advanced manufacturing of SiC and GaN modules that integrate components, a significant technology gap due to the special requirements imposed by the combination of high frequency, high voltage, and high temperature in WBG applications. Our numerous projects demonstrate the compelling advantages of SiC and GaN devices in power electronic systems, including a trimming of the weight of the unit, a reduction in its volume, a higher efficiency, and a reduced bill of materials—all essential to accelerating the adoption of SiC and GaN technology.

POWERAMERICA EXECUTIVE DIRECTOR/CHIEF TECHNOLOGY OFFICER VICTOR VELIADIS

The technological innovations of our members have improved the likes of laptop adapters, photovoltaic inverters, uninterruptible power systems, data center power systems, electric vehicle fast chargers and on-board chargers, solid-state circuit breakers, microgrid power conditioning systems, medium-voltage variable speed drives, traction inverters, and auxiliary power converters.

A workforce well trained in WBG power electronics is key to creating the large device demand that spurs volume manufacturing with its cost lowering benefits. PowerAmerica projects carried out by universities and industry collaborators provide students with "real world" WBG power electronics experience. In the past four years, we funded 63 university-applied projects at a total investment of $24 million providing practical WBG power electronics experience to more than 300 students. Additional educational activities we undertook in 2019 included an industry-driven short course taught by world renowned experts, tutorials and special sessions at major conferences, monthly webinars, and numerous student internships at leading companies.

There are compelling incentives for membership in PowerAmerica, a 50-member ecosystem that spans all areas of the GaN and SiC supply chain. Our device/module bank increases the availability and timely accessibility of long lead-time, pre-production engineering samples for power application development. We provide our members with unparalleled opportunities that help grow their businesses, find new customers and suppliers, create partnerships, recruit students educated in WBG technology and advance technology innovation. By participating in our annual winter and summer member-only workshops, individual companies improve their competitive position and deliver a collective, amplified voice on technology and business issues that affect the wide bandgap industry. Our 2019 effort also included completing our first four member-initiated, pre-competitive projects. These were selected by members from the members' technology roadmap and financed with membership funds. Working on projects of common interest and sharing generated IP is a cost-effective way to spur technological innovation and overcome barriers limiting the growth of our industry. To those contributing their valuable time and efforts to our Member Advisory, Executive, Roadmap, and Sustainability Committees, a special thank you for your hard work. You have made PowerAmerica a world-class institute and are at the forefront of defining the future of our industry.

I have closely witnessed the explosive growth of the wide bandgap power electronics industry and had the rewarding experience of partnering with some of the best minds in the fields of SiC and GaN electronics. Undoubtedly, PowerAmerica member contributions set the performance standard in today's wide bandgap technology and lay a sound foundation for its large-scale future growth. As we move forward, PowerAmerica is committed to working closely with our stakeholders and providing valuable services that catalyze continuous growth and success. *I look forward to our continued collaboration.*

OUR MISSION

As a Department of Energy-backed, Manufacturing USA Institute, PowerAmerica aims to support the cost-efficient, large-scale production of wide bandgap semiconductor power electronics. Through this, we enable high-tech job creation, technological innovation, and energy efficiency associated with a range of power electronics applications.

Our Success

$150 million	122 projects	32 projects	40 projects
in project funding*	funded to date	completed in 2019	kicked off in 2019

Projected growth

for wide bandgap power technology made with silicon carbide (SiC) and gallium nitride (GaN) materials.

$2 BILLION
2023

$1 BILLION
2019

*Over 5 years **SOURCE: (IHS Markit Data)

Real advantages.
Real-world applications.

From start-ups to Fortune 100 companies, PowerAmerica members are demonstrating the compelling advantages of SiC and GaN devices in power electronics systems – such as reduced weight and volume, higher efficiency, and a less expensive bill of materials—in market-ready applications.

POWERAMERICA FUNDED APPLICATIONS

- ELECTRIC VEHICLE FAST/ ON-BOARD CHARGERS
- PHOTOVOLTAIC INVERTERS
- SOLID-STATE CIRCUIT BREAKERS
- DATA CENTERS
- CONSUMER ELECTRONICS
- UNINTERRUPTIBLE POWER SUPPLIES
- MICROGRID POWER CONDITIONING SYSTEMS
- AND MORE










Proven SiC and GaN technology: Market adoption means market growth.

RELIABILITY

Wide bandgap devices have demonstrated application reliability to earn JEDEC and AEC-Q101 approvals.

MASS PRODUCTION BY POWERAMERICA MEMBERS

Leading SiC material supplier Wolfspeed and SiC foundry X-FAB are expanding production capacity. Infineon Technologies now offers Si, SiC and GaN products in mass production, while ON Semiconductor and Microchip are expected to follow suit. In 2020, most major silicon power semiconductor companies will offer wide bandgap semiconductors.

MARKET ADOPTION

SiC is being inserted in many applications, particularly in hybrid and electric vehicles and photovoltaic inverters.

Mass-produced GaN technology can be found in server and telecom power supplies, as well as power adaptors and chargers.

MEMBERSHIP

PowerAmerica provides a forum for members to improve the performance of SiC and GaN technology and develop new applications. Our membership network spans the wide bandgap technology ecosystem, from device developers and foundries to module manufacturers to end users, as well as universities that educate and supply the future workforce.

50 member organizations

Our 2019 membership is diverse and nationwide—comprised of Fortune-ranked companies, mid-sized ventures, start-ups, 17 universities and three national labs.

Members drive PowerAmerica

In 2019 our members:

Made it easier to join our network by devising and approving a new fee structure that lowered the barrier to entry for small businesses and mid-tier companies.

Introduced the first Member-Initiated Projects (MIP)
The MIP program is a way for members to collectively identify priority projects needed to advance wide bandgap commercialization and direct resources to address those challenges. Members voted on and funded four member-initiated projects for a total of $680,000 plus a cost share. Subsequent rounds of MIPs are planned in the near future.

2019 MEMBER INITIATED PROJECTS

Quantifying Power Device Reliability Due to Terrestrial Radiation: CoolCAD

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

High Voltage Bi-directional On-Board Charger with Integrated PCB Winding Magnetic Components: Virginia Tech University

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

PowerAmerica connects companies and practitioners across the wide bandgap supply chain, and provides members with unparalleled opportunities to establish business relationships, innovate technology, grow their business, and build their brand.

Our Value Proposition

Some of the benefits PowerAmerica members derive from membership with our institute include:

- Member-guided SiC and GaN project selection
- Member-driven technology roadmap creation
- Exclusive access to IP developed through member projects
- Exclusive access to engineering samples through members-only device bank
- Support of 3rd-party reliability evaluation centers to bolster confidence in SiC/GaN
- Assistance with device design and cost-effective manufacturing in high-volume foundries
- Semi-annual meetings that provide valuable networking opportunities and industry updates
- Exclusive access to future workforce through members-only portal of students studying wide bandgap technology
- Continuing education opportunities: tutorials on SiC and GaN devices and applications; annual SiC and GaN short course

EDUCATION & WORKFORCE DEVELOPMENT

A highly skilled workforce is essential to the long-term success of the wide bandgap ecosystem. PowerAmerica activities train the next generation of wide bandgap professionals to strengthen U.S. manufacturing.

During PowerAmerica's first four years of operation, we have:

Provided
$24 million
in funding to
63 hands-on university projects

Equipped more than
300 students
with real-world wide band-gap power electronics experience

Facilitated internships with PowerAmerica members like ABB, John Deere, GE, Lockheed Martin, Raytheon, & X-FAB

Conducted annual wide bandgap short course to train the workforce in SiC and GaN technologies

2019 PowerAmerica workforce development milestones

Linked more than **50 PowerAmerica students** on members-only portal of PowerAmerica website

Supported enrollment of **90 undergrads and 290 graduate students** in power electronics courses at member universities

Delivered numerous **tutorials** and organized **industry panels** to reach working professionals at WiPDA, ECCE, APEC and other professional venues

Organized and presented **eight well-attended technical webinars**

Facilitated the creation of **13 power electronics courses with 57 wide bandgap lectures** at member universities

2019 MEMBERS

SiC FOUNDRY & MATERIALS

SiCAMORE SEMI
soitec
Wolfspeed. A CREE COMPANY
X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

SiC DEVICES, CIRCUITS, & MODULES

APPLIED MATERIALS.
COOLCAD ELECTRONICS
GE
GeneSiC SEMICONDUCTOR
Microsemi
ON
SemiQ
Sonrisa Research, Inc.
UnitedSiC
Wolfspeed. A CREE COMPANY

GaN DEVICES & CIRCUITS

transphorm
NEXGEN POWER SYSTEMS
infineon

WIDE BANDGAP SYSTEMS

ABB
ATOM POWER
BAE SYSTEMS
BETA
GE
GM
JOHN DEERE
LOCKHEED MARTIN
NIR
Raytheon
SENSITRON SEMICONDUCTOR
TOSHIBA
United Technologies Research Center
Windlift

ACADEMIC

Arizona State University
Florida State University 1851
Georgia Tech Center for Distributed Energy
MARQUETTE UNIVERSITY
NC STATE UNIVERSITY
Rensselaer
SJSU RESEARCH FOUNDATION
SUNY POLYTECHNIC INSTITUTE
TEXAS TECH UNIVERSITY
THE OHIO STATE UNIVERSITY
The University of Akron
THE UNIVERSITY OF ALABAMA
UCSB
University of Colorado Boulder
UNC CHARLOTTE EPIC
THE UNIVERSITY OF TENNESSEE KNOXVILLE
VirginiaTech

GOVERNMENT LABS

Argonne NATIONAL LABORATORY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
Sandia National Laboratories

CONSORTIA

E4 CAROLINAS
iNEMI
PEAC
RESEARCH TRIANGLE CLEANTECH CLUSTER

SPONSOR

U.S. DEPARTMENT OF ENERGY

MEMBER REPORTS

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

REDUCING COST

IMPROVING RELIABILITY

ENHANCING PERFORMANCE CAPABILITIES

BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

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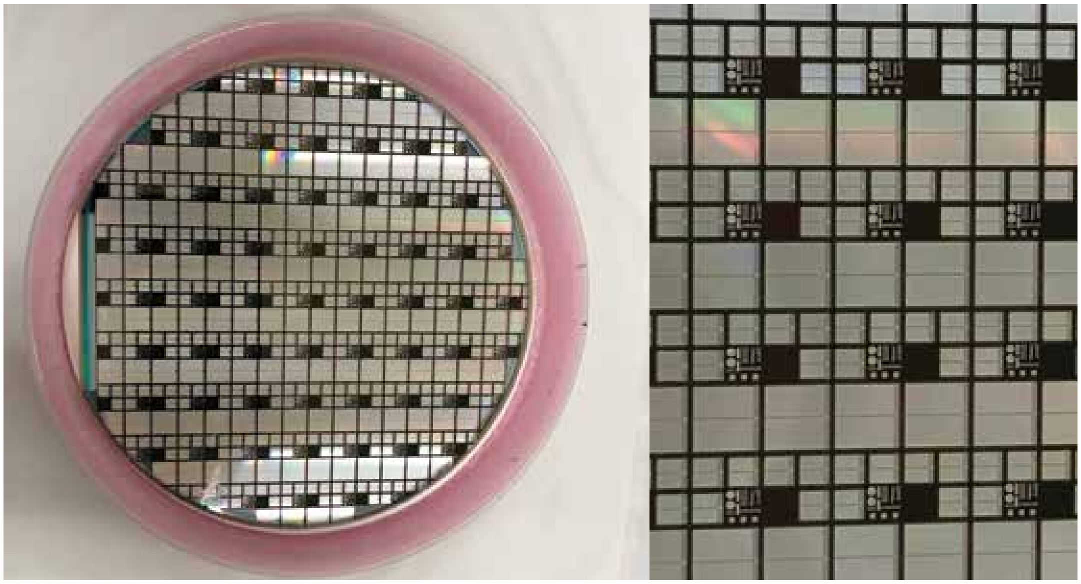
GeneSiC: 6.5kV SiC DMOSFET Development



(Left): Photograph of a completed 150mm SiC wafer populated with 6.5kV SiC DMOSFET dies and (Right) Zoomed-in photograph of 8.2mm x 8.2mm and 4.1mm x 4.1mm, 6.5kV SiC DMOSFET dies and various test structures.

GeneSiC Semiconductor Inc.

Contact:
Drs. Ranbir Singh and Siddarth Sundaresan

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

- RENEWABLE ENERGY
- RAIL TRACTION
- UPS DATA CENTER
- ELECTRIC POWER GRID
- MILITARY

Project Summary

GeneSiC intends to produce 6.5kV/100mOhm SiC MOSFET chips at X-FAB's 150mm foundry to lower the cost; standardize the supply chain, and increase the quality level of production. GeneSiC intends to offer 6.5kV MOSFET chips to module makers, and other interested end-users. In addition, GeneSiC is in discussions with module manufacturers to prototype 6.5kV power modules.

Technology Gap/Market Need

The successful development and demonstration of 6.5kV SiC MOSFETs is the first step for commercializing medium-voltage SiC MOSFET technology, which is desirable for a variety of grid-connected and traction applications. 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.

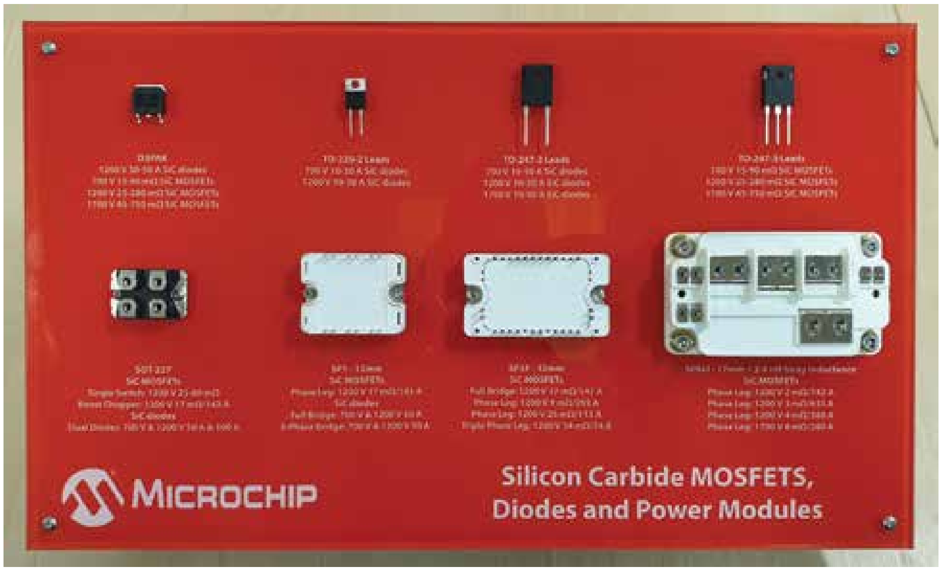
Accomplishments/Deliverables

A 6.5kV/400mΩ SiC MOSFET lot was conducted at the 100mm foundry. The fabrication of 6.5kV/100mΩ and 400mΩ MOSFET lot was recently completed at X-FAB. Devices from both lots will be submitted to the PowerAmerica Device Bank.

Impact/Benefits

6.5kV SiC power modules with >100A current ratings offer 100-500 times faster switching speeds as compared to state-of-the-art Si IGBTs based modules. Up to 150°C operating temperatures offered by SiC MOSFETs is a significant advantage that can be exploited in many applications.

Microsemi: Commercialization of 3.3kV & Technology Development of 6.5kV Silicon Carbide Devices



Silicon carbide MOSFETs, diodes, and power modules.

Project Summary

This project aims to validate the reliability of 3.3kV MOSFETs and Schottky Barrier Diodes (SBDs), optimize design per market needs and then ramp up to production via a 6" foundry. Additional goals are to develop and prototype next-generation 6.5kV SBDs to understand material quality and readiness for commercialization.

Technology Gap/Market Need

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

Accomplishments/Deliverables

3.3kV, 70mOhm devices were successfully fabricated with good yields. Preliminary reliability assessment of 3.3kV SBDs and FETs is complete. Initial electrical characterization demonstrates excellent performance including ruggedness. 6.5kV PiN diodes were successfully fabricated.

Deliverables: (a) 100 units of 3.3kV SBDs, (b) 100 units of 3.3kV MOSFETs, (c) 50 units of 6.5kV diodes.

Impact/Benefits

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

Microsemi, a wholly owned subsidiary of Microchip

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PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

- RENEWABLE ENERGY
- RAIL TRACTION
- ELECTRIC POWER GRID
- MILITARY
- OTHER (HIGH VOLTAGE DC/DC CONVERTERS)

North Carolina State University: 1.2kV SiC Shielded Trench Gate Power MOSFETs

NC STATE UNIVERSITY

X-FAB
MIXED-SIGNAL FOUNDRY EXPERTS

North Carolina State University and X-FAB

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PowerAmerica Roadmap Targets

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

Commercial Applications

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

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

1.2kV SiC Shielded Trench Gate Power MOSFET device specifications.

Project Summary

The goal of the project is to create a PowerAmerica foundry process kit for manufacturing 1.2kV trench-gate SiC Power MOSFETs at the X-Fab foundry. The specific on-resistance of planar-gate SiC power MOSFETs with breakdown voltages below 3kV is well known to be limited by the channel resistance. The trench-gate structure has been found to reduce the specific on-resistance of silicon power MOSFETs by eliminating the JFET component and increasing the channel density. Trench-gate SiC power MOSFETs have been manufactured by Rohm in Japan and Infineon in Germany with specific on-resistance similar to the planar-gate devices. The goal of our project is to create a device architecture and process flow that can allow manufacturing trench-gate SiC power MOSFETs at the X-FAB foundry for the first time. We intend to demonstrate that the specific on-resistance of our 1.2kV trench-gate devices is at least 50% better than that of planar-gate devices.

A process flow for creating these structures was defined in co-operation with X-FAB to ensure compatibility with their manufacturing capability. A mask set was designed at NCSU for the fabrication of these structures and approved by X-FAB. The fabrication of the first 1.2kV trench-gate SiC power MOSFETs with thick trench bottom oxide was initiated in 2019.

Technology Gap/Market Need

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

Accomplishments/Deliverables

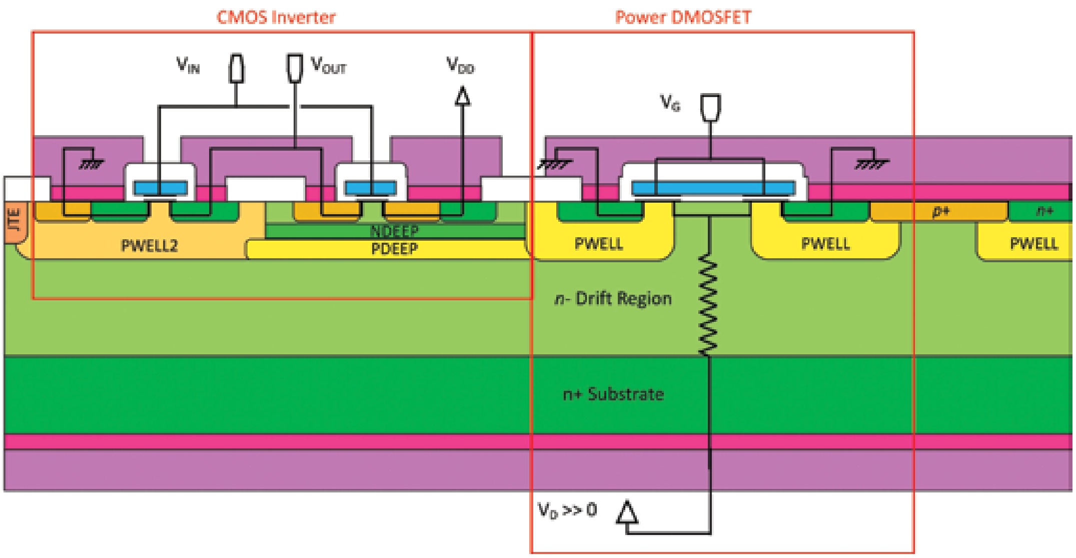
Two process flows for creating trench-gate SiC power MOSFETs were defined in co-operation with X-FAB to ensure compatibility with their manufacturing capability. The first process flow allows making trench-gate SiC power MOSFETs with a thick oxide at the trench-bottom. Numerical simulations were performed at NCSU to demonstrate that the specific on-resistance of these devices is at least 50% smaller than for planar-gate devices. A mask set was designed at NCSU and approved by X-FAB for the fabrication of these devices. A process lot was started at X-FAB to demonstrate the first trench-gate SiC power MOSFETs.

The second process flow allows fabrication of trench-gate SiC power MOSFETs with a P+ shielding region at the bottom of the trenches. Numerical simulations were performed at NCSU to demonstrate that the high frequency figure of merit for these devices is at least 50% smaller than for planar-gate devices. A mask set was designed at NCSU and approved by X-FAB for the fabrication of these devices.

Impact/Benefits

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

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



Illustrative cross section of a SiC CMOS/DMOSFET power IC.

Project Summary

This project improves the ruggedness of SiC power MOSFETs by incorporating sensing and protection circuits on the MOSFET die, and increasing the short-circuit withstand time by gate-charge scaling. CMOS protection circuits are monolithically integrated on power DMOSFET die, with the addition of only one photomask and one implant step to the standard DMOSFET process flow. In gate-charge scaling, we reduce the oxide thickness and gate drive by the same factor, say 4. This reduces the saturation current and increases the short-circuit withstand time by 4, without any impact on on-state or blocking performance. Gate-charge scaling requires no changes to the mask layout or process flow of existing MOSFET products, making it essentially a zero-cost option to increase ruggedness.

Technology Gap/Market Need

The CMOS IC process developed in this project enables the development of smart power devices and power ICs based on the proven SiC power DMOSFET technology. CMOS circuits are tolerant to process, supply voltage, and temperature variations, making them ideal for demanding applications. We are developing a PDK and a library of polycells that a customer can interconnect to implement any desired on-chip function. In a separate development, our concept for gate-charge scaling can increase the short-circuit withstand time of planar DMOSFETs, trench UMOSFETs, and IGBTs without impacting their static performance, and at zero added cost. Taken together, these enhancements increase the ruggedness and reliability of SiC power switching devices, opening new markets in more demanding applications.

Accomplishments/Deliverables

A set of basic CMOS logic gates has been designed and their noise margins optimized by simulation over a range of supply voltages. A library of digital polycells that conform to the X-FAB design rules has been created, and the polycells have been interconnected to implement ASIC circuits including half-adders, full-adders, XOR gates, and ring oscillators. PCMs to measure threshold voltage and channel mobility of both n- and p-channel MOSFETs have been designed, and layout of a mask set has been completed. The mask set includes CMOS demonstration circuits, PCMs, and power DMOSFETs protected by 1,200V edge terminations. The mask set and process flow have passed X-FAB design review, and fabrication of the initial process run has begun.

Impact/Benefits

This project advances WBG power device technology by developing the capability for integrating CMOS sensing and control circuits on a standard SiC power DMOSFET with the addition of one additional mask level and implant step. This project also introduces the concept of gate-charge scaling to increase the short-circuit withstand time up to 4, with no degradation in on-state or blocking performance and at zero added cost.

Sonrisa Research, Inc.

Sonrisa Research, Inc., partnering with 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

SUNY Polytechnic Institute: Development of 6.5kV SiC MOSFETs, JBS Diodes, and JBS Diode Integrated MOSFETs

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

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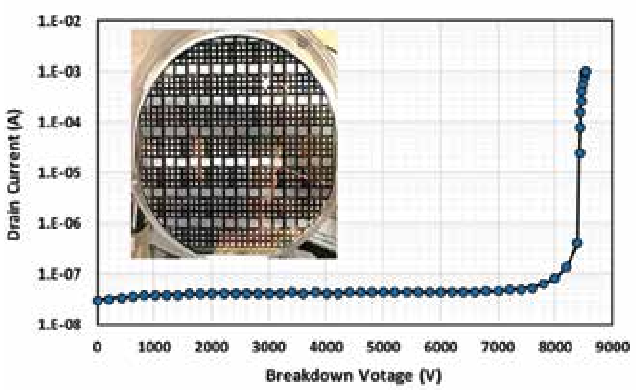
PowerAmerica Roadmap Targets

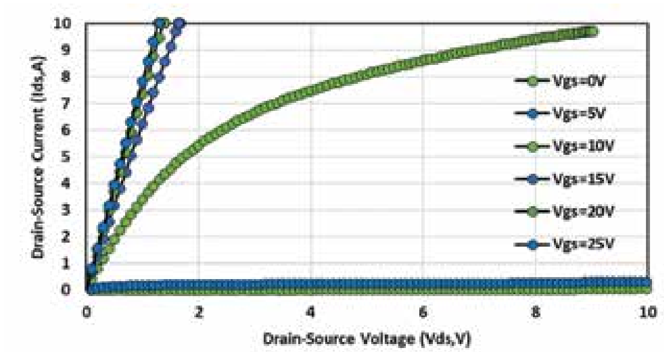
- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES
- ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

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



Typical forward blocking characteristics of the fabricated 6.5kV SiC MOSFET, measured at room temperature. Inset shows fabricated devices on 6-inch wafer.



Typical forward conduction characteristics of the fabricated 6.5kV SiC MOSFET, measured at room temperature.

Project Summary

This project intends to develop 6.5kV SiC MOSFETs, JBS diodes, and JBS diode integrated MOSFETs (JBSFETs). All devices and their design variations were included in a single mask-set. The proposed high voltage devices were successfully fabricated at X-FAB on a 6-inch SiC wafers. An ideal breakdown voltage was achieved with a specified drift design using floating field rings and JTE-based edge termination. The potential reduction in switching losses through the use of high voltage SiC devices has the potential to reduce fragmentation in the MV market by providing more straightforward systems that fit the needs of most customers.

Accomplishments/Deliverables

Critically designed considerations for the successful device include: efficient edge termination techniques, highly rugged cell designs, and efficient layout approaches of diode integration into the MOSFET structure. The cell area for the MOSFETs, diodes, and JBSFETS were critically designed to ensure superior forward characteristics. Both floating field rings and JTE-based edge terminations were designed to achieve an ideal breakdown voltage with a given drift design. Ideal blocking characteristics with very low leakage currents for the 6.5kV SiC MOSFET, diodes, and JBSFETs were successfully demonstrated.

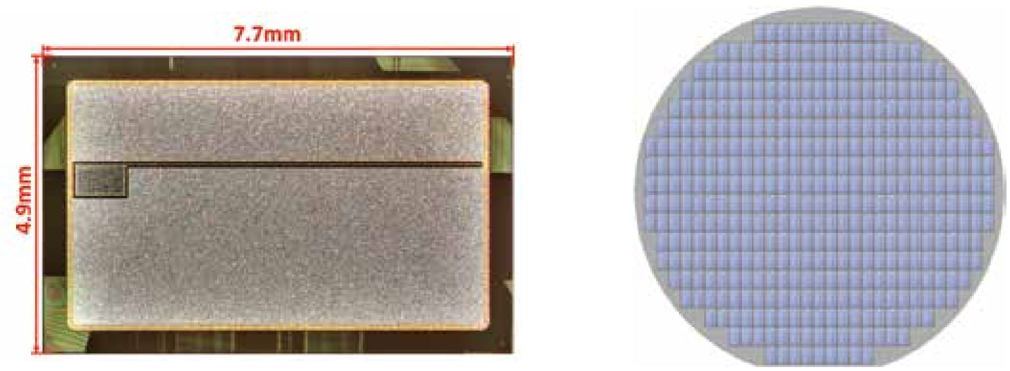
Technology Gap/Market Need

As of today, only a voltage rating of 1.2kV SiC device process baseline is available through PowerAmercia/X-FAB. This project aims to develop high voltage SiC devices that are otherwise difficult to attain from commercial vendors. The critical considerations for the successful development include: efficient edge termination techniques, highly rugged cell designs, and efficient layout approaches of diode integration into the MOSFET structure. An efficient edge termination design is the most critical technical feature in developing high voltage power devices to achieve high breakdown voltage and efficiently utilizes the periphery area as edge termination consumes a significant portion of the chip area.

Impact/Benefits

High voltage SiC devices will enable the development of efficient fast EV chargers, inverters for heavy-duty vehicles, medium voltage PV inverters, MV inverters for wind applications, microgrid power conditioning systems, motor drive inverters, converters for smart power grids, and so on. Currently, only a few companies have demonstrated >3.3kV SiC MOSFETs. The development of 6.5kV SiC MOSFETs, JBS diodes, and JBSFETs becomes a very important task for PowerAmerica to secure a large amount of chips for partners in the power electronics. This will also gear up for future customers seeking engineering samples or packaged chips.

Wolfspeed: Development of Manufacturable Gen3 3.3kV/50mΩ SiC MOSFETs Fabricated on 150mm 4HN-SiC Wafers Along With HTRB, HTGB, BDOL, TS, ESD, & TDDB Reliability Qualification



(Left) Photograph of Wolfspeed/Cree Gen3 3.3kV/50mOhm SiC MOSFET Device Die. (Right) 150mm 4HN-SiC wafer with Wolfspeed/Cree Gen3 3.3kV/50mOhm SiC MOSFET Device Die (414 Gross Die per Wafer)

Project Summary

This project will develop a manufacturable and reliable Gen3 3.3kV/50mOhm SiC MOSFET device fabrication process on 150mm 4HN-SiC wafers at the Wolfspeed/Cree 150mm SiC power device fabrication line. In addition, this project will establish High Temperature Revise Bias (HTRB), High Temperature Gate Bias (HTGB), Body Diode Operating Lifetime (BDOL), Thermal Shock (TS), Time Dependent Dielectric Breakdown (TDDB), and Electrostatic Discharge (ESD) reliability qualification according to JEDEC standards for these Gen3 3.3kV/50mΩ SiC MOSFET devices. These JEDEC qualification tests are a critical step in the process at Wolfspeed/Cree for the formal release of these large area, medium voltage SiC MOSFETs as commercial products for the sale of 3.3kV SiC MOSFET device die and ultimately 3.3kV SiC power modules using these devices.

Technology Gap/Market Need

Currently, there are no JEDEC-qualified 3.3kV SiC MOSFET die products available from any vendor in the world, even though there is an abundance of applications that would greatly benefit from the lower conduction and switching losses enabled by medium voltage unipolar 3.3kV SiC MOSFET power devices and the 3.3kV SiC power modules which would utilize these devices. This project helps to fill this market gap by completing the critical initial JEDEC qualification testing (i.e., HTRB, HTGB, BDOL, TS, TDDB, and ESD) that is required for ultimate commercial product release of these devices and ultimately modules using these devices.

Accomplishments/Deliverables

- Completed 150mm Fabrication Lots #1, #2, #3, #4, and #5 of Gen3 3.3kV/50mOhm SiC MOSFETs
- Gen3 3.3kV/50mOhm SiC MOSFETs device die from 150mm Fabrication Lots #1, #2, #3, #4 and #5 are being diced and picked to begin high voltage device packaging for JEDEC qualification
- When packaging of Gen3 3.3kV/50mOhm SiC MOSFETs devices from 150mm Fabrication Lots #1, #2, #3, #4, and #5 is completed, then HTRB, HTGB, BDOL, TS, TDDB, and ESD JEDEC qualification testing of these will be carried out
- Further characterization of Gen3 3.3kV/50mOhm SiC MOSFET device die from these 150mm fabrication lots is underway to generate a preliminary datasheet
- 250 pieces of Gen3 3.3kV/50mΩ SiC MOSFET die fabricated on 150mm 4HN-SiC wafers will be delivered to the PowerAmerica Device Bank

Impact/Benefits

SiC MOSFETs, such as the Gen3 3.3kV/50mOhm SiC MOSFETs being developed and JEDEC qualified on this project, allow for the realization of higher efficiencies when used in place of the incumbent 3.3kV Silicon IGBT technology. This comes from the unipolar nature of the SiC MOSFET, which all but eliminates losses incurred during each switching cycle of a power converter. The unipolar operation of the SiC MOSFET also eliminates the conduction “knee” that is present in 3.3kV Silicon IGBT bipolar devices, which incurs a heavy efficiency penalty when operating at less than 100% load, as is typical for real world traction and medium voltage motor drive applications. Therefore, this Gen3 3.3kV/50mOhm SiC MOSFETs power device technology allows for next-generation power electronics systems present in trains, industrial motor drives, grid-tied energy storage systems, and electric vehicle fast charging stations to operate more efficiently, enabling cost savings for the system owners in the form of less energy use, as well as enabling the design of smaller and lighter products.

Wolfspeed,
a Cree Company

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PowerAmerica Roadmap Targets

REDUCING COST

IMPROVING RELIABILITY

Commercial Applications

HYBRID/ELECTRIC VEHICLES

RENEWABLE ENERGY

INDUSTRIAL MOTOR DRIVES

RAIL TRACTION

UPS DATA CENTER

ELECTRIC POWER GRID

MILITARY

X-FAB: SiC Power Device Commercial Foundry Development

MIXED-SIGNAL FOUNDRY EXPERTS

X-FAB Texas, Inc.

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PowerAmerica Roadmap Targets

REDUCING COST

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
- OTHER (HIGH VOLTAGE DC/DC CONVERTERS)

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

Project Summary

With PowerAmerica support, X-FAB Texas has established an open 6-inch silicon carbide (SiC) commercial foundry, enabling companies with a variety of device technologies to utilize the foundry for volume production. Rather than building a SiC fab from scratch, X-FAB's existing 6-inch silicon foundry is utilized to process SiC wafers. This approach leverages existing silicon processing equipment, with the addition of select specialized equipment unique to SiC processing. By fully integrating this SiC foundry with X-FAB's high volume Silicon foundry line, customers are able to leverage the economies of scale that have already been established with high volume silicon. To provide scalability, a Process Installation Kit approach has been implemented. This approach utilizes documented and characterized standard process blocks that can be integrated with proprietary process blocks such that the foundry customer can bring highly differentiated products to the market.

Technology Gap/Market Need

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

Accomplishments/Deliverables

X-FAB Texas has completed the extension of the SiC pilot line foundry to a full high-volume SiC production line and is now actively expanding its capacity further. Our initial device partners continued their volume production ramp and they, along with additional new customers, are qualifying and delivering products to the marketplace. Through the use of X-FAB standard process blocks, both existing and new customers are able to accelerate their time to market for initial and next generation products.

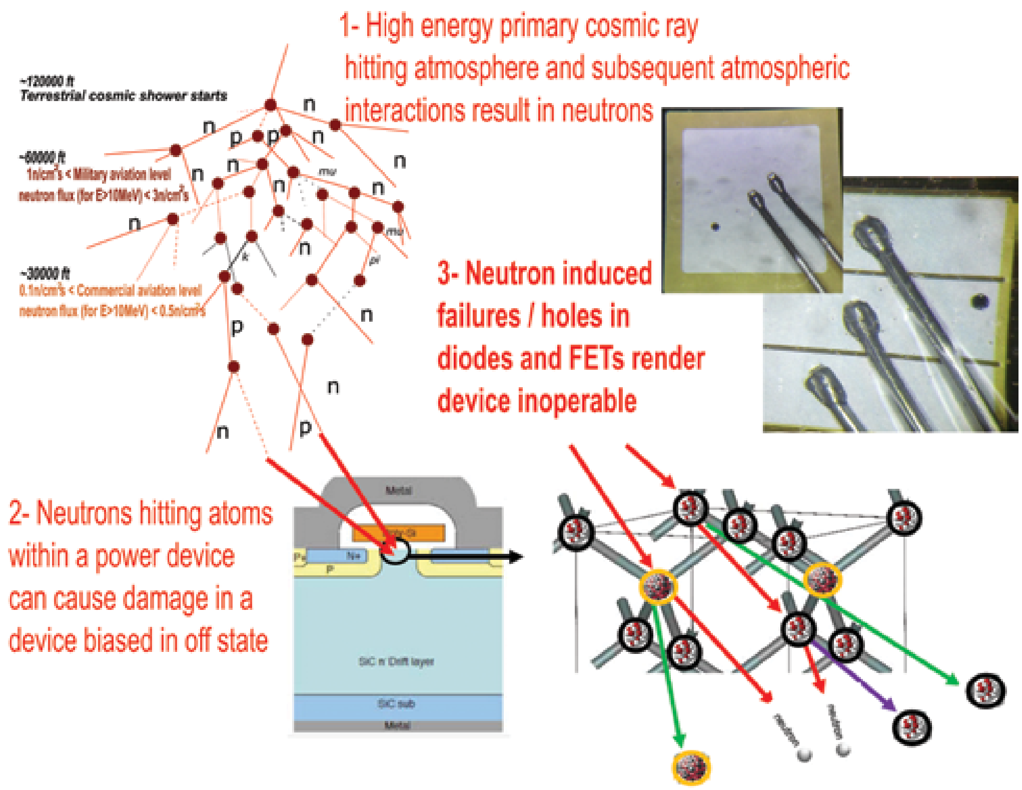
Initiated ongoing projects with select major universities to establish "Feeder Fabs" approach to provide access for small volume opportunities for R&D; start-ups and university products for customers who would not be able to afford access. When ready, these opportunities would allow swift transition to X-FAB for volume ramp.

The success of our customers in the market as well as the success of our standard process block implementation in shortening time to market is proof that the scalable foundry business model will support the needs of the SiC industry.

Impact/Benefits

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

CoolCAD Electronics: Quantifying Power Device Reliability Due to Terrestrial Radiation



Neutron radiation model.

Project Summary

This project is focused on measuring atmospheric neutron-induced failure rates in SiC power devices. Device and system failures due to cosmic rays or atmospheric neutrons on and above earth's surface have long been a problem for silicon power devices. Similar failures have also been observed in SiC power devices. To quantify failure rates in SiC power devices due to this background radiation, CoolCAD performs atmospheric neutron failure/reliability tests at Los Alamos Neutron Science Center (LANSCE), using a terrestrial neutron simulator with higher radiation levels, at biases of interest. The measurements are then used for obtaining bias dependent Failure-In-Time (FIT) curves for flagship SiC power devices of PowerAmerica members. The experiments also help with determination of failure mechanisms, the understanding of which would aid fabrication of more reliable and robust SiC power devices.

Technology Gap/Market Need

Providing failure rate curves to customers would ease the adoption of SiC power devices, especially by large power electronics companies, since they can predict the reliability and lifetime of their systems and circuits. Companies needing power devices for applications requiring deployment of large numbers of power devices may refrain from the use of SiC power devices without knowledge of failure rates due to the background radiation which power devices are known to suffer from.

Accomplishments/Deliverables

Terrestrial neutron experiments were performed successfully at Los Alamos Neutron Science Center using custom test boards and setups for SiC power devices. Up to 900 devices from six SiC device manufacturers were tested. Pre and post radiation characteristics were measured to determine possible performance drifts. Failure in time curves for the tested parts were calculated for these manufacturers to assess long term reliability of their parts in medium and large-scale applications.

Impact/Benefits

Understanding of terrestrial neutron-induced failure rates and failure mechanisms will aid fabrication of more reliable and long-term fail-safe power devices and circuits. Use of FIT curves will help fabrication of circuits and systems with significantly lower failure rates.

CoolCAD Electronics, partnered with Microsemi, Wolfspeed, Monolith, USCi, GeneSic, and SemiQ

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PowerAmerica Roadmap Targets

IMPROVING RELIABILITY

Commercial Applications

HYBRID/ELECTRIC VEHICLES

RENEWABLE ENERGY

AEROSPACE

GE Aviation Systems, LLC; GE Global Research, National Renewable Energy Laboratory

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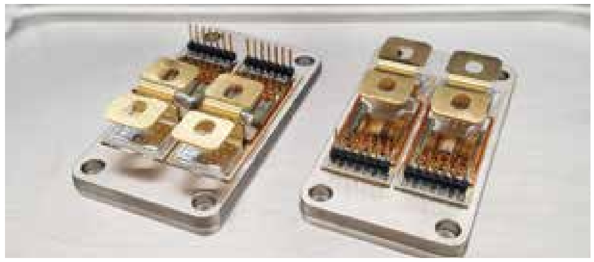
PowerAmerica Roadmap Targets

- REDUCING COST
- 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
- AEROSPACE
- HEAVY VEHICLES

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



(Left) GE Wirebond Free 1200V 475A SiC Modules. (Right) GE 1600A 475A Half Bridge 500A Six Pack.

Project Summary

GE Aviation's project provides five wide bandgap power modules of popular topologies to satisfy the need for advanced, reliable SiC and GaN complementary packaging. Standard IGBT packages are not suitable for WBG devices, yet new, high frequency capable packages have been a barrier to adoption. This project addresses PowerAmerica roadmap elements that include high performance power module packaging, and reliability and testing. GE has included the National Renewable Energy Laboratory (NREL) to support life modeling/analysis of module internal structures and interconnect 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.

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 will accommodate advanced cooling to achieve low Rth in order 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 entitlement 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 which replaces wirebonds with a planar copper interconnect layer.

Accomplishments/Deliverables

- Completed the build and testing of three WBG Module types using GE's 200°C SiC MOSFET die and delivered five of each type to the PowerAmerica Device Bank. Test report for each module was provided.
- Completed a 50 module qualification program to AEC-Q101 standard with +175°C Tj operation.
- Completed design of the full bridge rectifier. Awaiting components. Module was designed to accept multiple PowerAmerica members' SiC die.
- Design of GaN on POL Module in progress.
- A DC Link capacitor assembly was designed, built and tested to assist in the evaluation of the 48mm half bridge modules. Hardware is available to members of PowerAmerica.
- Interface circuit cards were designed, built and tested for the 48mm and 90mm half bridge modules. The interface card allows the modules to be tested using PowerAmerica member Agile Switch's commercial gate drivers. Hardware is available to members of PowerAmerica.
- GE Aviation has partnered with the National Renewable Energy Laboratory, which has developed thermal models and analyzed the packaging technologies, and will report to the membership as a third-party evaluator. NREL has performed thermal analysis, reliability analysis and structural analysis on the module packaging technologies.

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 gen technologies with 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 team.

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

(Left) Avalanche testbeds. (Right) High-temperature testbeds.

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 implemented 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 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 will be completed in budget period 5. 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 improving future generations of products and manufacturing techniques.

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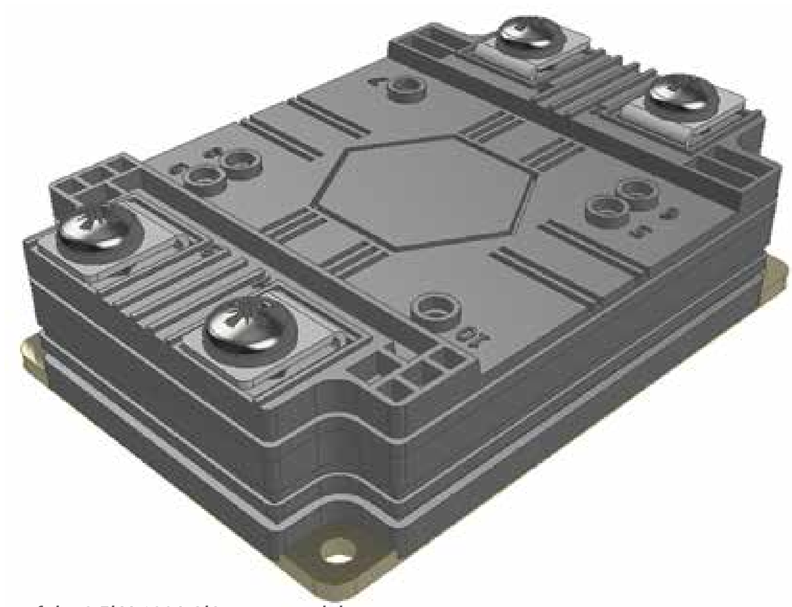
PowerAmerica Roadmap Targets

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

Commercial Applications

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

United Silicon Carbide: 100A, 6.5kV Half-Bridge Module



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

United Silicon Carbide, Inc.

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PowerAmerica Roadmap Targets

- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

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

Project Summary

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

The prototype modules have been manufactured. The prototype module can block over 6500V and has an on-resistance of 16.5mOhm at room temperature. The prototype module has been tested in an inductive load circuit. The testing results show the module can switch 10 times faster than Si counterparts. The module has a gate charge of only 247nC, and a reverse recovery charge of 14uC for the built-in body diode. With such excellent performance, the proposed module will revolutionize the design of megawatt power converters with higher switching speed, higher efficiency, and higher power density

Technology Gap/Market Need

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

Accomplishments/Deliverables

- The prototype 6.5kV-100A SiC module has been designed and manufactured.
- The prototype module has been tested, showing the module can switch 10 times faster than Si counterparts. The module has a gate charge of only 247nC, and a reverse recovery charge of 14uC for the built-in body diode.
- The SiC avalanche diode for use in the 6.5kV supercascode switch has been designed, fabricated and packaged.

Impact/Benefits

- The 100A-6.5kV SiC module would be the first commercially available SiC medium-voltage power module, enabling the quick penetration of SiC into multi-megawatt power conversion applications.
- The supercascode approach provides a high-performance and cost-effective solution to implement 4.5kV to 15kV medium voltage SiC power modules. The target cost structure is < 25$/A.
- UnitedSiC will launch engineering modules, which will add growth for the foundry and expand the supplier base for SiC-based medium-voltage modules. Impact on U.S. and worldwide energy efficiency will be significant. SiC power business growth creates employment opportunities for SiC supply chain providers, as well as advanced system developers.

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

6.5kV XHV-7 power module.

Project Summary

During this program, Wolfspeed was responsible for advanced configurations of 6.5kV SiC power modules through:

- Integrating Cree's latest generation of 6.5kV SiC MOSFETs and JBS diodes into an industry standard package;
- Developing 6.5kV, all-SiC diode phase leg, boost chopper, and buck chopper configurations;
- Performing initial JEDEC qualification tests on the diode phase leg module;
- Providing a reference design; and
- Providing comprehensive understanding of common-mode noise/EMI with the U. of Alabama (UA).

Technology Gap/Market Need

- U.S. 6.5kV all-SiC power module availability
- Global 6.5kV all-SiC diode bridge power module availability
- Global 6.5kV all-SiC buck and boost chopper power module availability
- Materials knowledge as a function of temperature for baseplate isolation and partial discharge standard conformance

Accomplishments/Deliverables

- High Current PCB bussing
  - 3-Phase tested and available
  - H-bridge tested and available
  - Laminated bussing design completed for final Evaluation Kit
- 6.5kV NPC Evaluation Kit spec document completed
- 6.5kV module parasitic analysis and measurements completed
- XHV-7 CM model developed and accurately predicted CM behavior of this system; CM model of power module only required characterization of baseplate capacitance values
- Delivered the following to the PowerAmerica Device Bank:
  - Six 6.5kV HB modules (H16ML16M), three 6.5kV HB modules (H26ML26M), three 6.5kV HB modules (H46ML46M) and one 6.5kV HB module (H86ML86M)
  - Six 6.5kV Buck Chopper modules (H16ML16D) and six (6) 6.5kV Boost Chopper modules (H16DL16M)
  - Six (6) 6.5kV Diode Bridge modules (H16DL16D)
- Laminated bussing design for the 6.5kV NPC phase leg was completed
- The UA MV EMI Characterization Testbed was completed
- NPC phase leg modelling and mixed-mode simulation were completed and compared
- Commutation path Application Note was completed
- 6.5kV Evaluation Kit testing was completed
- Validation of the CM model for the NPC with the optimized 6.5kV XHV-7 was completed

Impact/Benefits

1. Increase in efficiency, increase in volumetric/gravimetric density, with a reduction in losses in MV power electronic systems – using new industry standard footprints.
2. Market segments impacted: Rail, high-speed MV drives, grid-tied distributed generation and energy storage, FACTS controllers applied to sub-transmission and transmission systems.
3. Packaging designed to replace Si IGBT modules to enable an increase in end-system performance and available topologies, while mitigating potential sole source issues using an industry standard footprint.
4. WBG MFG Cost is reduced as device and module volumes start to approach economy of scale.
5. Job creation for highly technical R&D/MFG/Process Control personnel, as well as for highly skilled technicians to support design and production.
6. Proposed publications and reference designs are focused on WBG module/system design education for WBG industry development of all levels; supplemented through development of supporting module circuit simulation models.
7. Supports supply chain development for the ONLY vertically-integrated WBG supplier.

Wolfspeed A CREE COMPANY

THE UNIVERSITY OF ALABAMA

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PowerAmerica Roadmap Targets

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

Commercial Applications

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

ABB: Modular SiC-based 3-phase AC/DC Front End Rectifier with 99% Efficiency

ABB, Inc.

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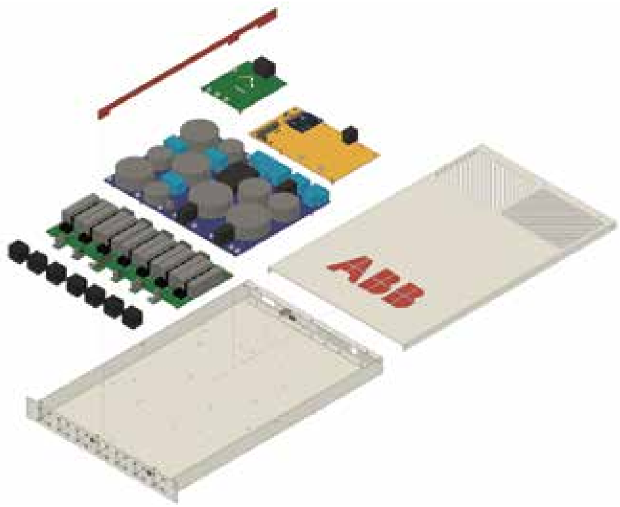
PowerAmerica Roadmap Targets

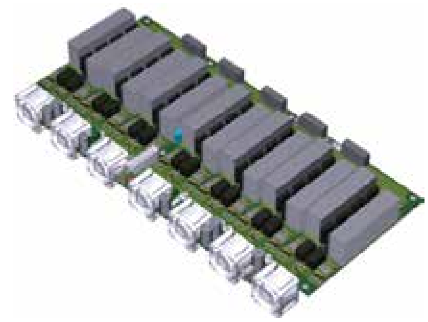
ENHANCING PERFORMANCE CAPABILITIES

Commercial Applications

UPS
DATA CENTER



(Left) 1u-assembly.



(Right) SiC phase legs.

Project Summary

This project is to develop and demonstrate a 20kW single-stage three-phase indirect matrix rectifier using SiC MOSFETs. The rectifier converts universal AC input voltage (380VAC – 480VAC) to 400VDC nominal (290V – 400VDC). The target efficiency is 99% or higher and the rectifier is fitted in an industry standard 1U rack mount power supply form factor with all the EMI/EMC filters to be able to comply with FCC part 15 class B both conducted and radiated EMI standards. Novel control strategies will enable easy paralleling of the rectifiers to scale up the power.

Technology Gap/Market Need

This project demonstrates the architecture enabled by the proposed topology and SiC devices. The high-efficiency and high power-density rectifier lowers the installation cost and Total Cost of Ownership (TCO) for the customers. The project will deliver the knowledge of circuit design and implementation with SiC devices. This will give a jump-start for the silicon device user to shift to SiC devices. Therefore, these measures will promote and expedite the adoption of SiC devices in data center applications.

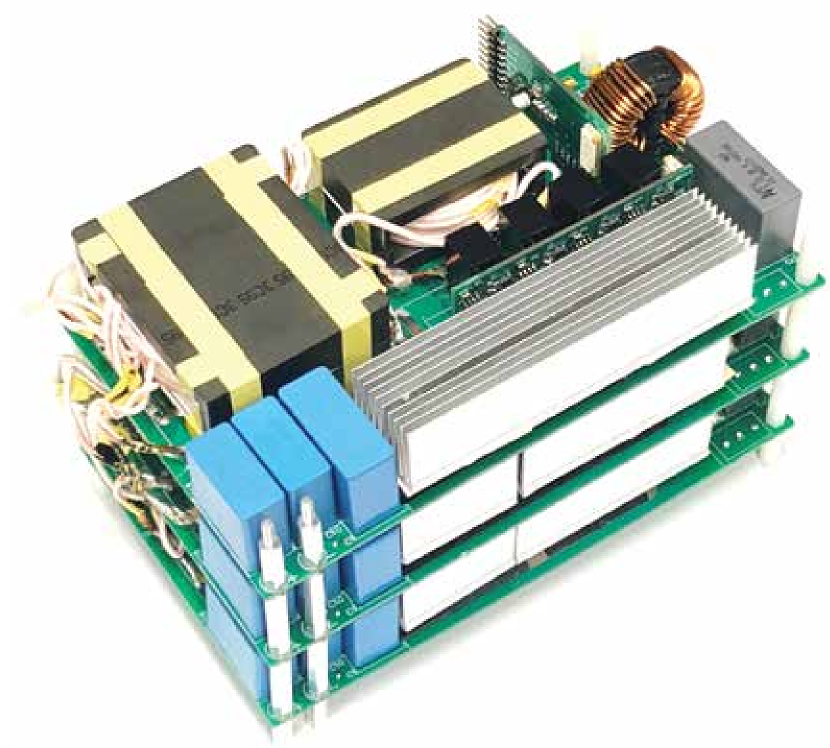
Accomplishments/Deliverables

- SiC device selection was completed. Wolfspeed's 1000V SiC MOSFETs are used in the rectifier.
- Full system powertrain hardware has been developed and segments have been verified in power testing up to 13kW.
- Full system thermal-mechanical design was completed and an enclosure of 17" x 27" x 1.56" was fabricated.
- Converter closed-loop control firmware development has been completed and verified with Hardware-in-Loop (HIL).
- Full system in closed-loop control has been tested up to 13kW in certain operating ranges (380VAC input and 300VDC output).

Impact/Benefits

- If successful, this technology will lead to a multi-million annual dollar business for the SiC device manufacturers alone.
- Potential for job creation through increased investments in data center infrastructure and equipment manufacturers.
- Workforce development and education-focused meetings will be planned with NCSU and Virginia Tech to share the project results and discuss technical issues.
- Improved U.S. competitiveness by using only SiC devices made by PowerAmerica members. Concept will have a deep impact on a wide range of data center-related products.

Arizona State University: Isolated, Soft Switching SEPIC with Active Clamp for 480V AC to 400V DC Rectifier for Data Centers



Phase-modular, active-clamp SEPIC based 10kW rectifier for data center applications.

Arizona State University, ON Semiconductor

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PowerAmerica Roadmap Targets

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

Commercial Applications

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

Project Summary

The project aims to develop a high-performance, modular rectifier for power conversion from a three-phase 480V AC source to a controllable 400V DC bus. The target application is in DC-powered data centers with 400 DC distribution bus. The proposed design will exploit the superior features of SiC power devices to achieve very high efficiency (98% for transformer-isolated, single-stage power conversion) and very high power density (> 100W/inch3 for the complete AC to isolated DC solution including heatsinks and EMI filters meeting FCC 15 Class B). The prototype will be developed at 10kW power level using 1200V SiC MOSFETs and diodes, and will be capable of modular configuration to support over 100kW systems.

Technology Gap/Market Need

This project addresses the need for a single-stage, isolated AC-DC three-phase power factor correction circuits with very high efficiency and power density.

Accomplishments/Deliverables

Achieved >97% efficiency and power density of 116W/inch^3 and switching frequency of 200kHz for a PFC with high-frequency transformer isolation, and developed a patent-pending totem-pole configuration of active clamp SEPIC based single-phase PFC.

Impact/Benefits

By demonstrating high performance in terms of efficiency, power density, soft switching with SiC devices along with efficient high-frequency magnetics, the project accelerates the adoption of SiC devices in data center and electric vehicle charger applications.

Florida State University: Transformer-less Medium Voltage Central PV Inverter

Florida State University, GE Aviation Systems

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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
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- INDUSTRIAL MOTOR DRIVES
- POWER QUALITY
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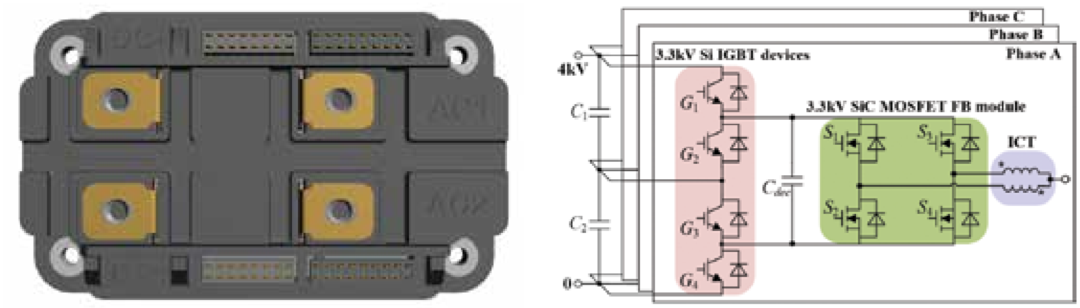
- HEAVY VEHICLES



Phase-modular, active-clamp SEPIC based 10kW rectifier for data center applications.

Project Summary

We have designed a downscaled transformer-less medium voltage central PV inverter, which is a 200kW/ 2.7kVAC magnetic coupled 5-level prototype with 3.3kV hybrid SiC/Si devices. In this project, the first 3.3kV SiC-MOSFET full-bridge power module is developed by GE Aviation Systems with advanced direct-bond-copper (DBC) technology. The FSU team has designed PCB busbars, gate driver circuits and inter-cell transformers (ICTs) with up to 5kV insulation capability. ICT's saturation issue has been analyzed and simultaneously verified. The inrush current issue has been suppressed to achieve the low temperature rise of sensitive components. An efficient thermal management method has been developed to reduce auxiliary power loss and improve power density. This project will demonstrate that a SiC/Si hybrid transformer-less medium voltage PV inverter can obtain performance advantages that cannot be achieved by full-Si-based and even full-SiC-based counterparts and is ready to be commercialized. Finally, this project has continued to educate undergraduate students and graduate students in WBG circuit design, thermal design, and high-voltage insulation design training.

Technology Gap/Market Need

Transformer-less medium voltage PV central inverters implemented by high voltage devices can save the cost and power loss of bulky line-frequency transformers. The use of high voltage Si-IGBTs (3.3kV and higher) with limited switching frequency (usually under 10kHz) dramatically impacts the overall converter size. Alternatively, the advent of high voltage SiC devices enables MV PV inverters to be more attractive. The technology developed in this project adopts the SiC/ Si hybrid configuration to effectively reduce overall converter cost and meanwhile achieve high system performance. This project also developed the world's first 3.3kV SiC-MOSFET full-bridge power module with advanced DBC technology.

Accomplishments/Deliverables

Our goal is to develop a downscaled transformer-less medium voltage inverter, 200kW/ 2.7kVAC magnetic coupled 5-level prototype with 3.3kV hybrid SiC/Si devices and 5kV ICT technology. This prototype was fabricated using the 3.3kV SiC MOSFET full-bridge power module developed by GE Aviation Systems. GE Aviation developed this first of its kind high-voltage SiC full-bridge power module using power overlay (POL) interconnect technology. POL provides a low inductance wire-bond free power switch assembly. The POL packaging enabled two half-bridge assemblies to fit within the smaller 62mm module format resulting in the full-bridge topology power module.

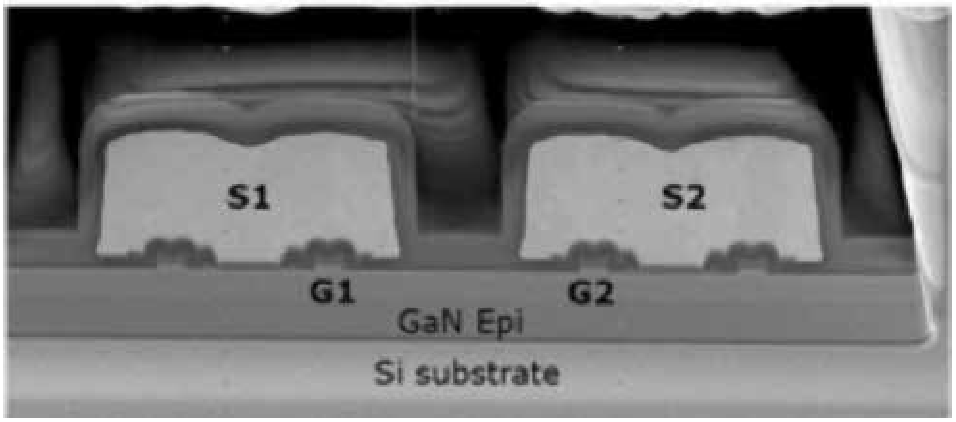
Specific deliverables include:

- 3.3kV SiC-MOSFET full-bridge power module design.
- Up to 5kV insulation design for PCB busbars, gate driver circuits and ICTs.
- ICT's anti-saturation control and current-sharing control.
- Inrush current suppression with proposed 3-level gate driver method.
- An efficient thermal management method based on pin-fin heatsink.
- Three undergraduate and three graduate students have been trained in this project.

Impact/Benefits

The commercial transformer-less medium-voltage central PV inverter can adopt the developed technology to achieve lower system cost, higher efficiency and lighter weight. The developed technology can be applied to other applications including motor drive and energy storage system. The developed 3.3kV SiC-MOSFET full-bridge power module can also be adopted in other applications including MMC and CHB center and electric vehicle charger applications.

Infineon: 600V GaN Dual Gate Bidirectional Switch



Monolithic GaN Bidirectional switch in Infineon's CoolGaN™ HEMT Technology

Project Summary

Infineon offers the highest quality discrete GaN-on-silicon devices based on its CoolGaN™ HEMT technology. The key objective of this project is to develop a unique low-cost 600V GaN Bidirectional switch (BDS or BiDi) in our CoolGaN™ technology and validate its superior figures of merit to state-of-the-art super-junction devices in bidirectional configuration. A dual gate common drain monolithic GaN BDS structure was fabricated. The resultant device demonstrates a very high breakdown voltage of >900V for dual polarity with very low on state resistance (Ron*A) of 4.85 mΩ-cm2. Monolithic GaN BDS exhibits much better figures of merit (FOMs) compared to even the best-in-class silicon super junction devices in BDS configuration. We've also addressed one of the major technology challenges of substrate instability due to its floating nature in GaN BDS with our patent-pending solutions and demonstrated stable switching behavior of the GaN BDSs at high voltages.

Technology Gap/Market Need

The GaN-based Bidirectional switch is a basic building block for many power conversion systems because of its unique ability to block and conduct in both directions, GaN BDS plays a key role in DC-DC, AC-DC as well as AC-AC conversion for applications such as SMPS, SSRs, matrix converters, etc. To the author's knowledge as this article is written, currently there are no GaN-on-silicon-based Bidirectional switches commercially available in the market. This novel concept of dual gate common drain monolithic GaN BDS offers a much smaller footprint compared to a silicon-based super junction device due to its lateral nature (~4x area improvement). Silicon technology has reached its theoretical limits and when it comes to applications where high power density and high frequency are required, a GaN-based solution is a much better option.

Accomplishments/Deliverables

We processed one full lot with 24 GaN-on-silicon wafers at Infineon's fab with monolithic dual-gate common drain GaN BDS designs. We demonstrated the concept design working in both AC and DC conditions with all four combinations of the gate voltages either as a switch or a diode. For DC mode, the device has bidirectional blocking voltages >900V. We showed that GaN BDS has much better figures of merit compared to best-in-class super-junction devices in bidirectional mode. We also verified switching data for the GaN BDS at high voltages and proved that our solutions can pin the substrate to much lower voltages compared to a standard case where it floats to high voltages in switching conditions.

Impact/Benefits

GaN-on-silicon, being a lateral technology, enables monolithic integration and hence a GaN-based Bidirectional device is possible as a single switch unlike any other technologies, such as Si or SiC where multiple components are needed to perform Bidirectional power flow functionality. GaN BDS can have all the technology advantages of GaN such as near-zero reverse recovery losses, high dv/dt switching speed and smaller footprint, etc. With lower switching and conduction losses compared to conventional silicon solutions, GaN BDSs can offer much better efficiency improvement in AC-DC or DC-DC conversion applications. It can be used in conventional applications such as SSR, high power SMPS, solar, automotive, motor drive and novel applications such as AC or DC conversion switch. Upon market adoption, this technology product will aid job creation for the U.S. market in the field of device design, manufacturing, packaging, applications and characterization.

Infineon Technologies Americas Corp

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PowerAmerica Roadmap Targets

- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES
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Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- RENEWABLE ENERGY
- INDUSTRIAL MOTOR DRIVES
- UPS DATA CENTER

John Deere Electronic Solutions, Inc. (JDES) – a business unit of Deere & Company in partnership with National Renewable Energy Laboratory (NREL)

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PowerAmerica Roadmap Targets

- IMPROVING RELIABILITY
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- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN
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Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- MILITARY
- HEAVY VEHICLES

John Deere: Power-Dense Engine-Coolant 200kW 1050 V DC Bus SiC Inverter for Heavy-Duty Vehicles

Power-density and capability progression of JDES's inverters.

Project Summary

The JDES project resulted in the design, manufacture and experimental validation of a modular 200kW 1050 VDC SIC dual inverter. The John Deere team has gotten closer to commercialization cost targets by reducing the number of SiC die in a six-pack SiC power modules from 48 to 30 die. A power-dense (43 kW/L) energy-efficient (>98% at 150kW power with coolant sweep from 25°C to 115°C) high-temperature (engine-coolant-capable) SiC inverter has been tested for ambient temperature sweep from 25°C to 75°C) and water-ethylene-glycol (WEG) coolant sweep from 25°C to 115°C while both sides of the SiC dual-inverter handle ~150kW power. Test results have proven that the 105°C rated 440 μF film capacitor module used in the 200kW SiC dual-inverter remains below 85°C hot-spot for about 10 minutes operation of the inverter at 150kW with 115°C WEG coolant flowing through inverter, therefore, the cyclic load profile required by the heavy-duty vehicle film capacitor and the rest of the electronic components will remain below their maximum temperature limit. This indicates that in a real-world application, this engine-coolant-capable power-dense SiC dual inverter will meet reliability and durability goals.

The DOE NREL has provided excellent engineering support in the timely execution of project tasks and milestones. Thermal analysis performed by NREL during the design stage quantified thermal performance, including the peak loading capability. Thermomechanical analysis was also performed to quantify potential reliability issues as compared to commercially available silicon inverter systems.

Technology Gap/Market Need

The technology gaps that the project worked to fill within industry included the following three items. First, the project was a direct application demonstration of potential WBG system cost advantages. This includes the sizing of inverter components such as DC capacitors, power density benefits, fuel efficiency improvements, and integration benefits with the vehicle engine coolant. 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.

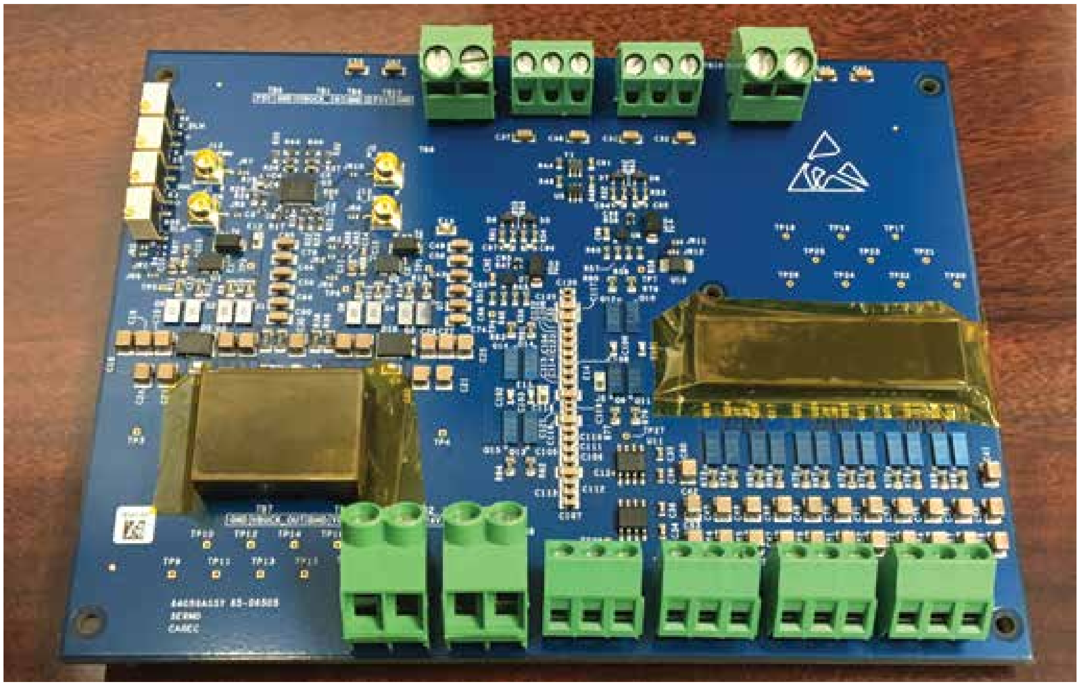
Accomplishments/Deliverables

The key accomplishment achieved during the project was the manufacture and hardware demonstration in JDES laboratory by simulating heavy-duty load profile and testing inverter under high-ambient (up to 75°C) and high-temperature-coolant (up to 75°C). Under this condition, the gate driver and all temperature sensitive electronics remained below 130°C. The John Deere team demonstrated high-capability and high-performance WBG power conversion technology by proving out a high power (150 kW continuous and 200 kW peak) SiC dual inverter system capable of full engine coolant operation up to 115°C.

Impact/Benefits

John Deere's team demonstrated a power-dense engine-coolant-capable high-efficiency SiC inverter system. The power density was improved to 43kW/L while capable of operation with 115°C coolant that is shared with the engine cooling system. The power-dense SiC inverter will enable integration of the inverter, traction motor and vehicle powertrain (gear box for speed and torque shift) in one assembly. Similarly, combustion engine, electric generator and generator inverter can also be integrated in one assembly. This has become possible due to the realization of the power-dense and high-temperature SiC inverter. The engine-coolant-capable SiC inverter will further simplify vehicle architecture due to the elimination of a dedicated cooling-pack required in the case of Si IGBT inverter-based drivetrain system - the SiC inverter no longer needs dedicated cooling pack. The miniaturized SiC inverter allows significant modularity and a common assembly that could be useful for many vehicle platforms with varying power levels. This will support John Deere to achieve higher number of inverters/year, all aggregated from many applications on different vehicle platforms. This will further accelerate objectives; cost reduction, realization of commercialization target, and proliferation of the WBG technology beyond niche and early adoption applications.

Lockheed Martin: High Frequency GaN Power Conversion



Virginia Tech high-density power converter using GaN power switches achieve 700W/in^3 power density.

Project Summary

Lockheed Martin worked with the Virginia Tech Center for Power Electronics Systems and VPT to understand the capabilities of GaN power MOSFETs and their performance when switching at high frequencies in a power module. The project investigated the performance of high switching frequencies and the ability to achieve high power density using these technologies. Virginia Tech developed a very high-density power converter using GaN power switches achieving 700W/in^3 power density. Lockheed Martin and VPT leveraged the knowledge derived from VT CPES work to realize similar designs that provide understanding of the performance using the high-frequency switching GaN power MOSFETs. The development of these power modules helped investigate the capabilities of the surrounding components that enable fast switching power conversion. Through these combined efforts the project helps enable workforce education for VPT and Lockheed Martin providing the capability to realize GaN power converters for their products.

Technology Gap/Market Need

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

Accomplishments/Deliverables

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

Impact/Benefits

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

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PowerAmerica Roadmap Targets

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

Commercial Applications

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

North Carolina State University: Asynchronous Microgrid Power Conditioning System Connector to Microgrid

NC STATE UNIVERSITY

North Carolina State University

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PowerAmerica Roadmap Targets

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Commercial Applications

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

Project Summary

The goal of the project is to design, develop, optimize and test the isolated and bidirectional Dual Active Bridge (DAB) DC-DC converter and integrate it with Active Front End Converter (AFEC) for implementing the Asynchronous Micro-grid PCS (Power Conditioning System) as MV-MV SST. To achieve MV DC bus of 22kV the converter 3-level NPC [Neutral Point Clamped] poles are designed with two series-connected SiC 10kV MOSFETs per switch. The tasks include in-depth analysis and simulation of the whole system under different operating conditions. DSP and FPGA-based controller boards were implemented. Full scale hardware, including the three-level Neutral Point Clamped (NPC)-based Dual Active Bridge (DAB) was built and tested with integration of AFEC, at full load conditions. This will implement the complete Asynchronous Micro-grid PCS with AFEC on both MV sides and DAB as the intermediate DC/DC isolated and bidirectional converter.

Technology Gap/Market Need

The Microgrid PCS connector is required for all Microgrid PCS connections to the utility grid or microgrid-to-microgrid connection. This solution eliminates the 60Hz line frequency transformers and achieves higher power density with HV SiC 10kV MOSFETs based PCS. This PCS will accelerate the adoption of MV power conversion systems in several applications.

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

Accomplishments/Deliverables

- Continuous heat run test of the latest XHV-9 power modules with 10kV SiC MOSFETs.
- Development of a high-frequency transformer with reduced coupling capacitance for operation of isolated and bidirectional DAB DC-DC converter.
- Single phase 3-level NPC-based DAB DC-DC converter enabled by single 10kV SiC MOSFET or two series connected 10kV SiC MOSFETs per switch.
- Three phase 3-level NPC-based DAB DC-DC converter enabled by single 10kV SiC MOSFET or two series-connected 10kV SiC MOSFETs per switch.
- Integration of 3-phase DAB DC-DC converter and AFEC system enabled by single 10kV SiC MOSFET or two series-connected 10kV SiC MOSFETs per switch.

Impact/Benefits

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

Currently, Pareto energy is the main supplier of the Microgrid Power Conditioning Connectors, which have maximum efficiency of 88-92%, implemented with low voltage (1200V) Si IGBTs and bulky 60Hz line frequency transformers on both MV sides, with high system cost of $1M/MW. In today's world of advanced power electronics with WBG power devices, this solution can easily be improved. A quantum jump in power density and reduction of footprint size, weight and volume is possible with HV SiC 10kV MOSFETs. Further, this can be enabled by forced air or heat pipe-based cooling rather that liquid cooling.

Medium-Voltage DC (MVDC) Transmission has received considerable attention as an alternative to the HVAC transmission. DAB DC-DC converter is an optimal topology for implementing bidirectional DC/DC converter with galvanic isolation for MVDC applications. It can provide bidirectional power flow at MW power scale with minimal losses and reduced footprint of the converter. The BP4 deliverables will lead to successful building of a three-phase Dual Active Bridge (DAB) at medium voltage (MV) scale of 22kV DC bus. This will be the first DC/DC converter in the world operating at switching frequency of 20kHz. The development and successful operation of DAB DC-DC converter at MV level can open a new avenue for intelligent MVDC applications.

National Renewable Energy Laboratory: Power-Dense Engine-Coolant 200kW 1050V DC Bus SiC Inverter for Heavy-Duty Vehicles

Rendered CAD model of the Gen-2 Inverter built and tested by John Deere. Image was generated and provided by John Deere.

Project Summary

This project, led by John Deere, resulted in the design, manufacture and experimental validation of a 200kW 1050 VDC silicon carbide (SIC) dual inverter. NREL's role in the project was to support JDES in the thermal design optimization and thermo-mechanical modeling of critical inverter components. The JDES/NREL thermal design for the wide bandgap inverter enables improved performance and integration within the full range of engine cooling system temperatures (≤115°C). Thermal analysis performed by NREL in partnership with JDES during the design stage quantified thermal performance, including the peak loading capability. Thermomechanical analysis was also performed to quantify potential reliability issues as compared to the commercially available silicon inverter systems.

Technology Gap/Market Need

The technology gaps that the project worked to fill within industry included the following three items. First, the project was a direct application demonstration of potential WBG system cost advantages. This includes the sizing of inverter components such as DC capacitors, power density benefits, fuel efficiency improvements, and integration benefits with the vehicle engine coolant. Second, the project supports training and workforce development of WBG technologies and applications. Finally, the project supports the U.S.-based design and manufacturing of WBG systems.

Accomplishments/Deliverables

The key accomplishment achieved during the project was the manufacture and hardware demonstration by John Deere of the high power SiC dual inverter system capable of full engine coolant operation up to 115°C. NREL contributed to several supporting accomplishments including:

- Performed analysis for severe thermal load conditions for estimation of temperature distribution within the module package.
  - Evaluated power module temperature gradients as a function of load, position, and time.
  - Evaluated cooling system impacts and coolant flow distribution as affected by extreme thermal loading and uneven thermal loading.
- Developed thermo-mechanical models to investigate and compare module stresses resulting from thermal loading profiles in relation to the inverter mechanical design.
  - Developed thermo-mechanical models to investigate and compare module stresses resulting from thermal loading profiles and the impact of the inverter housing thickness.
  - Completed a study showing substrate and die attach strain energy density from thermal cycling within the full inverter enclosure.
  - Completed a study showing die attach strain energy density from thermal cycling was primarily independent of the die location within the overall module.

Impact/Benefits

The John Deere-led project demonstrated a power-dense engine-coolant-capable high-efficiency SiC inverter system. The power density was improved to 43kW/L while capable of operation with 115°C coolant that is shared with the combustion engine cooling system.
The demonstrated ability to operate with coolant temperatures up to 115°C resulted in the successful elimination of a dedicated cooling system required for the current commercial Si IGBT-based inverter system. The reduced size resulting from the increased power density supports the implementation of the technology across vehicle platforms.

National Renewable Energy Laboratory (NREL) partnered with John Deere Electronic Solutions (JDES)

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PowerAmerica Roadmap Targets

- ENHANCING PERFORMANCE CAPABILITIES
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Commercial Applications

- HYBRID/ELECTRIC VEHICLES
- HEAVY VEHICLES
- MILITARY

The Ohio State University
John Deere
Wolfspeed
A CREE COMPANY

The Ohio State University
John Deere
Wolfspeed

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PowerAmerica Roadmap Targets

- IMPROVING RELIABILITY
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Commercial Applications

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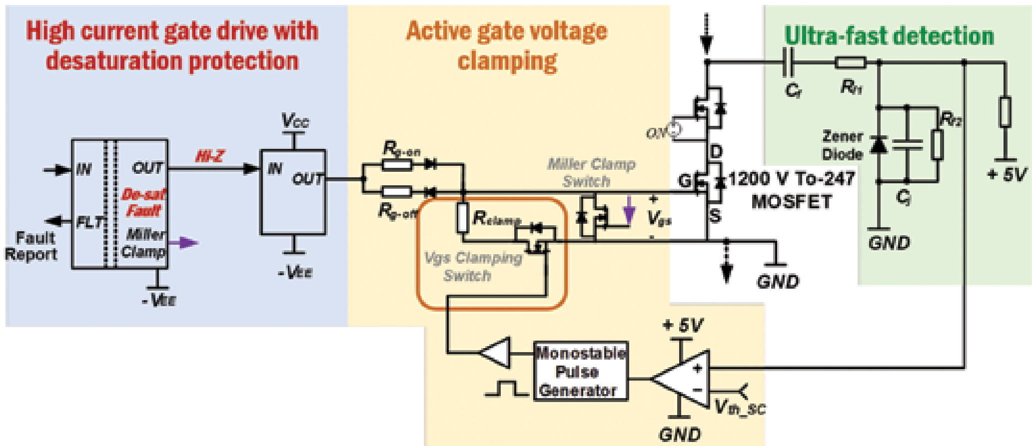
The Ohio State University: Short-Circuit Behavior and Protection of Next Generation 1.2kV SiC Modules and Devices



The three-step protection method:

Step 1: Ultra-fast detection: fast response to detection voltage dip on the FDC snubber capacitor

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

Step 3: Confirmation: based on desaturation detection and soft shut down

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

Project Summary

The project aims to test up to 40 SiC modules and 100 TO247 SiC devices 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 devices and finished short circuit capability evaluation of devices from four device makers at three different temperatures.

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

Toshiba: Development, Demonstration and Commercialization of SiC-Based 1MW Medium Voltage Motor Drive System

The Toshiba project team.

Project Summary

The objective of the project is to develop and commercialize a 1MW SiC-based Medium Voltage Motor Drive (MVD) System for the general-purpose MVD market (50/60 Hz motor) and regeneration MVD market (four-quadrant operation). The expected outcome of this project is an industry-level 1MW SiC MVD system tested with 4kV 1MW motor and 4.16kV Grid. The inverter portion achieves 99.2% efficiency and the active rectifier portion achieves 99% efficiency under full-load conditions. The 1MW SiC MVD system achieves four-quadrant operation.

This work serves as a pilot study for a future generation of SiC-based integrated medium voltage drive systems, which will significantly advance high-power density transformerless drive technologies, improve overall system efficiency, and reduce the weight of medium voltage drive system. The evaluation and verification of SiC power modules in this project increases the possibility of adopting wide bandgap devices in industries, which is creating more U.S. manufacturing job opportunities.

Technology Gap/Market Need

Conventional MVDs require a multi-pulse transformer for 4.16kV power grid connection, and uses Si-based Insulated Gate Bi-polar Transistor (IGBT) as power devices, which limited efficiencies to the 85-94% range.

The SiC-based MVD designed and built in this project is the world's first commercial level 1 megawatt 4.16kV active-front-end MVD which utilizes a full wide bandgap power semiconductor. The adoption of a SiC semiconductor device, with proper control, dramatically increases the efficiency to 99.2% for the inverter portion and 99% for the active rectifier portion under full-load conditions. The weight of the entire system is reduced to almost 50% of the conventional design because the multi-pulse transformer is removed from the system as one of the benefits of using a wide bandgap semiconductor device.

Accomplishments/Deliverables

At the end of this project, the expected accomplishments include the first commercial level 1 megawatt full wide bandgap semiconductor-based active-front-end 4.16kV MVD System in the United States for general-purpose MVD market and regeneration MVD market, and evaluation report of new SiC-based 3.3 kV and 6.5 kV switching devices and power modules.

Impact/Benefits

The wide bandgap semiconductor-based Medium Voltage Drive 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 which utilizes a full wide bandgap power semiconductor. The technology and product in this project enhances the leading position of United States in power and energy industry, and serves as a milestone for a future generation 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 United States. 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 boosting the United States economy and the share of U.S.-manufactured products in the global market.

TOSHIBA

THE OHIO STATE UNIVERSITY

Toshiba International Corporation partnering with The Ohio State University

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PowerAmerica Roadmap Targets

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

Commercial Applications

- INDUSTRIAL MOTOR DRIVES

UNC CHARLOTTE EPIC

ATOM POWER

University of North Carolina at Charlotte
Industry Partner: AtomPower Inc.

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PowerAmerica Roadmap Targets

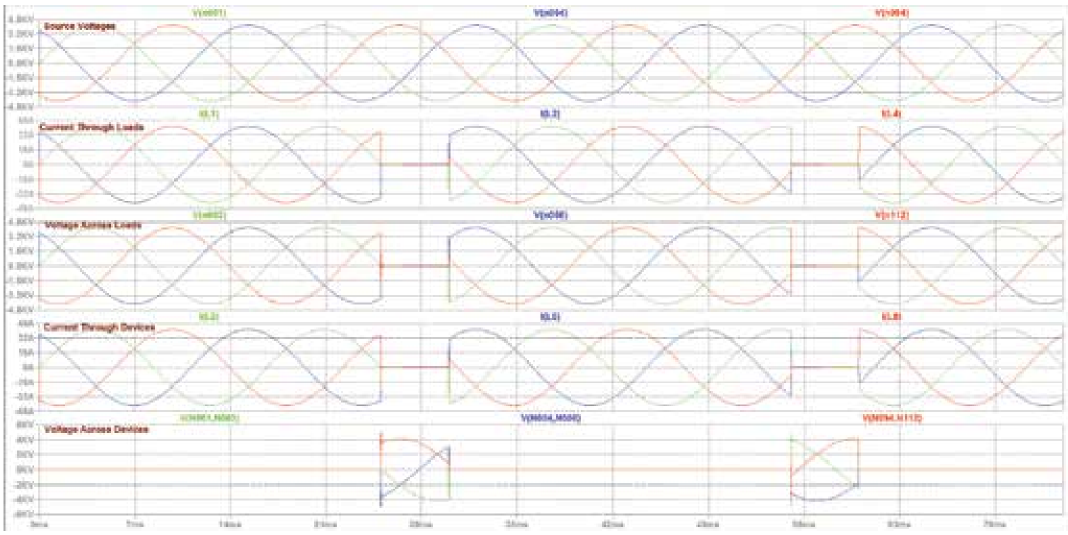
BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

ELECTRIC POWER GRID

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



SPICE Simulation results of the JFET based supercascode MVSSCB design.

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 (MVSSCB). The transition in the protection field from electromechanical breakers towards solid-state started with low voltage SiC devices in 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

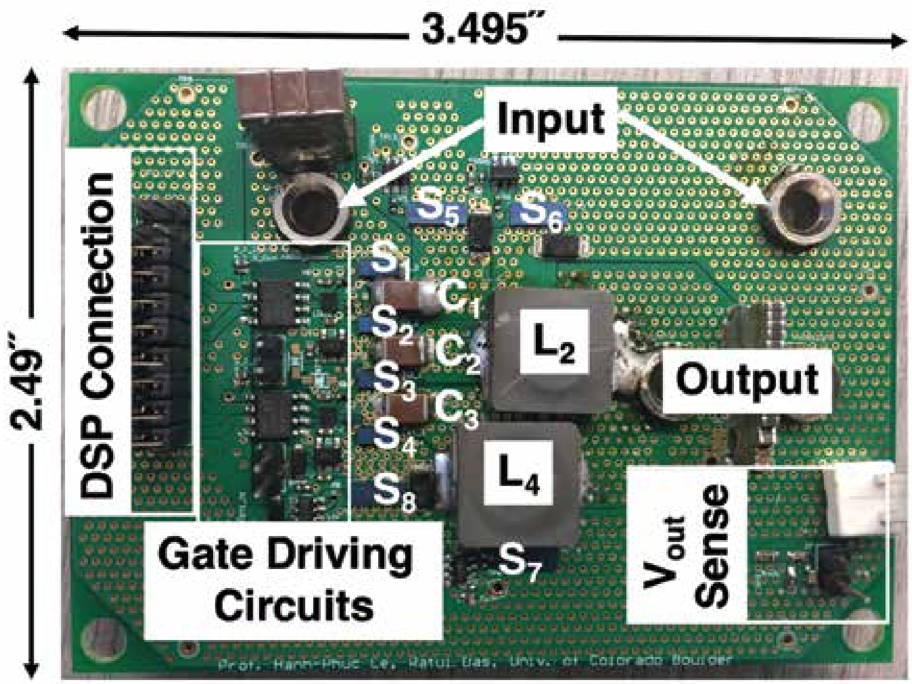
A comprehensive review of prior art in the design and application of WBG-based solid state breakers was carried out, along with commissioning and operation of UNCC's FlexLab 1MW 460/4160V Energy Loop for MVSSCB testing. For housing the prototype, a medium voltage DUT (device under test) enclosure was adapted from an inverter enclosure donated by Parker Inc. Finally, detailed modeling and simulation of a SiC JFET Super-Cascode design for the MVSSCB was carried out. A system reference and design report were provided covering: architecture, circuit topology and simulation results.

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 MVSSCBs through partnership with the WBG industry (eg: United SiC, Wolfspeed) for provision of SiC hardware, combined with leveraging AtomPower'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.

Photo of FlexLab Breaker testbed showing DUT enclosure and two 480V/4160V 1MVA transformers.

University of Colorado, Boulder: Dual-Inductor Hybrid Converter for Direct 48V To Sub-1V POL DC-DC Module



A regulated 48V-to-1V/5V Hybrid Converter for POL applications in data centers and telecommunication systems, achieving 100A peak output current, and peak efficiencies of 90.9% at 1V/26.7A output, 93.6% at 2V/28.3A, and 95.6% at 5V/40A.

Project Summary

This project develops a novel direct 48V-to-1V DC-DC conversion using a novel GaN-based, multi-inductor-hybrid (MIH) converter architecture, which has substantial advantages compared with state-of-the-art solutions for large conversion ratios and high output currents, including an overall >10X higher output current density, and more than 2X loss reduction. The DIH converter utilizes a multi-level approach and low-voltage GaN devices, leading to significant size reduction for critical passive components, and eliminating the need for electrolytic capacitors. The converter demonstrations and technology evaluation will be done in collaboration with industry partner, Lockheed Martin.

Technology Gap/Market Need

This project's main goal is to provide a new power delivery platform, both power-efficient and space-efficient, for a growing network of power-hungry data centers and telecommunication systems. Data center networks around the world have become the backbone of online information traffic estimated to triple from 4.7 ZB/year in 2015 to 15.3 ZB/year in 2020, accounting for ~73 billion kWh in power consumption in 2020, the equivalent of ~$7.3 billion cost of electricity, in the U.S. alone. Traditional power delivery has been costing ~15% of the total power consumption, i.e. ~11 billion kWh or $1.1 billion, because of inefficiency in power conversion stages, not to mention the growing need for land and space. In addition, space limit and power delivery inefficiency together drastically increase stress on system cooling efforts and high associated costs. This project provides a promising solution to mitigate these problems.

Accomplishments/Deliverables

- A generation-1 (1V, 50A, 93%, 100W/in³) converter unit with lab-test results, including student engagement report
- A generation-2 (1V, 100A, 94%, 500W/in³) converter unit with test results using practical loads in Lockheed Martin
- A generation-3 (1V, ~200A, 95%, ~1000W/in³) converter with performance and EMI test results.

Impact/Benefits

- This project and its results contribute to facilitate a faster adoption of WBG devices across various market segments, especially in power delivery for data centers and telecommunication systems.
  - Mass production will in turn reduce the cost of WBG devices compared with Si devices, especially for power electronics applications.
- The results of this project when applied to real-life systems can contribute to reduce the $1.1 billion loss in the U.S. data center power consumption alone.
- The project helps train the next generation of skilled engineers in WBG technology, so far contributing a Ph.D. student and two undergraduate students.

University of Colorado Boulder

LOCKHEED MARTIN

University of Colorado, Boulder
Lockheed Martin

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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

UPS
DATA CENTER

University of Tennessee, Knoxville: GaN-based High-Efficiency Multi-Load Wireless Power Supply

THE UNIVERSITY OF TENNESSEE KNOXVILLE

University of Tennessee, Knoxville

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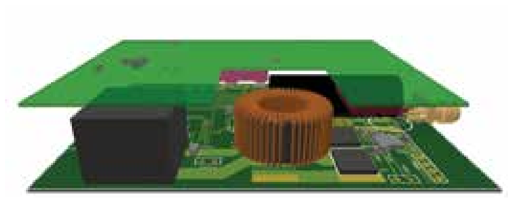
PowerAmerica Roadmap Targets

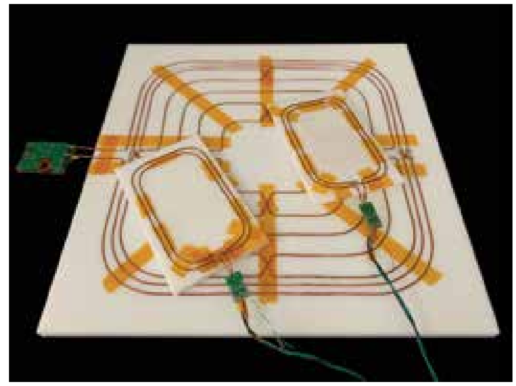
ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

MOBILE CHARGER ADAPTER





(Left) 100W PFC + 6.78 MHz transmitter and (RIGHT) protype multi-receiver WPT system

Project Summary

Leveraging the capabilities of GaN devices, and employing simultaneous co-design of power electronics and RF filtering systems, this project has designed and demonstrated a completely wirelessly-powered workstation. A single, 6.78MHz, GaN-based transmitter wirelessly powers up to 100 W of mobile electronics placed anywhere within a half-meter square charging area with high end-to-end efficiency and high transmitter power density.

Technology Gap/Market Need

For consumer electronics, wireless power transfer (WPT) represents the ultimate transition away from wired technology; the commercialization of WPT technologies represents a paradigm shift comparable to the development of WiFi and Bluetooth before it. Unfortunately, current commercial WPT systems exhibit poor efficiency, often lower than 50% from line-frequency AC to DC output power. This issue arises from both topological approaches which are limited by current silicon power devices, and a disjointed design process which considers power stage and passive elements independently. To make the application tractable, current approaches focus on constrained, one-to-one charger/receiver hardware pairs. This approach fails to capitalize on the promise of spatial freedom and thought-free ubiquitous charging which makes wireless power transfer attractive.

Accomplishments/Deliverables

The UTK team developed and demonstrated a prototype wirelessly-powered workstation with over 90% efficiency from AC line to receiver-side DC, and over 25 W/in^3 transmitter power density. The 100W system has been tested with multiple, variable-position receivers.

To implement this system, the team developed:

1. A 98% efficient GaN-Based CRM Totem Pole PFC
2. A high-efficiency GaN-based 6.78MHz ZVS Class D transmitter
3. A constant-current, uniform-field, low-EMI transmitter coil design methodology and 0.5m prototype with Q>600
4. An active, GaN-based ZVS full bridge receiver, with online synchronization control and adaptive impedance
5. A passive, AA battery-replacement wireless receiver for wireless electronics <1W
6. Techniques for shielding and coupling coefficient enhancement for metal-body receivers

Impact/Benefits

The prototype workstation demonstration showcases the capability of wireless power transfer to deliver on high-efficiency, unobtrusive charging of multiple devices without constrained positioning. When incorporated into future consumer electronics, this technology creates a market for high frequency, high voltage, fast-switching power devices which can only be served through WBG power devices. Additionally, the advanced design and control techniques required to achieve the design targets helped to train students who will enter the workforce with significant experience in designing and testing WBG-based power electronics.

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

Three-phase four-wire DC/AC PCS converter with 13.8kVac and 100kVA power rating using 10kV SiC MOSFET.

THE UNIVERSITY OF TENNESSEE KNOXVILLE

The University of Tennessee, Knoxville

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

ELECTRIC POWER GRID

Project Summary

The overall objective is to develop a power conditioning system (PCS) module for the asynchronous microgrid employing high voltage (10kV) SiC power semiconductors with > 10kHz switching frequency to deliver more than 100kW power at required ac voltage level of 13.8kV. The PCS module should achieve the overall efficiency target of 98% and 95% with low/partial load (<30% loading), volumetric density of 4m3/MW, footprint of 3m^2/MW, and specific power of 1kW/kg, and provide the bandwidth (voltage control bandwidth > 300Hz and current control bandwidth > 1kHz) needed for both the grid- and microgrid-support system-level functions. The focus here is a three-phase four-wire DC/AC PCS converter with 13.8kV ac output and 100kVA power rating, and grid function validation in the Hardware Testbed.

Technology Gap/Market Need

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

Accomplishments/Deliverables

The accomplishments include: 1) Grid requirement impact on PCS design including unbalance load, common mode reduction, etc. and scalability investigation; 2) Three-phase four-wire PCS converter design; 3) PCS module controller demonstrated including stability enhancement and other grid functions (e.g. voltage/ frequency ride through, operation in different modes, fault, etc.) with grid-emulation Hardware Testbed; 4) Three-phase four-wire PCS converter prototype building and testing at rated voltage and power.

The three-phase, four-wire DC/AC PCS converter prototype with 13.8kVac and 100kVA power rating was completed as a deliverable.

Impact/Benefits

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

United Technologies Research Center: High Efficiency High Speed HVAC Drive

United Technologies Research Center

United Technologies Research Center

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

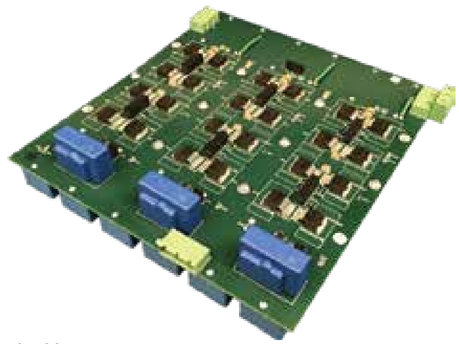
Commercial Applications

INDUSTRIAL MOTOR DRIVES

MILITARY

AEROSPACE

MARINE



Stacked inverter prototype

Project Summary

United Technologies Research Center (UTRC) developed a wide bandgap device-based 5kW high speed motor drive based on a five level stacked topology that has the following achievements: a) Capable of synthesizing up to 3300Hz fundamental, b) Efficiency higher than 99% at full load, c) Motor current THD of 5.17%, d) No smoothing inductors and dv/dt filter between drive and motor and e) Power density of 3.9kW/liters with fan cooling. UTRC utilized the permanent magnet motor sensor-less control algorithms for practical use of the high-speed motor drive operation. In addition, this work strongly supports the PowerAmerica mission to deliver energy savings through accelerated large-scale adoption of WBG semiconductor devices in power electronic systems due to its large impact on energy efficiency of electrical drives and converters. Such drives are broadly used in Heating Ventilation and Air Conditioning (HVAC) applications, standard industrial drives and on aircraft electrical systems. In terms of energy consumption, the nation's 114 million households and more than 4.7 million commercial buildings consume nearly 40 percent of total U.S. energy. In aerospace there is strong penetration of electric equipment with electrical drives and converters at the expense of traditional propulsion and hydraulic systems. Therefore, the development of key enabling technologies using WBG devices would help the Department of Energy (DOE) and aerospace industries to achieve the more than 30% energy efficiency improvement target by 2030 upon full commercialization.

Technology Gap/Market Need

One of the key enabling technologies needed is electrical drives in the range of 5 to 20kW at high speeds up to 100,000 rpm with an efficiency greater than 98%. To achieve this speed with a four-pole permanent magnet motor, the inverter needs to synthesize a 3300Hz fundamental frequency which will require the inverter to have an effective switching frequency greater than 66kHz to ensure a low motor current Total Harmonic Distortion (THD). Due to the limitation of IGBT silicon devices, today's high-speed drives use a switching frequency (up to 20kHz) and add a smoothing inductor connected between the drive and the motor to reduce the motor current distortion. However, there is a limit on the maximum inductor value that can be used. Therefore, the motor current usually has a high THD (≥ 30%). A motor current with a high THD content has a negative impact on the motor air gap flux distribution and causes additional eddy current losses in the motor elements, reducing the motor efficiency and increasing rotor temperatures. Furthermore, smoothing inductors are bulky and costly, and produce additional system losses.

Accomplishments/Deliverables

- **High power density:** The FR-4 based first prototype achieved a power density of 3.9kW/liter with fan cooling, exceeding the initial target of 2kW/liter. The second prototype based on metal core PCB technology is expected to achieve a power density of 5.3kW/liter with natural convection, by implementing a metal core PCB and WBG devices.
- **High fundamental frequency capability:** In order to achieve a high fundamental frequency, the five level WBG-based Stacked Multi-level Converter (SMC) was developed. The fundamental frequency of 3300Hz was achieved based on 40kHz switching frequency.
- High efficiency: The system achieved efficiencies higher than 99% at full load.
- **Low motor current THD:** Motor current THD is lower than 8%, achieving a value of 5.17%. Thus smoothing inductors are not required.
- **WBG-based stacked multilevel inverter functionality demonstration in laboratory dynamometer and on a real high speed compressor system is in progress:** The system has demonstrated operation at a fundamental frequency at 3.3kHz at 99% efficiency at nominal load.

Impact/Benefits

Thanks to the collaboration with PowerAmerica, the SiC high speed motor drive technology advanced from a TRL 3 proof of concept to a full demonstration in a relevant environment (TRL 5). This accomplishment brings this technology closer to a product development program, by reducing key technical risk and positioning this technology for further corporate investment. In addition, in order to take full advantage of WBG devices for high power applications and achieve high levels of integration, it is very important to have an ecosystem of components that support their high switching frequency capability i.e. (low inductance modules, capacitors, bus bars, inductors etc.). This project addressed this fundamental issue by bringing system level specifications and requirements to the various components and looking at system level integration to support the unique capabilities of WBG devices.

Virginia Tech: Direct-To-Line Central Inverter for Utility-Scale PV Plants Using 10kV SiC MOSFET Devices

Project Summary

This project was formulated to develop a direct-to-line central inverter building-block for photovoltaic (PV) applications using 10kV silicon carbide (SiC) MOSFET devices and rated for 200kW, 11kV AC, 16kV DC, and a ±0.8 power factor. With a California Energy Commission (CEC) efficiency of 99%, and a specific power of 5 kW/kg, the project set out to minimize the system complexity by adopting the simplest three-phase topology to realize the inverter. To this end, the project proposed to use two series-connected MOSFET to realize an equivalent 20 kV 'switch,' enabled by an active gate-driving scheme developed to dynamically balance the voltage sharing across the series-connected devices.

Technology Gap/Market Need

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

Utility-scale PV inverters are typically limited to operate from a 1–1.5kV DC bus due to the intrinsic limitation of the PV converters used; namely two- and three-level converters using 1.2kV and 1.5kV IGBTs. The operation at a higher DC bus voltage would however increase the DC distribution efficiency of the PV farm and simultaneously enable higher power strings. If the inverter itself is rated at higher voltages then each unit could naturally handle higher power. Recent development in boost DC-DC converters further favors this approach of stepping up the PV string voltage, rendering the direct connection to a MV DC bus feasible.

A factor limiting the adoption of MV power converters for PV farms is the inherent complexity of these units if rated for voltages in the 10–20kV range. Specifically, these units suffer from a large number of semiconductors and energy storage devices, as well as a large number of ancillary components to support their operation. In consequence, their cost and reliability are ultimately affected for this reason. The PV industry has historically favored the simplest power conversion topologies, only recently increasing from two to three-level units in some cases. This points to a strong need for power semiconductors rated in the 10–20kV range, for which SiC can be readily adopted.

Accomplishments/Deliverables

- Development of time-delay FPGA-based active gate-driver for series-connected 10kV SiC MOSFETs with integrated drain-source voltage sensor and Rogowski switch current sensor.
- Demonstration of 20kV 'switch' using two series-connected SiC MOSFET devices utilizing a standard Wolfspeed XHV-9 package.
- Development of PCB-based distributed DC bus capacitor bank using low voltage (1.5kV) film capacitors and a motherboard-daughtercard structure that doubled the power density and specific power of the DC bus when compared to a unit built using conventional cylindrical-type MV capacitors.
- Development of a PCB-based AC capacitor using low voltage 1.5 kV capacitors that doubled power density and the specific power of the DC bus when compared to a unit built using conventional cylindrical-type MV capacitors.
- Development of 3D-printed bobbins for AC inductors featuring controlled electric fields, and design and grounding scheme procedure to test inductors.
- Demonstration of direct-to-line PV inverter building-block rated at 200kW, 16kV DC, 11kV AC, and 10A rms.

Impact/Benefits

A key contribution of this project has been the development of PCB-based distributed AC and DC capacitors to replace the use of conventional MV capacitors, whether in cylindrical or boxed form factors. These are rated in the 2–5kV range and hence cannot be adopted directly in MV converters rated at 10 kV or higher. They are typically bulky (low energy density), and also built to order, so typically long lead times are associated with any purchase. The use of PCBs on the other hand and low voltage capacitors not only eliminates these shortcomings, but allows for a precise control of the electric field within and without the busbars and interconnects to ensure the converter operation without any partial discharge and insulation degradation. The approach naturally favors advanced and automated manufacturing.

The project also improved on the understanding of common-mode ground currents and their propagation within the power converter, which ultimately affect EMI emissions and the power flow within the unit.
Lastly, the active gate-driving scheme developed with integrated drain-source voltage sensor and switch current measurement using a Rogowski coil proved its unparalleled performance. Further, controlled by a local FPGA, this unit could potentially be commercially produced.

VirginiaTech

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PowerAmerica Roadmap Targets

- REDUCING COST
- 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
- HEAVY VEHICLES
- MARINE

Virginia Tech: MV AC to Low-Voltage DC Power Conversion for Data Center

Virginia Tech
Infineon

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PowerAmerica Roadmap Targets

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

Commercial Applications

- UPS DATA CENTER
- OTHER (HIGH VOLTAGE DC/DC CONVERTERS)

Project Summary

The conventional AC data center power architecture has too many stages, which causes excessive power loss in power distribution. Furthermore, in current AC data center power architectures, a line frequency transformer is employed to step down medium voltage AC to 480VAC and distribute 480VAC throughout the facilities. With ever-increasing power consumption of mega data centers, presently, the 480VAC lines carry thousands of amperes of current. This leads to very bulky and costly transmission bus and large conduction losses within the data center. In this project, we developed a much more streamlined power architecture that eliminates the redundant power conversion stages. Each necessary power conversion stage is optimized with improved efficiency and much higher power density by using WBG semiconductor devices and novel circuit topologies. The proposed power architecture is highly scalable to meet future needs. In the proposed solution, the MVAC (e.g. 4.8kVAC) will be brought to the server hall directly. Within each server hall, a high frequency isolated AC/DC power converter is used to step down MVAC to 380V DC. The 380V DC bus is distributed directly to server cabinets. Inside server cabinet, high density DC/DC converters with further step down 380V DC to 48V. Replacing 480VAC with 4.8kVAC would reduce copper usage (an increasingly expensive commodity) by 90%. At the same time, the I2R conduction loss will also be reduced by a factor of 10. The energy savings is calculated at 300TWH annually, which is equivalent to the total outputs of 40 nuclear power plants, each with an annual production of 8 TWH. Also, by eliminating the bulky 60Hz transformer, the proposed architecture is easily scalable. At the end of this project we developed two key building blocks for the proposed data center power architecture. The first one is a 15kW, 800V/380V isolated DC/DC module with 98.8% peak efficiency, 3.7kW/L power density and MVAC insulation capability, which is the key building block for MVAC to 380V DC power conversion. The second one is a 3kW, 380V/48V isolated converter with 97% peak efficiency and 29kW/L power density. By paralleling several of those 3kW modules, people can easily get different power levels for different server cabinets.

Technology Gap/Market Need

Hyperscale cloud datacenters are growing rapidly as they replace enterprise web server farms with cloud computing and with cloud 2.0 automated process computing. The implementation of secure, large computing capability inside data center buildings provides economies of scale not matched by current state of the art enterprise data center standalone server technology. Reducing cost for datacenters is a significant benefit that operators understand and are willing to invest in, because they benefit directly from the return on investment. Traditional server power supplies with 240V AC input and 12 or 48V DC output are already available as commodity products with excellent efficiencies greater than 94%. But the datacenter infrastructure from the Medium Voltage (MV) utility connection through multiple 60 Hz transformers and AC UPS are legacy designs, losing 10-15% of the total power through inefficiency. This is where the big opportunities for improvement are. The old datacenter power distribution architecture of 60Hz transformers, AC UPS and low voltage cabling can all be replaced with a modular rack that converts MVAC (e.g. 4.8kVAC) to isolated 400 V DC for distribution to a dozen server rack cabinets. Not only is this a much smaller, lower cost solution up-front, but it dramatically reduces OPEX due to the much higher overall efficiency of the single-stage conversion using state-of-the-art converters deploying wide bandgap semiconductors (SiC and GaN), and thus significantly lower power consumption (which is by far the largest single component of OPEX for the datacenter). The benefit from this approach is far greater than the incremental benefit of upgrading from Platinum to Titanium efficiency server power suppy, for example. So, the product opportunity is the modular MVAC to DC converters that are assembled into rack systems by the datacenter architect/builder.

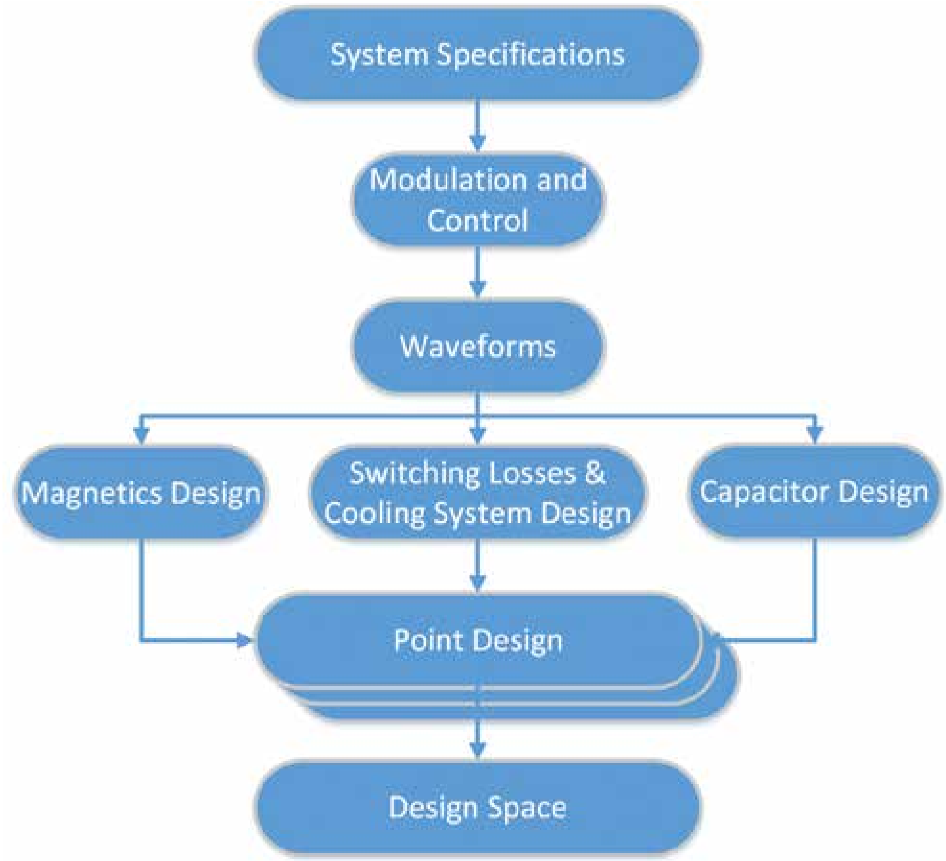
Accomplishments/Deliverables

At the end of this project we developed two key building blocks for the proposed data center power architecture. The first one is a 15kW, 800V/380V isolated DC/DC module with 98.8% peak efficiency, 3.7kW/L and MVAC insulation capability, which is the key building block for MVAC to 380V DC power conversion. The second one is a 3kW, 380V/48V isolated converter with 97% peak efficiency and 29kW/L power density. By paralleling several of those 3kW modules, designers can easily get different power levels for different server cabinets.

Impact/Benefits

The old datacenter power distribution architecture of 60Hz transformers, UPS and low voltage cabling can all be replaced with the proposed modular rack that converts MVAC to isolated 400V DC for distribution to a dozen server rack cabinets.
The design and manufacture of the wide bandgap devices used in the proposed topology occurs at many sites around the world. But for GaN in particular, one of the highest value-add in the production chain is the preparation of substrates, and the growth of GaN epitaxy on those substrates. This engineering and production activity takes place in Infineon facilities in Chandler and Mesa, Arizona and El Segundo, California. For the power supply OEMs, the design teams for new products and technologies are predominantly in the U.S. especially at these higher power levels. We believe the primary early adopters of this technology will be U.S.-based power equipment OEMs, as they too have close relationships with the decision-makers at Amazon, Google, Facebook, and Microsoft.

North Carolina State University: Wide Bandgap Power Converter Design Space Exploration



Simplified representation of power electronics design space exploration.

Project Summary

The goal of this effort is to develop an open-source tool that integrates the concept of design space exploration into all aspects of the power converter design and construction to enable efficient trade-off of design parameters using a library of previously engineered components.

Technology Gap/Market Need

This project will develop a tool suite to allow for engineers at all levels of their career to get exposed to the trade-offs inherent in power electronics converter design, and to explore the benefits in performance that introduction of WBG components provide at the system level. The hands-on learning experience allows students to perform advanced multi-objective optimization at an early stage in the educational process. In research, this tool will facilitate technology benchmarking and will allow designers to answer "what-if" questions and roadmap technology performance and targets at the component and converter levels.

Accomplishments/Deliverables

- Developed and demonstrated a simulation of a Buck and Boost Converters using Modelica as a Hardware Definition Language in OpenMETA software tool suite.
- Developed a documentation that explains the modeling approach of power devices in Modelica, and the process for building a design space in OpenMeta. Current documentation spans over 50 pages, and covers the tool fundamentals, modeling approach for various components, and sample design optimization studies
- Material was presented to undergraduate student team for initial evaluation.
- Concepts of design space exploration were introduced in a graduate course at NCSU.

Impact/Benefits

This project provided educational opportunities and tools to engineers at all levels of their career by exposing them to the trade-offs inherent in power electronics converter design, with specific emphasis on understanding the system level benefits afforded by the use of WBG devices.

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

North Carolina State University: Universal Platform of Education, Research, and Industrial Rapid Prototyping for High-Power WBG Applications

NC STATE UNIVERSITY

North Carolina State University

Contact:
Wensong Yu

PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

RENEWABLE ENERGY

SiC-based 50kW platform of education, research, and industrial prototype.

Project Summary

The objective of this project is to develop a hands-on platform of education, research and industrial rapid prototyping for high-power WBG applications. A modular 50 kW SiC power electronic building block with high bandwidth real-time control by the reconfigurable software operates as WBG source emulators, WBG power electronics under test, and WBG load emulators. The intellectual merit of this project is both in the hardware, which will utilize innovations in power converters built with SiC devices, and in the application software, which can be updated without the need to change the hardware for multiple experiments and testing covering a wide range of applications.

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 saving in passive component and performance improvement over the Si-based system. The high-performance FPGA based controller platform can fully utilize the high switching frequency of the SiC power devices and translate it into high control bandwidth. Considering the reconfigurability of the platform, the FPGA based controller has more performance headroom that DSP, which would be beneficial for more complicated applications.

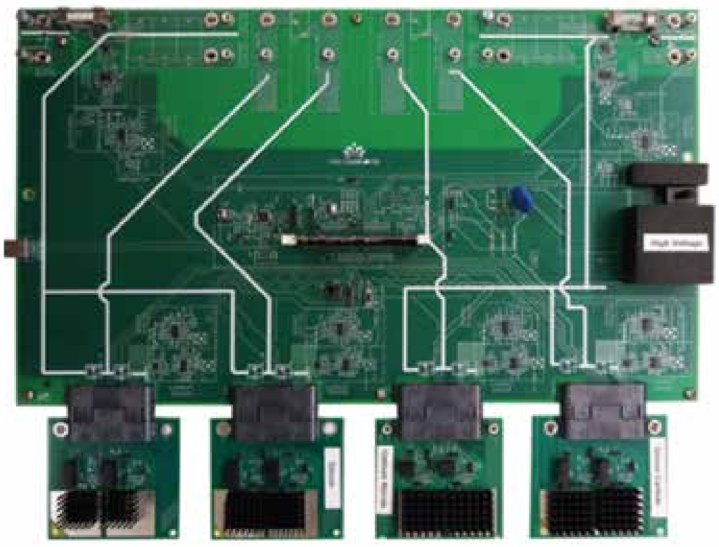
Accomplishments/Deliverables

- Design of 50kw SiC hardware completed.
- Low-profile high-performance SiC gate driver design completed.
- Reconfigurable FPGA software for different application developed.
- Reference design document of 50kw SiC hardware with BOM and performance described.
- Delivery of 3 education kits of 50kW SiC hardware and reconfigurable application software.
- Delivery of graduate lab course of the 50kW SiC platform implementation.
- Student engagement report.

Impact/Benefits

The high-performance universal platform serves as a great education and research resource since it provides reconfigurable software for various applications which can save huge amounts of time and money when compared to building dedicated hardware for each and every application. For the industry, the increased control bandwidth of the platform enables higher accuracy for rapid prototyping high-power WBG applications.

University of North Carolina at Charlotte: Power Electronics Teaching Lab Incorporating WBG Semiconductor Switches and Circuits



Plug & Play modular hardware for hands-on power electronics teaching lab.

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PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Commercial Applications

OTHER (EDUCATION)

Project Summary

This project aims to develop a hands-on power electronics teaching lab incorporating WBG semiconductor switches and circuits. The main approach in this project is to build a plug and play power electronics education board that allows students to use different semiconductor modules, analyze different characteristics, and finally construct different power electronics circuits along with improving their theoretical knowledge on power electronics and WBG devices. The second part of this project focuses on developing lab manuals to guide students to conduct the developed lab sessions and workshops such as building and operating power electronics converter circuits and switching characterization of different semiconductor devices. Finally, lab workshops with UNC Charlotte's ECE students were conducted to assess the developed modular education setup and the lab sessions.

Technology Gap/Market Need

Hands-on experience is one of the most important qualifications for engineers who handle real hardware at power electronics and WBG industries or research institutions. For academia, self-learners, special-purpose application engineers or large-scale audiences, however, it is not easy to find proper hands-on training/teaching resources that can satisfy their specific objectives, especially incorporating WBG semiconductor switches and circuits. Besides, from our previous experiences, UNC Charlotte's Power Electronics Workshops using a generic multi-function Si-based power electronics board, we found that it is more effective if a student (or a team of students) has the opportunity to develop their experimental setup by performing specific and interrelated exercises. Thus, this project developed hardware and curriculum resources for "experiencing the impact of WBG semiconductors by observing switching waveforms of different semiconductor switches" and "reconfigurable hardware design so students can construct different power electronics circuit topology by themselves and easily construct circuits with SiC, GaN, and Silicon MOSFETs."

Accomplishments/Deliverables

- Fabricated the plug and play modular education hardware consisting of a motherboard and different types of daughter boards including a half-bridge leg module and a double pulse tester module. Each type of daughter board has three different versions based on the semiconductor devices used: Si (part # IXFA22N65X2)/SiC (part # C3M0120090J)/GaN (part # GS66516B) MOSFETs.
- Developed lab manuals to assist students to understand how to use the developed hardware and conduct the WBG power electronics teaching lab sessions including a power electronics converter lab and a device characterization lab.
- Successfully conducted hands-on lab workshops with the selected ECE students of UNC Charlotte and their assessments.

Impact/Benefits

The developed plug and play modular education board and lab curriculum resources can contribute to train more WBG power electronics engineers with hands-on experience. The more well-trained engineers, the faster growing a WBG power electronics society will be in the U.S. Flexibility and reconfigurability are the key characteristics of the developed teaching lab.

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