ANNUAL REPORT 2017

GaN

SiC

We are accelerating the next generation of silicon carbide and gallium nitride power electronics.

PowerAmerica

FROM THE EXECUTIVE DIRECTOR

To our valued PowerAmerica members, partners, and associates:

THE POWERAMERICA TEAM

Nick Justice
Executive Director

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Principal Investigator

Victor Veliadis
Chief Technology Officer/ Deputy Executive Director

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Power Electronics Manager

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Project Manager

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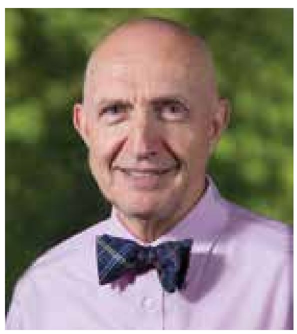
Communications Manager

Meg Chester
University Program Specialist

Janna Martin
Administrative Support Specialist

It's never been a busier or more exciting time to be a part of PowerAmerica and the Manufacturing USA network. In our institute's second full year of operation, we worked alongside 22 industry partners ranging from multinational organizations to start-ups, and 12 universities with an incredible depth of expertise in power electronics. Together, we're making great strides to accelerate the next generation of wide bandgap power electronics. These efforts have never been more timely. The news at the recent International Conference on Silicon Carbide and Related Materials in Washington, D.C., is that our industry is at full capacity and expanding.

Our members are braving new frontiers with their research and accomplishments. SiC and GaN power electronics have enormous potential to reduce size and increase energy efficiency across a wide range of applications, from electric vehicles to data centers (more on their benefits on page 2). Member projects are focused on some areas that will prepare this technology for wide-scale adoption – including reducing costs, improving reliability and performance, strengthening and connecting the supply chain and prepping an advanced manufacturing workforce.



POWERAMERICA EXECUTIVE DIRECTOR NICK JUSTICE

Our largest sustaining partner, Lockheed Martin, has lent expertise to several projects and continues to be a key player driving the expansion and development of our ecosystem. We're also excited about the continuing involvement of Wolfspeed, a Cree Company, a longtime leader in the field making significant contributions to the ongoing success of the Institute.

Key project highlights, noted on pages 11-48 of this report, include X-FAB's establishment of the first U.S. open foundry for six-inch silicon carbide wafers and companies, such as USCi, working to qualify their products at X-FAB. Other examples are the successful testing of a SiC inverter in John Deere's heavy duty equipment; and ABB's efforts to improve the efficiency of uninterruptible power supplies using silicon carbide. These projects are just a small sampling of the incredible work our members are doing, and I encourage you to take the time to learn more.

At PowerAmerica, we continue to strive to build the premier network of SiC and GaN professionals in the United States. Attendance at our annual meeting, held each winter, continues to grow, and in 2017 we added our first summer workshop as an additional networking opportunity. These events help spur collaboration between various industry, university, and federal partners.

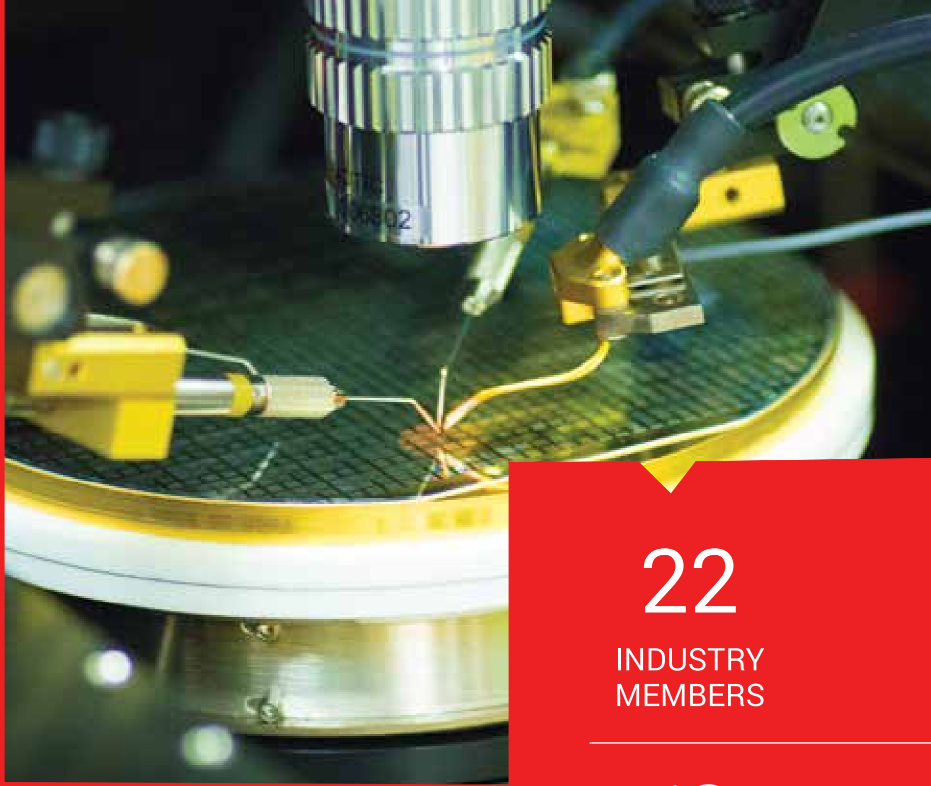
This year, we also added value for our members with the creation of a device bank to improve access to research-critical devices. In late 2017, we're looking forward to another offering in the form of short courses aimed at working professionals to enhance their understanding of wide bandgap technology.

We hope that the information contained in this annual report provides insight into the groundbreaking work we're doing to engage with industry and accelerate the next generation of silicon carbide and gallium nitride power electronics. We've come a long way in the past two years, and I look forward to seeing what we'll do over the next decade.

Sincerely,

Nick Justice

Our Mission



The PowerAmerica Institute at N.C. State University was founded in 2015 and is one of 14 Manufacturing USA Institutes nationwide. Each institute is narrowly focused on growing a sector of advanced manufacturing, thus making the U.S. better poised to compete economically on a global scale. PowerAmerica is backed by $70 million in funding from the Department of Energy, with matching funds from industry partners and the State of North Carolina.

Specifically, our mission is to 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 and gallium nitride in power electronics systems.

We do this by funding projects that advance wide bandgap technology and bringing together many of the world's leading wide bandgap semiconductor manufacturers and end-users with experts from top research universities and government agencies. *(Learn more about how our ecosystem works on page 5).* To date, we've funded 47 projects in the areas of foundry and device development, module development and manufacturing, commercialization applications and education and workforce development.

The choice of North Carolina State University as the central hub for PowerAmerica was a strategic one. The land-grant university has a 130+ year history of technological innovations in fields such as energy, biomanufacturing and materials science. Centennial Campus, where PowerAmerica is located, has spawned numerous successful business partnerships and public-private research. The region is also home to the Research Triangle Park. Today, N.C. State is directly involved in seven Manufacturing USA institutes—the most of any university in the country.

This annual report focuses on the institute's second complete year of operation, from June 1, 2016-June 30, 2017.

22
INDUSTRY MEMBERS

12
UNIVERSITY PARTNERS

3
NATIONAL LABS

20
INVENTION DISCLOSURES FILED

$140
MILLION IN PROJECT FUNDING

WHAT ARE POWER ELECTRONICS?

Systems that control the flow of electrical energy.

WHAT'S THE CHALLENGE?

Today's silicon-based power devices have nearly reached their operational limits.

Why wide bandgap?

SiC

GaN

Silicon carbide and gallium nitride-based semiconductors are the next generation of power electronics devices. They have a wider bandgap when compared to silicon-based components. This enables:

- INVERTERS
- RECTIFIERS
- CONVERTERS
- MODULES

Higher operating temperatures, frequencies & voltages

And smaller, more efficient devices

Leading to faster switching & lower power losses (compared to silicon)

Where is wide bandgap technology making an impact?

Silicon carbide and gallium nitride semiconductors improve the performance of power electronics systems beyond the limits of traditional silicon-based designs.

Industrial

Precision variable-speed drives & high temperature operation

Electric Utilities

A more resilient, secure energy grid

Electric Transportation

Efficient charging & increased range

Renewable Energy

Higher efficien - cies in power conversion

Military

Smaller, faster, lighter, & more rugged power electronics

Creating a Roadmap for SiC and GaN

Collaboration is a key driving force of PowerAmerica, and the institute's technological roadmap is the best example of this principle in action. The roadmap was developed by PowerAmerica members working closely to condense their extensive knowledge of technical, market and supply chain objectives into a cohesive plan to guide the institute's technical activities in the coming years. Wide bandgap technologies have the potential to reduce energy consumption and harmful emissions in a variety of industries, while also creating manufacturing jobs across the United States. To capitalize on this potential, the roadmap offers a strategy for making WBG semiconductors cost competitive with silicon-based power electronics and accelerating the adoption of SiC- and GaN-based components in new markets and applications.

A public version of the roadmap is available on the PowerAmerica website, while a more detailed version is available to members only.

The Process

To create the roadmap, the institute's semiconductor and power electronics experts met first in person, then virtually over several months, to discuss technical challenges, determine research priorities and come to an agreement on current status and near and long term targets for development. While challenging, this process helped cement strong working relationships between members and created a process for future roadmap updates, which will occur annually.

Key Roadmap Features:

- Identifies the key markets and application areas for SiC and GaN power electronics;
- Estimates the timeframe when they will be commercially viable;
- Estimates the performance targets GaN and SiC technologies are expected to meet over time;
- Identifies the technical barriers to achieving those targets; and
- Identifies the activities needed to overcome those barriers.

The roadmap will guide PowerAmerica's strategic decisions for demonstrating the benefits of SiC and GaN, improving wide bandgap semiconductor device performance, and increasing commercial use of these technologies.

The PowerAmerica Ecosystem

We connect the brightest minds in SiC and GaN technology with the companies that use semiconductors in their products so American industry can develop the next generation of smaller and more efficient power electronics technology.

3.75
BILLION $
GLOBAL MARKET
BY 2020*

REDUCE
U.S. ENERGY USE
UP TO 2.2%
IN 2025**

ENGINEERING DESIGN
Research & funding speeds SiC & GaN innovation & materials production

WBG SEMICONDUCTOR MANUFACTURERS
Access to WBG design & processes enables new, more powerful devices

RESEARCH
Connecting university & goverment WBG experts with industry to accelerate innovation

FUNDING
Providing industry-driven funding to improve WBG performance & processes

SYSTEM INTEGRATION
Testing, reliability & packaging to meet end user needs

END-USERS
Power electronic products built with WBG devices are smaller, more efficient

EDUCATION PIPELINE
Preparing the next generation of wide bandgap technologists to meet industry needs

GROW
The U.S. manufacturing workforce

* *¼ of $15 billion global market in four largest industry segments for discrete power electronic components by 2020. SOURCE: https://www1.eere.energy.gov/manufacturing/rd/pdfs/wide_bandgap_semiconductors_factsheet.pdf*

** *Based on current energy use in the U.S. power conversion, electric utlity, electric transportation, renewable energy & military sectors. SOURCE: Wide Bandgap Semiconductor Opportunities in Power Electronics," Oak Ridge National Laboratory, December 2016*

Education & Workforce Development

Working Professionals: Offerings such as tutorials, workshops, webinars, and short courses ensure the workforce is provided with cutting edge information, resources, and laboratory experiences. In the fall of 2017, PowerAmerica will offer short courses on wide bandgap technology geared to working professionals.

Graduate: N.C. State University offers a Master's of Science in Electric Power Systems with a concentration in wide bandgap. The concentration, established in 2014, is offered both online and on campus. Our university partners also offer WBG courses and have specialized experience in important WBG power electronic domains.

Undergraduate and Community College: Programs offered by PowerAmerica and the FREEDM Systems Center allow undergraduates at universities and community colleges to conduct research in a laboratory under the guidance of faculty and graduate mentors. This includes a 10-week summer research experience, as well as the Undergraduate Research Scholars Program that runs during the academic year. These programs provide students with technical and professional skills, and conclude with a required presentation at a symposium or conference. Graduate students serve as mentors, helping them to develop leadership, teaching and evaluation, and project management skills.

746 COLLEGE-LEVEL STUDENTS ENROLLED IN POWER ELECTRONICS COURSES

113 STUDENTS DIRECTLY INVOLVED IN POWERAMERICA PROJECTS WITH HANDS-ON APPLICATIONS

Highlights from the Year:

PowerAmerica merged its education and workforce program with the Future Renewable Electric Energy Delivery and Management (FREEDM) Systems Center, an Engineering Research Center located at N.C. State University. Through the leveraging of resources, including shared faculty, students and facilities, PowerAmerica is able to better provide students with the professional and technical skills identified as critical by industry.

PowerAmerica funds projects to equip students and professionals with skills needed to work in the field of wide bandgap semiconductors. Learn more about them in the member projects section of this report.

As part of its undergraduate and high school summer programs, PowerAmerica/FREEDM offered for the first time a wide bandgap workshop lab experience for undergraduates. The lab met weekly and was led by a Ph.D. student working on a PowerAmerica project, who developed the course material and lab activities.

"PowerAmerica has advanced John Deere's wide bandgap power electronics R&D work by more than five years."

- BRIJ SINGH,
SENIOR STAFF ENGINEER,
JOHN DEERE

Membership in PowerAmerica

At the end of our second year of operation, PowerAmerica membership consisted of 22 industry partners (from major corporations to small startups, 12 universities, three associate partner organizations and three national labs.

PowerAmerica helps members grow their businesses by providing access to the latest developments and key industry players in wide bandgap semiconductor technology. By funding projects that accelerate the concept-to-product cycle, we provide opportunities for companies to remain globally competitive and grow their bottom line.

Benefits of membership in PowerAmerica include:

- Networking with potential customers and suppliers
- Access to the PowerAmerica technology roadmaps for SiC and GAN
- Workshops and webinars related to the latest developments in SiC and GaN technology and applications
- Hands-on instruction on the use of SiC and GaN technology from application engineers in industry
- Access to a SiC MOSFET device design tailored to member's specifications and applications, and cost-effective device manufacturing at high-volume U.S. fabs
- Access to PowerAmerica Device Bank engineering samples
- Competing for funding to demonstrate improved SiC and GaN technologies and applications
- Promotion of the benefits of SiC and GaN technology through sponsorship of conferences and trade shows
- Access to academic experts in SiC and GaN technology at leading universities, and a pipeline of students educated in these subjects
- Access to valuable intellectual property

FULL SUSTAINING MEMBERS

LOCKHEED MARTIN

FULL MEMBERS

Wolfspeed. A CREE COMPANY

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

AFFILIATE MEMBERS

Raytheon

qorvo

transphorm

TOSHIBA

GM

USCi United Silicon Carbide, inc.

Microsemi

infineon

ABB

Wolfspeed. A CREE COMPANY

JOHN DEERE

Bendix*

ON*

VPT*

United Technologies Research Center*

STARTUP MEMBERS

AgileSwitch®

COOLCAD ELECTRONICS

MONOLITH SEMICONDUCTOR INC.

GeneSiC SEMICONDUCTOR

ATOM POWER

Navitas SEMICONDUCTOR

JENOPTIK

InnoCit

GlobalPower TechnologiesGroup*

Sonrisa Research, Inc.*

ACADEMIC MEMBERS

Arizona State University

AUBURN UNIVERSITY

FLORIDA STATE UNIVERSITY 1851

UC DAVIS UNIVERSITY OF CALIFORNIA

NC STATE UNIVERSITY

TEXAS TECH UNIVERSITY

THE OHIO STATE UNIVERSITY

THE UNIVERSITY OF TENNESSEE KNOXVILLE

KETTERING UNIVERSITY

Rensselaer

VirginiaTech

UCSB

Georgia Tech Center for Distributed Energy*

M DEARBORN*

SUNY POLYTECHNIC INSTITUTE*

The University of Akron*

FEDERAL PARTNERS

Argonne NATIONAL LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

ASSOCIATE MEMBERS

PEIC

iNEMI

RESEARCH TRIANGLE CLEANTECH CLUSTER

SPONSOR

U.S. DEPARTMENT OF ENERGY

*Members that have joined as of July 1, 2017.

MEMBER REPORTS

Together we are accelerating the next generation of SiC & GaN power electronics.

REDUCING COST

IMPROVING RELIABILITY

ENHANCING PERFORMANCE CAPABILITIES

BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Contents

Development of An Open Gate Dielectric Process for SiC MOSFET Manufacturing

Technology Gap/Need

SiC MOS devices would strongly benefit from a new gate oxide and channel technology with higher carrier mobility. This would provide a competitive edge to SiC MOSFETs with blocking voltage ratings of 600 V or lower. This would also open up new areas of application and improve performance in the current applications.

Project Summary

The objective of this project was to develop a MOS gate oxide process for SiC resulting in higher mobility and equivalent or better stability than the current nitrogen passivated interface. Our course of action was to start from preliminary interface modification processes which are promising and determine their performance for SIC MOSFETs relevant for power devices. Four MOS process technologies were selected:

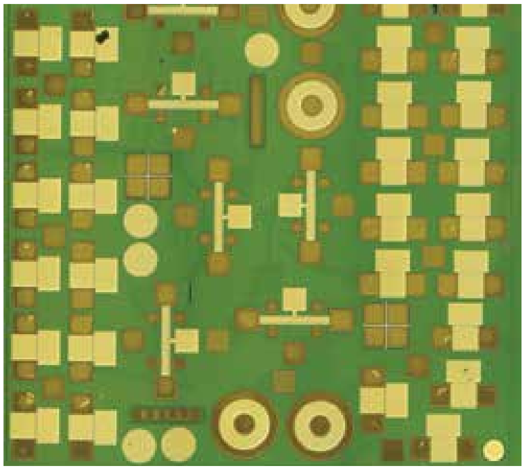
- Ultra-High growth temperature oxide gate dielectric
- Ultra-High growth temperature oxides on counter doped channel
- Borosilicate glass oxide gate dielectric
- Ge strained SiC channel

Accomplishments

Ultra-High Temperature Oxidation: We confirmed that Ultra-High temperature oxidation can be used to improve the oxide interface quality. Depending on the chosen process parameters, interface passivation can be observed. A temperature of 1430°C was the highest we could reach without forming crystal like structures in the oxide. Growth in pure oxygen has yielded very poor interfaces. Study of the effects of O2 concentration would improve this technology. Although no MOSFET was obtained from this technique, MOS capacitors show a 2V shift for a stress of 1.5MV/cm @150°C for 5 min and a breakdown field of 5MV/cm.

Ultra-High Temperature Oxidation with Sb Surface Counter Doping: Doping MOSFETs channel (p type body) with Sb an N type dopant for SiC, improves the field effect mobility by reducing the transverse electric field in the channel and providing extra carriers. The fabricated UHT+Sb MOSFETs show a mobility of 25 cm2/Vs which is lower than expected, indicating either an ineffective UHT process or an un-optimized oxide growth depth for effective counter doping profile. Still, the devices would be at par with NO passivation technology. The devices showed more instability than UHT MOS capacitors, indicating possible increased trap concentration.

BoroSilicate Glass Oxide: MOS device with Borosilicate Glass (BSG) gate oxides were obtained using several different methods which are B2O3 solid source, BN solid source for reduced parasitic oxide growth, Plasma Enhanced Chemical Vapor Deposition (PECVD) for



Close-up view of lateral MOSFET and MOS capacitor and MOS Hall devices.

better BSG purity, boron ion implantation for purity and better control of boron concentration. B2O3 solid source process gave a mobility of 140cm2/Vs with instabilities at1.5 MV/cm 150°C reaching 8V, BN solid source gave weak oxides, PECVD very low mobility, and B implant resulted in weak trap ridden interfaces.

Germanium Strained SiC: Germanium was implanted in SiC at doses corresponding to 0.4% and 0.04% of the substrate atoms with the objective to have enough Ge to strain the structure. Results from capacitors show this does not work for MOS devices. Interface trap densities appear to be proportional to the implant concentration and are at a level that preclude the building of a functional MOS transistor device. Separating strained and channel layers would be a straight forward improvement on this process.

Summary: Of the four tested technologies, BSG from solid dopant sources shows greatest promise in terms of mobility but great challenges in terms of stability remain, Ultra-high temperature oxide being the next contender with better promise in terms of stability but with mobility and process challenges.

Deliverables

The most important outcome of this work is the insight gained from the research, offering to the community processes that can be further refined into valuable IP. Devices have been produced that will be further analyzed and undergraduate and graduate students have been trained in the project.

Impact/Benefits

Improvement in SIC MOS device process ripples through all the power management system up to the individual user's electricity usage efficiency.

Auburn University, Monolith Semiconductor Inc.

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PowerAmerica Roadmap Targets

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

Towards Low Cost Rectifiers and Medium Voltage Diodes with High Yields and Stable Processes

GeneSiC SEMICONDUCTOR

GeneSiC Semiconductor, Inc.

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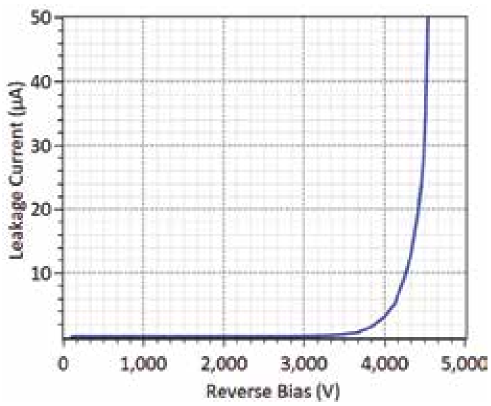
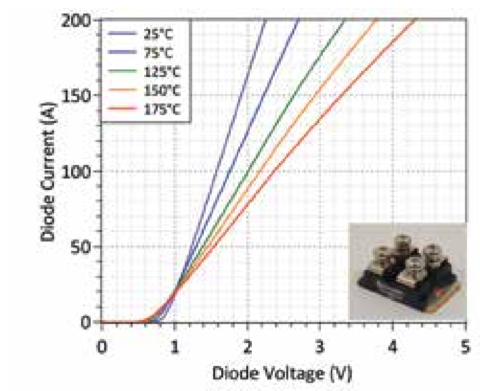
PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES



4500V Blocking SBD.



1200V 100A SBD forward I-V.

Technology Gap/Need

Fully-qualified 1200V and 3300V SiC Schottky rectifiers with low cost and high reliability/performance are essential for reducing the size, volume, weight, device count and cost of a wide variety of power electronics systems that are presently using low-performance bulky silicon-based power devices.

Project Summary

This project is focused on developing device designs and process technology for realizing 1200V and 3300V SiC Schottky rectifiers with high yields and low cost enabled by fabrication on 150 mm SiC substrates. The main objective of this project is to transfer GeneSiC's mature SiC Schottky process line from the existing 100 mm foundry to the automotive qualified, high-volume 150 mm foundry, X-FAB. Transferring production to X-FAB will help to realize low $/A manufacturing cost, which is vital for displacing the entrenched silicon power rectifier technology.

Accomplishments

1200V/1-100 A SiC Schottky rectfiers were successfully demonstrated on 150 mm SiC wafers at X-FAB. Ultra-low nA level leakage currents were achieved after process optimization. Medium voltage SiC Schottky rectifiers with > 4500V breakdown voltage were demonstrated on 150 mm wafers at X-FAB with high yields and low on-resistance.

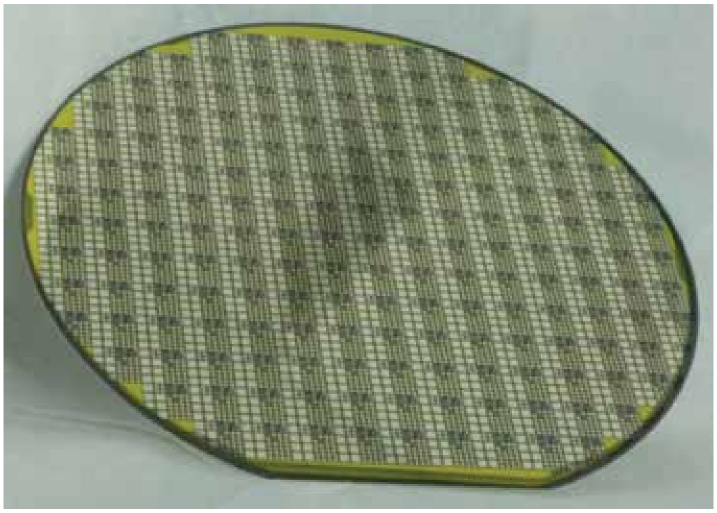
Deliverables

One hundred pieces of packaged 3300V/0.3 A SiC Schottky rectifiers were delivered.

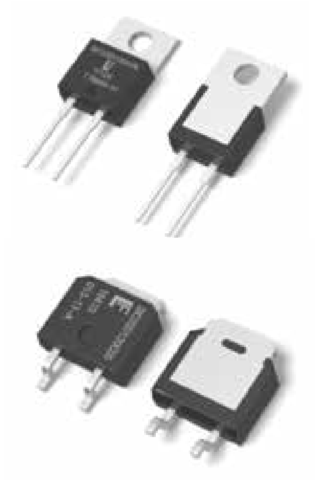
Impact/Benefits

A wide variety of power supply and motor control applications requiring ultra-fast switching 1200V and 3300V rectifiers will be enabled by these developments.

1200V SiC Schottky Diode Commercialization and Production



A 150mm SiC wafer fully processed at X-FAB Texas using Monolith's 1200V SiC diode process.



1200V, 5A SiC Schottky diodes assembled in 2L TO-220 package (top) and a 2L TO-252 surface mount package (bottom).

MONOLITH SEMICONDUCTOR INC.

Monolith Semiconductor Inc.

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PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Technology Gap/Need

The lack of cost-effective, high reliability SiC devices is limiting the widespread adoption of SiC devices in commercial power electronic applications. Monolith's approach to address this issue was to manufacture SiC devices in a high-volume 150mm Silicon CMOS fab. Monolith selected X-FAB Texas as its SiC device manufacturing partner in 2013. Monolith has been working with X-FAB Texas in developing SiC wafer handling procedures, SiC unit process steps and an integrated process flow for manufacturing of SiC MOSFETs and diodes.

Monolith's process development approach has focused on compatibility of the majority of SiC MOSFET and diode process steps with the tools and processes already available at X-FAB Texas. Silicon process steps have been re-used when possible and new process steps have been developed only when existing process steps were inadequate. Through smart process integration, exploiting the strengths of advanced Silicon CMOS fab with innovative device design and through the Monolith team's long experience in SiC R&D and Si power device manufacturing in foundries, Monolith aims to achieve the technical objectives of the Power America program.

Project Summary

The key objectives of Monolith Semiconductor's PowerAmerica project are (a) To enable transformation of a commercial 150mm Silicon CMOS fab into a high-volume SiC foundry and (b) Develop manufacturable, high yielding and low-cost 1200V SiC diodes with best-in-class performance and reliability at the 150mm SiC foundry. In this project Monolith has developed a high yielding SiC Schottky diode process and successfully qualified and released its first 1200V SiC Schottky diode products manufactured at X-FAB Texas.

Accomplishments

Monolith has developed a high yielding 650V, 900V and 1200V SiC Schottky diode process at X-FAB Texas. We have successfully completed the qualification of 1200V, 5A and 10A SiC Schottky diodes in 2L TO-220 and 2L TO-252 packages. Working with our strategic partner Littelfuse Inc., the diodes are available through distributor websites.

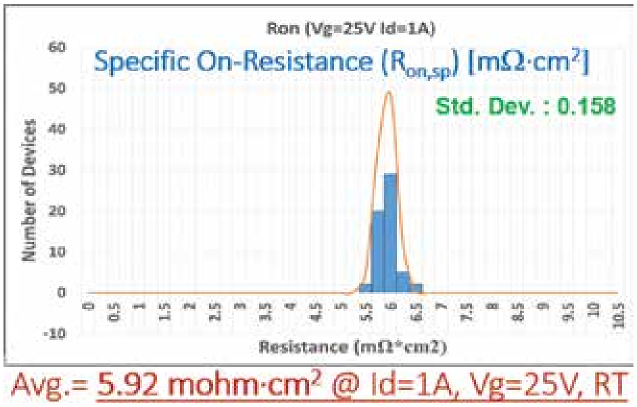
Deliverables

We have successfully qualified and released 1200V, 5A and 10A diodes in 2L TO-220 and 2L TO-252 package. These products are commercially available via distributor websites.

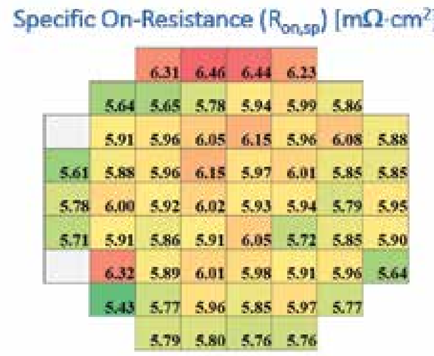
Impact/Benefits

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

Foundry Process Kit for 1.2kV SiC Power MOSFETs and JBS Rectifiers



Statistical Distribution



Wafer Map

NC STATE UNIVERSITY

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

North Carolina State University, X-Fab

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PowerAmerica Roadmap Targets

REDUCING COST

Technology Gap/Need

Prior to this project, several companies have been manufacturing SiC power devices at the X-FAB foundry using proprietary processes that are not available to any other companies. This has prevented the entry of new companies for manufacturing SiC power devices resulting in limiting the wafer volume. Our goal is to increase the wafer volume at X-FAB to drive down the cost for manufacturing SiC power devices.

Project Summary

The primary goal of the project is to create a PowerAmerica foundry process kit for manufacturing 1.2 kV SiC power MOSFETs, JBSFETs, and JBS rectifiers at the X-FAB foundry. Our intention is to generate an open domain process to encourage greater participation in PowerAmerica by fabless companies and power device companies that do not have expertise in manufacturing SiC devices. Greater industry participation will increase wafer volumes at the X-FAB foundry, driving down the cost of the SiC technology.

A process, named PRESiCE ™: PRocess Engineered for Manufacturing SiC Electronic-devices, has been created by NCSU at X-FAB over two-years of effort. Optimum designs and processes for 1.2 kV SiC power MOSFETs, JBSFETs, and JBS rectifiers have been defined. Statistical data has been gathered to demonstrate very tight distributions of all device electrical parameters. Wafer maps have been generated to show good production yield. This process creates a licensing opportunity for PowerAmerica for future sustainability.

Accomplishments

1.2 kV SiC power MOSFETs with both inversion-mode and accumulation-mode channels with state-of-the art electrical characteristics were successfully fabricated at X-FAB using a process engineered by N.C. State University. 1.2 kV JBS rectifiers with state-of-the art electrical characteristics were also successfully fabricated at X-FAB using a process engineered by N.C. State University. In addition, we proposed and successfully demonstrated a JBSFET structure that merges the SiC power MOSFET and the JBS rectifier into a single device. This reduces package count by half and saves 40% of SiC area, resulting in significant cost reduction.

Multiple wafer lots have been run at X-FAB to demonstrate that the process is stable and produces devices with high yield with tight parametric distributions. Datasheets for various devices have been generated for comparison with devices available from commercial sources.

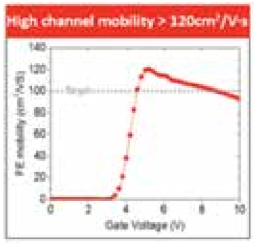
Deliverables

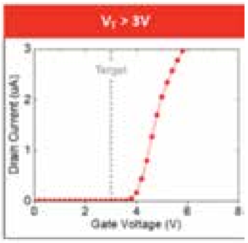
A process named PRESiCE™ was successfully created by N.C. State University at X-FAB to provide an open domain manufacturing technology to the semiconductor industry.

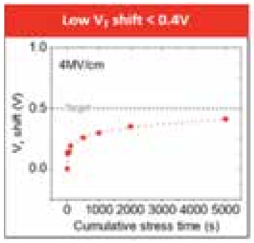
Impact/Benefits

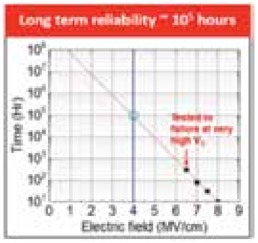
The output of this project will increase participation in PowerAmerica by both fabless companies and power semiconductor companies that want to enter this market but have not developed expertise in SiC power devices and processes. This will increase wafer volume and drive down cost.

SiC Channel Mobility Enhancement









NC STATE UNIVERSITY

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

Technology Gap/Need

A critical need for a SiC foundry is the availability of standard and open processes for typical SiC device flows. This requires a lot of development steps. For example, one of the main process steps that are currently protected under patent is the gate oxide. To overcome this, we will develop a unit process for the deposited oxides using Atomic Layer Deposition providing the same or better performance than grown SiO_2.

Project Summary

This project aims to develop highly manufacturable and novel high mobility SiC metal-oxide-semiconductor field effect transistor (MOSFET) devices for medium voltage (<1700V) power switch device application.

Develop a key module process with X-FAB
To work with the X-FAB engineering team for the implementation of unit processes for the deposited oxides using ALD. For this development, we will use X-FAB's existing process flow and substituted different ALD gate oxides layers.

Higher inversion channel mobility MOSFET by ALD
Fabricated SiC MOSFET using separate and independent control of the interface layer by incorporating ultrathin La-silicate layer with ALD SiO2 bulk dielectric. Devices are fabricated to explore the effect of process parameters on the device performance in terms of ALD deposition conditions, post dielectric process conditions, and forming gas annealing conditions.

Evaluate long term stability and reliability for SiC MOSFETs with novel gate stack
Evaluation techniques included Positive Bias Temperature Instability (PBTI), Negative Bias Temperature Instability (NBTI), Time Dependent Dielectric Breakdown (TDDB), and High Temperature Gate Bias (HTGB) stress to study ALD dielectric quality and threshold voltage stability.

Accomplishments

By optimizing process condition of La2O3 interfacial layer and ALD SiO2 bulk dielectric, advanced SiC MOSFETs having high channel mobility while maintaining minimal VT shift are realized. Improvement can be attributed to effective removal of traps located in the SiC/La2O3 interface, La2O3/SiO2 interface and SiO_2 layer.

Specific accomplishments include:

- We have demonstrated an enhanced channel mobility (>120 cm2/V·s) maintaining positive VT (>3 V) by optimizing the La2O3 interfacial layer thickness and FGA condition.

- We proposed a gate stack method to improve reliability of SiC MOSFETs with SiO2 gate dielectric deposited by ALD. By optimizing the ALD deposition process as well as post deposition process, we are able to achieve the VT shifts is less than 0.5V under 4MV/cm of static • electrical stress. Moreover, our optimized dielectric is predicted to have a lifetime of 10 years or more when the device operates at 4MV/cm of gate field.

Deliverables

- SiC lateral MOSFET with novel gate dielectrics enabled by ALD.
- SiC lateral MOSFET with mobility value of >120 cm2/V·s while maintaining VT shift < 0.5V under 4MV/cm Stress at RT.
- SiC lateral MOSFET with excellent TDDB characteristics (> 10 years).

Impact/Benefits

Our project embodies a disruptive device technology that provides excellent system level performance (high energy efficiency) at a cost lower than current SiC technologies. Therefore, the technology has great market potential and can drastically change the SiC market landscape.

North Carolina State University, X-FAB

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PowerAmerica Roadmap Targets

REDUCING COST

IMPROVING RELIABILITY

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Manufacturing, Testing, and Heavy-Duty Vehicle Deployment of a 200 kW 1050 VDC SiC Dual-Inverter

National Renewable Energy Laboratory (NREL)

John Deere Electronic Solutions (JDES)

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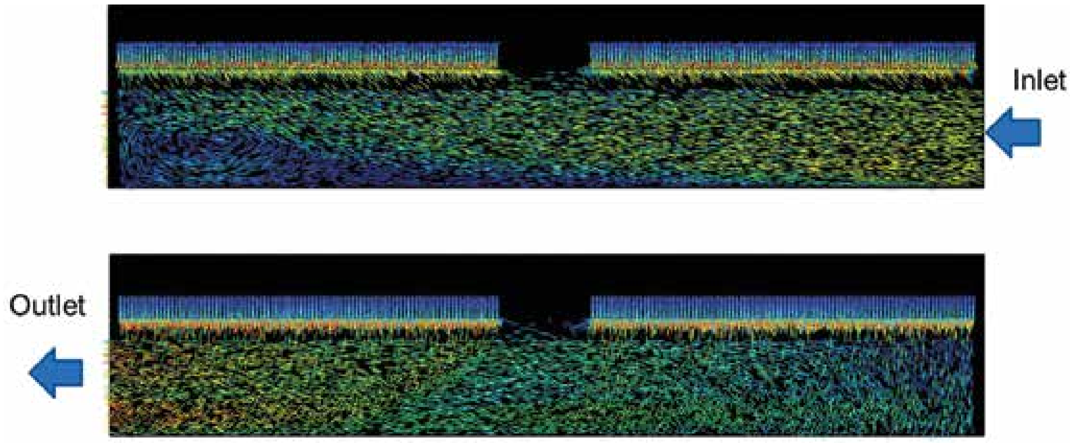
PowerAmerica Roadmap Targets

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



Velocity vector plot for computational fluid dynamics analysis of SiC power module cooling. This is an example of the analysis for the ultimate design optimization of the inverter thermal management system.

Technology Gap/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 practitioners. Finally, the project supports U.S.-based design and manufacturing of WBG systems.

Project Summary

Through this project, led by John Deere Electronic Solutions (JDES), a 200kW 1050 VDC SiC dual inverter was designed, prototyped, and tested within a prototype vehicle. NREL's role in the project was to support JDES in thermal design optimization and thermo-mechanical modeling of critical inverter components. This work included thermal analysis and characterization during the design stage of the project to quantify thermal performance. In addition, thermo-mechanical analysis was performed to determine potential reliability issues to support design controls to mitigate them early in the product development phase.

A SiC inverter was demonstrated and tested in a John Deere hybrid electric construction vehicle. The operating loader was demonstrated at a John Deere test facility in Dubuque, Iowa. The JDES/NREL thermal design for the WBG inverter enabled improved performance and integration with the engine cooling system (≤105°C). NREL directly contributed to the design and development of the SiC inverter incorporated in the prototype construction vehicle. The project was selected to move forward into the Institute's third budget period to support the next generation dual inverter design capable of full engine coolant operation up to 115°C.

Accomplishments

The key accomplishment achieved during the project was the SiC inverter demonstration in a John Deere hybrid electric construction vehicle. The John Deere/NREL thermal design for the WBG inverter enabled improved performance and integration with the engine cooling system (≤ 105°C coolant).

Deliverables

The final result of the project was the successful vehicle demonstration performed by John Deere.

Impact/Benefits

The real-world application of the final product is a WBG dual inverter for hybrid construction equipment.

Manufacture Vertical GaN Devices on Bulk GaN Wafers

Technology Gap/Need

The need to close technology/ investment gaps to achieve higher switching speeds, lower switching & conduction losses with >10X lower cost/Amp compared to state of the art SiC MOSFET.

Project Summary

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

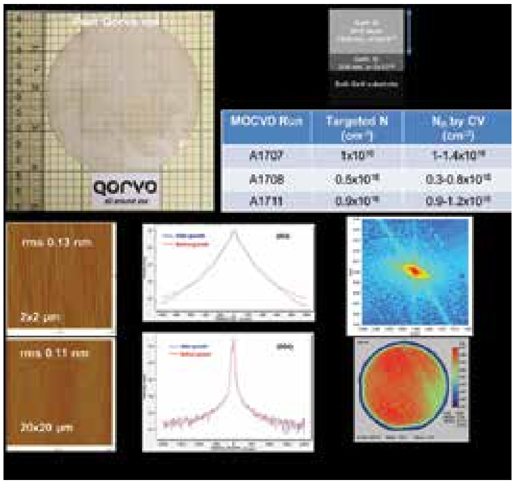
Accomplishments

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

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

Second, Qorvo has designed and fabricated an innovative 100mm mask set that greatly improved the process uniformity. By using engineered mask patterns including dedicated dummy patterns to avoid abrupt changes in mask and etched feature dimensions, the uniformity of key processes, such as MOCVD regrowth has been greatly improved.

Third, Qorvo has developed key individual processes that are critical for vertical device performance, including development of n-Ohmic contact with specific contact resistance ~ 4 x 10-8 Ω.cm2 and transfer length ~0.3 µm, (The program goal is to set at contact resistance < 1 x 10-6Ω.cm2 and transfer length < 1 µm), development of thick interconnect / overlay metal



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

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

Last, using the 100mm vertical GaN epi, the newly designed high uniformity mask sets and individual process elements developed above, Qorvo has started 3 lots of GaN vertical transistor fab run. As of today the 3 lots are still in the fab line and we expect to finish the fabrication by end of September 2017. The device results will be reported after the devices are fabricated and tested.

Deliverables

Based on the final program plan, the deliverables will include technical report including quarterly reports and annual report.

Impact/Benefits

This will be a first demonstration of 100mm wafer scale vertical GaN-on-GaN transistor fabricated in a high-volume manufacturing line.

Qorvo Inc.

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PowerAmerica Roadmap Targets

- REDUCING COST
- IMPROVING RELIABILITY
- ENHANCING PERFORMANCE CAPABILITIES

Development of a Static Induction Transistor

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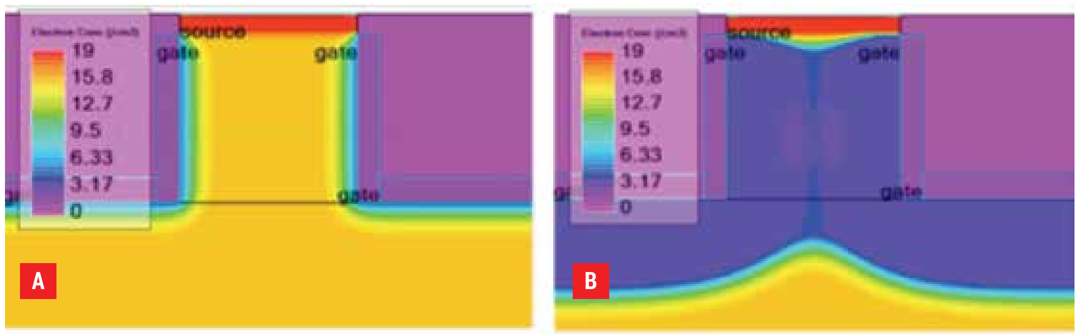
PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE



ATLAS simulation of electron distribution in a SIT under on state (A) and off state (B) conditions.

Technology Gap/Need

Theoretical studies based on experimentally-verified material properties predict GaN Static Induction Transistors (SITs) offer higher efficiency at all frequencies compared to their SiC or Si counterparts. The medium-voltage power transistor market is expanding quickly with demands in several key areas, such as electric vehicles. This places the necessary commercialization time within the next 5-7 years. The high power density compared to current technologies in lateral GaN devices and SiC devices make vertical devices such as the SIT very attractive for enhancing performance and efficiency of emerging applications. The impacts of this technology are: lower system cost and higher efficiency due to reduced size of passive circuit elements and reduced cooling requirements; and creating new skills at all levels: modeling, materials engineering, device design, circuits, and systems.

Project Summary

The goal of this project is to adopt vertical GaN technology via SITs, both Ga-polar and Nitrogen-polar, to develop highly innovative solutions to push the performance limits in power transistors beyond those possible with Si and SiC. This will enable proliferation of GaN-based high speed power electronics by developing a platform that addresses the current technological deficiencies not addressed by commercially available GaN lateral devices, building upon and developing the fabrication processes, and creating the skilled workforce required to maintain U.S. leadership in scientific achievement, engineering,
and manufacturing.

This project demonstrated a powerful modeling tool that can be shared with partners involved in R&D or industry from the device through application levels. The model was verified by experimental data in two critical ways. It provided Schottky barrier data, which is necessary for optimizing gate function in the transistor, and demonstrated high-voltage and low on-resistance SIT devices.

Accomplishments

- Achieved an accurate 2-D drift-diffusion model of SIT performance, which allows us to identify the critical design parameters for device design.
- Developed smooth sidewall etches that maintain good Schottky barrier performance – a capability that previously did not exist within the GaN fabrication toolbox
- Developed methods for highly scaled and self-aligned device technologies
- Demonstrated SITs with Ron<1.5mΩ.cm2

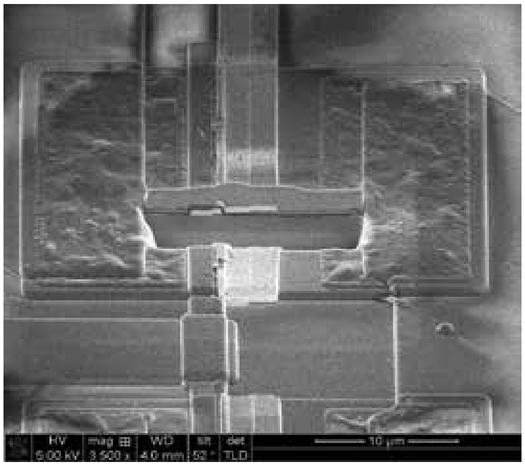
Deliverables

- Conference presentations, including: Design and Fabrication of Self-Aligned GaN Static Induction Transistors
- Journal publications including: GaN Static Induction Transistor (SIT) Using Self-Aligned Technology for High Frequency and High Power Application

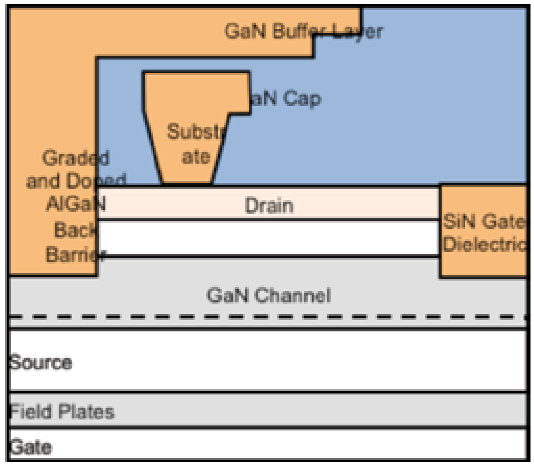
Impact/Benefits

SITs will provide a definitive advantage in systems operating in the medium-voltage regime, particularly those that require high current density.

N-Polar GaN Power Devices



A Scanning Electron Microscopy (SEM) image of a fully fabricated Nitrogen-polar GaN HEMT. Part of the device was cut using the Focused Ion Beam (FIB) technology to make the cross-sectional view of the buried layers visible.



The cross-sectional schematic of the fully fabricated device. The dotted line represents the two-dimensional electron gas (2DEG), which constitutes a highly conductive channel.

University of California, Santa Barbara

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PowerAmerica Roadmap Targets

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

Technology Gap/Need

The need for highly efficient, reliable, and fast switching transistors keeps growing. Wide bandgap semiconductor devices, including GaN, have been providing the industry with high performance devices; however, the efforts on GaN have so far focused on the Ga-Polar orientation. N-Polar GaN transistors developed for mm-wave power amplifiers have provided a big leap in performance with respect to Ga-Polar. This project will create a similar leap for high-voltage GaN devices, delivering higher performance at a potentially lower cost with better reliability.

Project Summary

This project aims to develop Nitrogen-Polar (N-Polar) GaN high-electron-mobility transistors (HEMTs) for high-voltage switching applications on epi-layers grown by metal-organic chemical vapor deposition (MOCVD). GaN devices are typically fabricated on the Ga-Polar orientation. N-Polar HEMTs possess a number of advantages over their Ga-Polar counterparts, and have recently demonstrated record mm-wave performance. This project develops the N-Polar GaN framework for high-voltage applications, and focuses on all aspects of the device development cycle including design, fabrication, testing/characterization, and optimization.

Accomplishments

The efforts of this project have resulted in the demonstration of high performance switching transistors with a good understanding of underlying device physics, and the capacity to design devices in the future to meet the specifications desired by the particular application. Specifically, the accomplishments include:

- The demonstration of 600V power devices with low dynamic on-resistance:
  - Breakdown voltages in excess of 1.4 kV have been demonstrated.
  - Dynamic on-resistance <50% have been accomplished.
  - Specific on-resistance of 5.2 Ω · mm, corresponding to 1.6 mΩ · cm2 with chip area, have been achieved.
- A fundamental understanding of N-Polar GaN power device design and optimization has been developed.
- Measurement and characterization capabilities for high-voltage N-Polar GaN transistors have been developed.

Deliverables

- Fully characterized 600V power transistors
- Device and process design for 900V operation
- 3 presentations in international conferences
- 1 peer-reviewed journal article

Impact/Benefits

Wide bandgap semiconductor devices are transforming the power electronics industry. N-Polar GaN constitutes a great alternative to the technologies that are already in mass production, offering a competitive advantage through the delivery of high performance, high reliability transistors at potentially lower costs.

1.2 kV Diode and MOSFET Foundry Qualification of 150mm SiC Line

United Silicon Carbide, inc.

United Silicon Carbide, Inc.

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PowerAmerica Roadmap Targets

- REDUCING COST
- ENHANCING PERFORMANCE CAPABILITIES
- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN

Technology Gap/Need

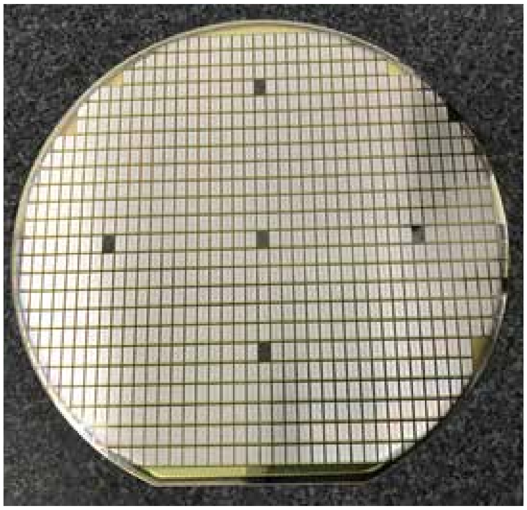
The major gaps being addressed in this project are the lack of a U.S.-based, cost-effective, high-volume SiC foundry at 6-inch, which is intended to improve volume driven cost reductions, which in turn will spur the rapid growth of SiC device applications. This virtuous cycle will establish a strong U.S. position in this market.

Project Summary

The goal of this project is the full qualification of 650V to 1200V Diodes and 1200V MOSFETs at X-FAB. By enabling the manufacturing of these product lines, the price and availability of SiC power devices will improve. This will lead to an increase in adoption into emerging and traditional power electronics applications. We are qualifying a range of products in each voltage class; 650V diodes range from 4A to 200A, and 1200V diodes range from 2A to 100A devices. The MOSFET device used to establish the platform is a 1200V 40mOhm device used in solar inverters and EV battery chargers. Increasing the adoption of SiC technology can contribute to improved energy efficiency across a wide range of industrial applications.

Accomplishments

The key accomplishments have been to develop a robust SiC processing supply chain, and exercise it sufficiently to prove it to be a high quality, high yield, high-volume manufacturable process. We have developed key SiC-specific process modules. By utilizing these modules in conjunction with the capabilities of the Si foundry, we have been able to develop processes for 650V and 1200V diodes and 1200V MOSFETs. The diode processes have been exercised on 11 different products and over 100 wafers with excellent yield and parametric performance. Our 1200V series offers the highest surge capability on the market. The diodes have passed the AEC-Q101 reliability standard. A state-of-the art SiC MOSFET technology has been developed at 6-inch and will finish reliability testing shortly.



1200V 40mOhm MOSFET wafer.

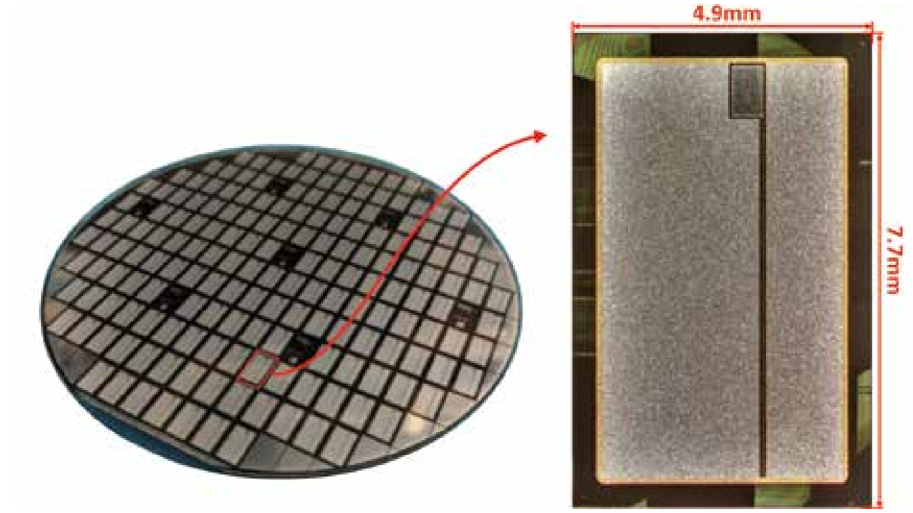
Deliverables

The final goal of the program is to have high yield, high volume, fully qualified 650V and 1200V diode and 1200V MOSFET processes. We have built a robust process that is ready for mass production.

Impact/Benefits

The SiC diode and MOSFET production in a U.S.-based manufacturing model will not only enhance energy efficiency and reasonable costs for our customers, but strengthen the U.S. position as a manufacturer which also leads to high wage U.S. jobs.

HTGB, Thermal Shock, ESD, Body Diode, & H3TRB Qualification of Gen3 3.3kV/45 mΩ & 10 kV/350 mΩ SiC MOSFETs



Photograph of 4" SiC wafer with 3.3 kV/45 mΩ MOSFETs (left) and macrophotograph of 3.3 kV/45 mΩ SiC MOSFET die (right).

Wolfspeed, a Cree Company

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PowerAmerica Roadmap Targets

IMPROVING RELIABILITY

Technology Gap/Need

Currently, there are no JEDEC-qualified 3.3 kV or 10 kV SiC MOSFET die products from any vendor in the world, even though there are an abundance of applications that could benefit from the lower conduction and switching losses enabled by these medium voltage unipolar SiC power devices. This project helps to fill this market gap by completing the necessary JEDEC qualification of SiC medium voltage MOSFET die that is required for product release.

Project Summary

This project will complete the required JEDEC qualification tests for both 3.3 kV/45 mΩ and 10 kV/350 mΩ MOSFET die, including High Temperature Gate Bias (HTGB), Temperature-Humidity Bias (THB), Thermal Shock (TS), Electrostatic Discharge (ESD), High-temperature Operating Lifetime of the MOSFET body diode (BD-HTOL), and Time-Dependent Dielectric Breakdown (TDDB). JEDEC qualification is required for formal release of these large area, medium voltage SiC MOSFET die as commercial products.

Accomplishments

- 3 lots x 77 devices per lot HTRB complete on 10 kV Schottky Diodes
- 3 lots x 77 devices per lot HTRB complete on 3.3 kV MOSFETs
- 3x qualification lots completed for both 10 kV and 3.3 kV MOSFETs
- Intrinsic gate lifetime test (TDDB) completed for 3.3 kV and 10 kV MOSFETs indicating >3000 year MTTF for die of both voltage classes.

Deliverables

A passing qualification report for 3.3 kV and 10 kV MOSFET die.

Impact/Benefits

SiC MOSFETs allow for the realization of higher efficiencies when used in place of the incumbent Silicon IGBT technology. This comes from the unipolar nature of the SiC MOSFET, which all but eliminates losses incurred during each switching cycle of a power converter. The unipolar operation of the SiC MOSFET also eliminates the conduction "knee" that is present in Silicon bipolar devices, which incurs a heavy efficiency penalty when operating at less than 100% load, as is typical for a real-world traction application. This allows for next-generation power electronics systems present in trains, industrial motor drives, and grid-tied energy storage systems to more efficiently operate, enabling cost savings for the system owners in the form of less energy use, as well as designing smaller and lighter products.

SiC Power Device Commercial Foundry Development

X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

X-FAB Texas, Inc

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PowerAmerica Roadmap Targets

REDUCING COST

Technology Gap/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 have 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.

Project Summary

With PowerAmerica support, X-FAB Texas is developing an open 6-inch silicon carbide 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 will be converted to process SiC wafers. This approach will leverage existing silicon processing equipment, but will require the addition of specialized equipment unique to SiC processing.

By fully integrating this SiC foundry with X-FAB's high volume Silicon foundry line, customers will be able to leverage the economies of scale that have already been established with high volume silicon.

To provide scalability, a Process Installation Kit will be developed. This kit will contain documented and characterized standard process blocks that can be implemented along with proprietary process blocks such that the foundry customer can bring highly differentiated products to the market.

Accomplishments

While >90% of the processes required to fabricate a silicon carbide device wafer can be realized using standard silicon fabrication equipment, this equipment needs to be modified to accommodate the fact that SiC wafers are thinner than Si wafers and transparent while Si wafers are opaque. All necessary equipment conversions were completed this year.

The balance of the processes require specialty equipment. X-FAB finalized installation and qualification of equipment that will allow for in-house production of all processes required in a typical SiC power device.

- High Temperature Ion Implanter
- High Temperature Anneal Furnace
- Backside Metal Sputter Tool
- Laser Marker
- Laser Anneal Tool
- Wafer Thinning Tool
- Temporary Bond/De-bond Tools

X-FAB also started work to document and characterize standard process blocks that will become the basis for a foundry Process Installation Kit.

Deliverables

The official deliverables for this project are technical reports documenting the qualification of equipment installed / converted to support SiC device fabrication – however the true success of this project lies in the outputs of our SiC Foundry. X-FAB has had 2 device partners complete full production qualification of SiC power devices fabricated in our foundry line. We fully expect these devices to ramp into production in BP3.

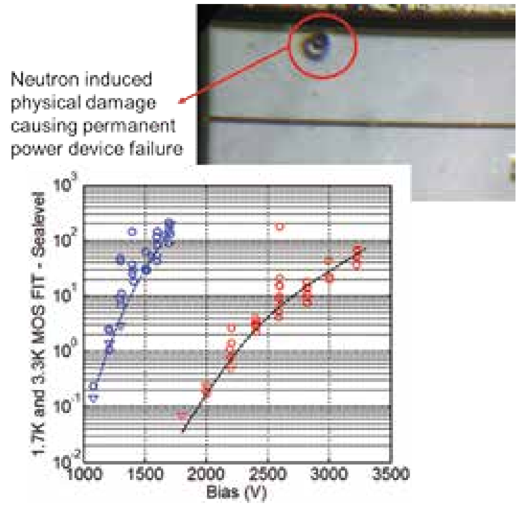
Impact/Benefits

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.

Terrestrial Neutron Induced Reliability Concerns in Very High Voltage Silicon Carbide Power Devices

Technology Gap/Need

Terrestrial neutrons are byproducts of cosmic ray interactions with the earth's atmosphere. Due to their charge neutrality, these neutrons are capable of traveling vast distances in the atmosphere, even reaching sea level with relative abundance. These neutrons have been shown to cause failures in power devices via interactions with lattice atoms. These neutron induced single event effects are not new and were first reported in the late 1990s in Si power devices. Unlike Silicon, reliability of SiC devices is a big unknown for power and energy system designers since they lack legacy data due to their recent adoption. The absence of data for this type of long-term reliability problem has been an obstacle for the accelerated adoption of SiC. These measurements and data mitigate this perceived "prejudice" by presenting the empirical results and also comparisons to similarly rated silicon parts.



Left: Terrestrial neutron induced SiC power device failures. Right: Terrestrial neutron cosmic shower.

Project Summary

We determined Failure In Time (FIT) data of very high voltage silicon carbide devices due to terrestrial neutrons, and pursued first-order analysis of these failures. Here FIT is defined as the failure rate of one device per billion device hours, and is a commonly used metric by designers to determine the failure probability of a system or a circuit for a given time and at a given location. The accelerated measurement of FIT values for silicon carbide devices mitigate the effects of the lack of this kind of reliability data for the nascent SiC power devices due to their relatively recent adoption. The measured data also proves the relative terrestrial neutron radiation hardness of the currently available SiC power devices at high voltages compared to similarly rated silicon counterparts. The empirical and calculated data show that the FIT rates for the currently commercially available SiC power MOSFETs and diodes are low. Also the FIT rates roughly scale with device voltages normalized by the breakdown or avalanche ratings, indicating the push for the fabrication of ever higher voltage SiC power components is beneficial from reliability as well as circuit complexity points of views.

Accomplishments

We successfully performed pre-radiation reliability testing of several hundred SiC and Si power devices. These initially characterized power components were later successfully radiation tested using the one of a kind terrestrial neutron simulator at the Los Alamos Neutron Science Center. We then examined the irradiated components for failure modes and also pursued post radiation analyses. The calculated and measured data indicate the relative radiation hardness of SiC power devices near their rated voltages compared to similarly rated silicon devices. Our extensive analyses, measurements and modeling provide a foundation for the early adoption of this wide bandgap technology in the industry by quantitatively presenting a proof of their long-term reliability.

Deliverables

The summary of our pre- and post-radiation testing analyses, as well as FIT curves for high voltage SiC components were presented to PowerAmerica to bolster the early adoption of this technology by quantitatively providing proof regarding their long-term reliability.

Impact/Benefits

There are many power circuit and system designers reluctant to switch to SiC because of its unproven reliability especially due to terrestrial neutrons. Quantifying the long-term reliability of SiC power components is likely to ease the designers' and system builders' concerns, and pave the way for faster market penetration for SiC.

CoolCAD Electronics, LLC

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PowerAmerica Roadmap Targets

IMPROVING RELIABILITY

Reliability Benchmarking of Lateral GaN Power HEMTs on Si Substrates and Assessment of GaN/Si Epitaxy

Rensselaer

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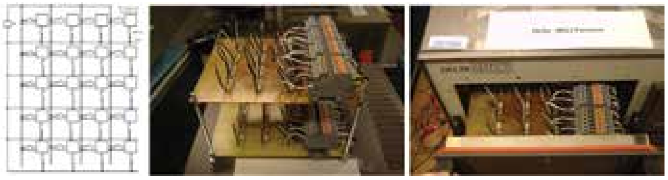
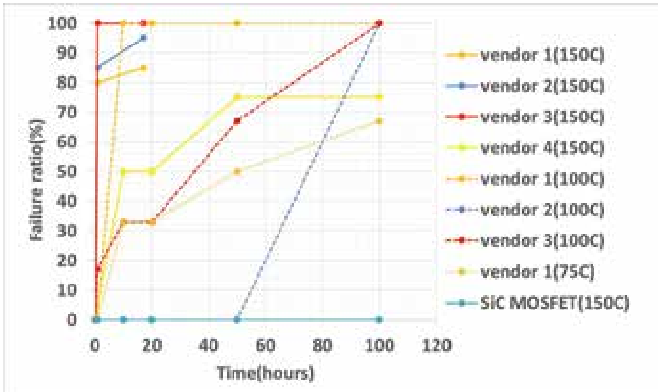
PowerAmerica Roadmap Targets

IMPROVING RELIABILITY

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE



Custom HTRB stress: circuit, apparatus, oven installed.



Summary of HTRB stress tests to-date.

Technology Gap/Need

With gallium nitride devices entering the commercial market relatively recently, little independent information is available concerning long-term reliability of commercial offerings. We evaluate four commercial offerings and make quantitative comparisons between both the test devices and the more mature silicon and silicon carbide power device technologies.

Project Summary

We investigate the reliability of available commercial lateral GaN power HEMTs on Si substrates including an assessment of the GaN/Si epitaxies. We follow JEDEC industrial standards to conduct reliability tests and to reveal the maturity of commercial GaN power device technology. Our early work concentrated on temperature accelerated device stress testing, simulating continuous device operation for long time periods. With the availability of failed devices from early experiments, post-mortem study to determine point and method of failure including the role of epitaxial defects is being investigated.

Accomplishments

We have designed and built custom stressing and aging systems used for the reliability tests of the commercial HEMTs. Before stressing, we performed full static, dynamic, and temperature characterization on the approximately 150 commercial devices (of four varieties) included in this study. Decapsulation of failed test devices and analysis of failure mechanisms is underway.

Deliverables

A full documentation of reliability results and analysis of failure modes is the principal program deliverable.

Impact/Benefits

These devices are now available for industrial use and can be ordered by the general public in small quantities for specialty use as well. Data from our analysis will be useful to all end users in evaluating product selections and to device manufacturers for improving product quality.

Power Module Development and Manufacturing

Technology applications include electric vehicles, electric utility and electric transportation.

Wolfspeed,
A Cree Company
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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

Technology Gap/Need

Traditional module designs for silicon power electronics have smaller temperature swings, high inductances, fewer paralleled die and low power density compared to optimized WBG module designs. These legacy module designs do not fully enable the end user to exploit SiC power devices to maximize the overall system performance. Wolfspeed's PowerAmerica project helps to fill the spectrum of power modules available within the industry by covering various performance ranges and cost targets, while simultaneously providing educational materials on the state-of-the-art SiC technology to greatly reduce the product's insertion timeline.

Project Summary

This project expands the throughput capability of Wolfspeed's ISO 9001 & Aerospace AS9100 certified SiC power module manufacturing line, while adding industry standard power modules and advanced high voltage modules to an industry-leading product portfolio. As a result of the PowerAmerica project, Wolfspeed's manufacturing line qualified new, higher volume equipment; upgraded key in-line quality and assembly equipment to better accommodate legacy module technologies as well as advanced materials and processes; in addition to enhancing reliability and enabling module qualification testing. For each of Wolfspeed's WBG power modules, a companion gate driver and power supply, reference design or evaluation kit, and circuit simulation models are created to help accelerate the adoption of the WBG modules and educate the user/academic community. Wolfspeed's SiC modules exhibit industry-low inductances, low thermal impedances and high temperature capability, and are available through the PowerAmerica Device Bank.

Accomplishments

- Improved throughput, foundry in-line testing for modules, and process automation
- Developed 900-1700 V Econodual™ prototype package
- Provided low-cost COTS gate driver solutions to enable quick SiC power module adoption
- Developed user manuals, with reference design strategies, for ease of use of optimized, all-SiC modules
- Performed Initial Stress & HALT testing on 3.3 kV modules
- Performed Initial Stress testing on 10 kV modules
- Sampled modules, gate drivers, and application notes to the user community

Deliverables

- Successful qualification of the in-line inspection equipment
- Successful stress testing to enable iteration of products for improved robustness
- Test data and reference design information at world-wide conferences to educate community on SiC power module usage
- Sample all products across voltage ranges to user community, while aiding with integration, testing, and reviewing field data to improve product iteration

Impact/Benefits

- Industrial: Motor & Traction Drives
- Transportation: Automotive Hybrid Electric Vehicles / Electrics Vehicles + Rail Applications
- Energy: Electric Utility & Grid-Tied Applications

Ultra-High Efficiency SiC Modular UPS

ABB

ABB

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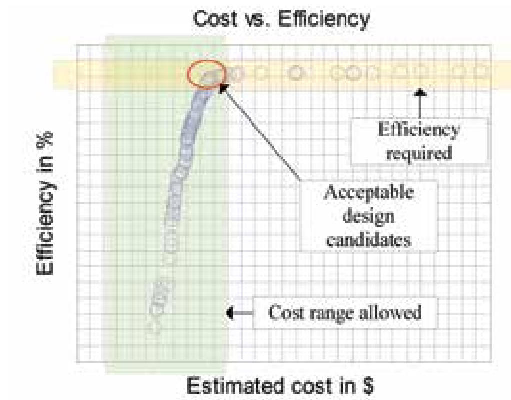
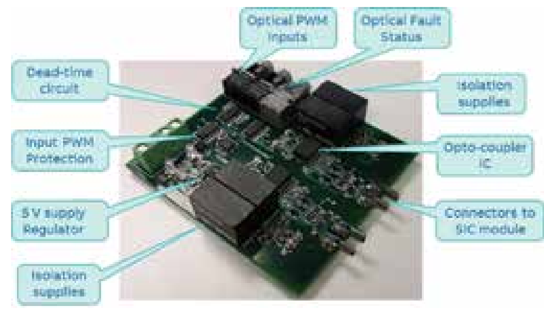
PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE



Pareto-optimal front of designs showing the trade-off between cost and efficiency.



Gate drive for SiC module.

Technology Gap/Need

Wide bandgap semiconductors provide an opportunity to improve the performance of a variety of critical power electronics-based products. There is a need to understand the changes that need to be made in these existing products and the performance enhancements required, to enable the widespread use of WBG devices. Uninterruptible Power Supply (UPS) is becoming increasingly critical to reliable power in applications like datacenters. Improving their performance (higher efficiency, smaller footprint) can lead to large savings in electricity consumption and, in turn, operating cost.

Project Summary

This project aims to drive the efficiency of a 100 kW double conversion UPS unit to greater than 98% using commercially available SiC technology. The current ABB product offers a true online efficiency of up to 96%. The main challenge towards quick commercialization using SiC MOSFETs is that multiple aspects of the existing product need to be changed considerably: the control platform needs to be upgraded to support a higher switching frequency; the magnetics may need change based on the objective at hand, e. g., power density, efficiency, etc.; the gate drives need to be re-worked to support the turn-on and turn-off voltage of the SiC MOSFETs; and EMI and related issues may also be tricky to handle. Additional protection functionalities may also be incorporated into the gate drive. In this project, a 100 kW prototype based on modifying the existing product to address the aspects mentioned above will be demonstrated.

Accomplishments

Key accomplishments of the project include:

- Development of a power stage design tool which uses genetic algorithm-based optimization to determine key parameters such as switching frequency, low-pass filter design and inductor design
- Development and testing of a gate driver with a specific form factor and additional protection functionality
- 15% reduction in power loss has been demonstrated using Si IGBT and SiC diode (hybrid) in the product
- During the course of this work, it was determined that a full SiC solution was better for this application in the long term
- Testing and integration of the full SiC solution (SiC MOSFET + SiC diode) is underway

Deliverables

The main deliverable of the project will be a demonstration of a full SiC 100 kW double conversion UPS power stage prototype with greater than 98% efficiency.

Impact/Benefits

Uninterruptible power supplies are seeing widespread use, as the necessity for reliable power keeps growing. The main goal is to achieve higher online double conversion efficiency. This reduces power loss and leads to lower consumption of electricity. As an example, datacenters in the US are projected to consume 73 billion kWh in 2020[1]. Even a 1% reduction in the losses for UPSs supporting these data centers leads to a large amount of power and operating expenditure saved. The adoption of SiC technology in the UPS can boost electrical engineers' confidence in the commercialization potential of SiC in various applications.

(1) United States Data Center Energy Usage Report 2016, https://eta.lbl.gov/publications/united-states-data-center-energy

Promote SiC and GaN Applications Through Development of WBG Evaluation Kits

The Gate Driver is mounted to a daughtercard which in-turn connects to the Power Devices.

Technology Gap/Need

The WBG power semiconductors market has yet to mature and hence there is lack of standardization. This creates a burden on the power device manufacturers to co-develop an ecosystem around their devices to help accelerate adoption. The commercially available AgileSwitch Evaluation Systems have helped spur new business for the device manufacturers by lifting this burden.

Project Summary

The project objective is to enable commercial, industrial and research organizations to immediately evaluate and incorporate SiC power semiconductor devices into existing applications through use of “WBG Evaluation Kits.” Users of the WBG Evaluation Kits should realize a significant improvement in performance (~50% reduction in power module losses, voltage spikes and ringing – compared to conventional driving solutions) through the use of AgileSwitch patented and proprietary gate drive technology. This translates to both system cost savings and volume and weight reduction (by way of smaller cooling systems and magnetics).This project supports a range of additional WBG package types from Monolith Semiconductor, Littelfuse, Wolfspeed, Infineon, ABB, Fuji, Mitsubishi, Semikron USA, Global Power, and others.

Key elements of the WBG Evaluation Kits (made in the USA) include:
- Various SiC module package compatibility through a universal “Motherboard” and module-specific “Daughtercards”
- Up to 1700V Module capability (Current WBG Evaluation Systems work up to 1200V Modules)
- Up to 250kHz Switch frequency (Current WBG Evaluation Systems work up to 100kHz)

Accomplishments

Development of the WBG Evaluation Systems led to a larger group of engineers and graduate students experimenting with WBG power devices. AgileSwitch’s Augmented Switching Technology was also proven to be key in reducing second order effects of EMI, Voltage Overshoot etc.

The key accomplishments achieved were:
- Successfully partnering with WBG device manufacturers and overcoming second order effects while providing a reliable and high efficiency gate driver solution.
- Integration of the passive components and cooling systems so as to reduce parasitic effects.
- Education of a large workforce on the benefits of design flexibility – in this case provided through software configurability of the Evaluation Kit functions.

Deliverables

WBG Evaluation Kit – The WBG Evaluation Kit will be fully configurable, with an independent GD. “Motherboard” that controls the SiC half-bridge/ chopper modules either directly or through a module specific “Daughtercard” that connects directly to the module (thereby significantly reducing system impedance, and providing flexibility in stack design. (The GDB technology is referenced in a United States patent US 9,490,798 titled: Gate Drive Control System for SiC and IGBT Power Devices).

The WBG Evaluation systems are complemented by a programmer kit which are used to modify the configuration settings on the gate driver.

Impact/Benefits

Evaluation Tool – The WBG Evaluation Systems are used by universities as research tools and used by system design engineers to quickly evaluate SiC platforms. The tools demonstrate the need for a re-think in the way systems are designed when using WBG devices. They highlight the design trade-offs of EMI, efficiency and reliability.

The software configurable evaluation kits also highlight the importance of providing designers with flexibility – especially when dealing with new designs.

The results obtained compare favorably with existing products:
- Voltage Overshoot reduced by up to 80%
- Short Circuit detected up to 20% faster

AgileSwitch®

AgileSwitch, LLC

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High Performance Solar PV String and Micro Inverters with SiC and GaN Devices

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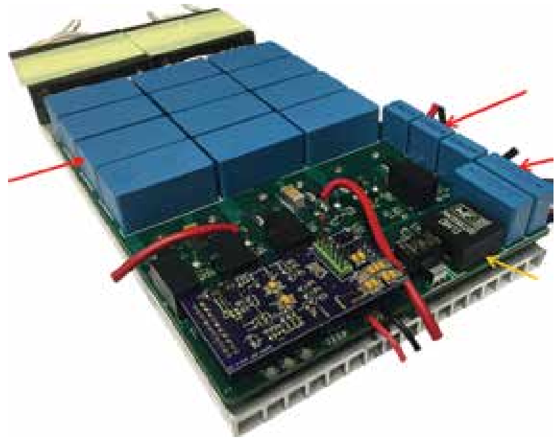
PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE



A 3kW string inverter prototype.

Technology Gap/Need

- Large common-mode voltage induced leakage currents in transformer-less inverters resulted in safety, reliability and EMI issues in conventional photovoltaic (PV) inverters
- 120 Hz power pulsation in single-phase inverters required use of large banks of electrolytic capacitors that compromise reliability and power density

Project Summary

The two objectives of the project are to develop:

- Two different types of transformer-less PV string inverters with >98% CEC efficiency, > 30 W/inch^3 power density and all-film capacitor implementation
- A transformer-less 300 W micro inverter with 96% CEC efficiency, >10 W/inch^3 power density and all-film capacitor implementation

These objectives are achieved through topological innovations that exploit the superior characteristics of SiC and GaN devices. A class of doubly-grounded, wide-voltage-swing DC link topologies with active power decoupling has been developed for the transformer-less inverters. The main advantages are elimination of PV capacitive coupled leakage currents and elimination of the need for large electrolytic capacitors. High gain DC-DC converters and zero voltage transition auxiliary circuits have also been developed. These topologies using SiC and GaN devices have been demonstrated in several hardware prototype PV inverters achieving power density above 30W/inch^3 and CEC efficiency above 98%.

Accomplishments

- Five new topologies developed and validated in hardware
- Power density > 30 W/inch^3 and CEC efficiency >98% achieved while simultaneously eliminating electrolytic capacitors and common mode leakage currents
- WBG device operation close to their maximum ratings has been demonstrated (>1kV operation with 1.2 kV SiC MOSFETs)
- Published 21 technical papers (several more under review) from this work in leading power electronics journals and major IEEE conferences (ECCE and APEC) in addition to a patent application and two invention disclosures

Deliverables

The final deliverables are three hardware prototypes – two for transformer-less string inverters and one for transformer-less microinverter using new circuit topologies and meeting the challenging performance targets.

Impact/Benefits

The project solves two major problems of single phase, transformer-less PV inverters, and demonstrates that high power density and high efficiency can be achieved simultaneously with wide bandgap devices. It can help accelerate widespread adoption of WBG devices in the PV inverter industry.

Mass Market SiC Solid-State Circuit Breaker Development

Atom Power Microgrid Island product.

Technology Gap/Need

The reliability and availability of SiC power semiconductors coupled with the size and efficiency of computing have certainly been enabling technologies behind the commercial viability of solid-state circuit protection. The need for solid-state circuit protection is vast, consisting of the following highest level value propositions: digital control of circuit breakers, arc flash reduction or complete mitigation (in the case of Atom Power), available short circuit reduction, surge suppression, and integrated motor starting.

Project Summary

The goal for this project is to build upon our existing knowledge base and develop higher ampacity SiC solid-state circuit breakers to penetrate the full commercial and industrial building market; specifically an 800-amp, 3-phase, 480VAC solid-state circuit breaker. Atom Power has taken an uncommon approach to the use of SiC devices by implementing them as short circuit and overload protection and is therefore opening up an entirely new industry for the WBG community.

Accomplishments

Atom Power has developed a commercially viable 800-amp solid-state circuit breaker (called an Atom Switch) through this project and has already found customer bases within the domestic United States.

Deliverables

Our final product result was to deliver one working prototype of the 800-amp Atom Switch solid-state circuit breaker. Prototype within our group in reality represents a product that is ready for review by UL for UL 489 standards.

Impact/Benefits

The 800-amp Atom Switch solid-state circuit breaker has already received requests for pilots and product integration within the energy storage and motor control markets. Specific to the energy storage markets, we have developed what we call a "Microgrid Island™" product that incorporates the 800-amp Atom Switch within and is the key technical enabling device. Additionally, the 800-amp Atom Switch has many other features built into it such as metering, ANSI relay protection, and short circuit limits which are valuable for the motor control and motor protection markets.

Atom Power, Inc.

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PowerAmerica Roadmap Targets

- BRINGING TOGETHER ALL FACETS OF THE SUPPLY CHAIN
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SiC Commercial PV Inverter

Florida State University

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Technology Gap/Need

The current technologies in the power electronics industry are suited for Si devices. There is lack of optimized circuit design, thermal design, EMI design and system design for SiC device based converters. Our technology filled this gap.

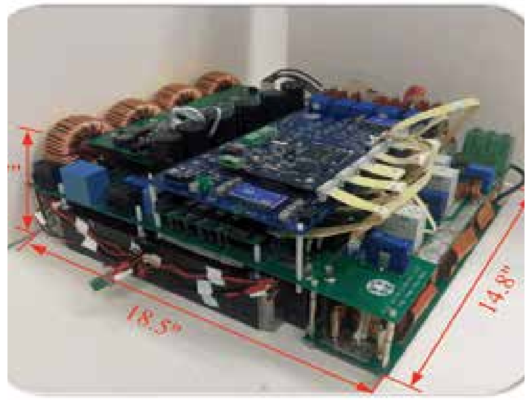
Project Summary

This project aims to develop a world-record first utility-scale photovoltaic (PV) converter with the size of a residential-scale converter. Gen-I is a 50 kW PV converter with 2.5 kW/kg power density and 99% peak efficiency. This project has developed a Gen-II PV converter that doubled power density and doubled power rating with the efficiency higher than 99%. In addition, the ground leakage current is limited to less than 300 mA at 100 kW output power. An EMI filter has been designed for this converter to meet 47 CFR 15.107 standard. A new thermal management method has been developed to improve the power density further. Moreover, a SiC JFET cascode device has been compared to a SiC MOSFET device applied to this PV converter in terms of efficiency and power density aspects. This project has demonstrated that a SiC PV converter can obtain performance advantages that cannot be achieved by Si based-converters and is ready to be commercialized. Finally this project has continued to educate undergraduate students and graduate students with WBG circuit design, thermal design, EMI design and system design training.

Accomplishments

We have developed and successfully tested a 100 kW transformer-less SiC PV inverter to double the power density of the Gen-1 prototype with efficiency higher than 99%, and ground leakage current less than 300 mA. Specific accomplishments include:

- A Gen-II prototype has been designed, built and tested under 100 kW operating condition.
- An optimized heatsink design to improve power density.
- A base line EMI filter has been designed to meet 47 CFR 15.107 standard.
- A common mode choke has been designed to suppress the ground leakage current at 100 kW operation.
- A 1200 V SiC JFET cascode device has been compared with SiC MOSFETs in terms of loss and power density.
- Five undergraduate students have been involved in this project to design the advanced thermal management system.
- Five graduate students have been trained in this project.



Photovoltaic inverter prototype.

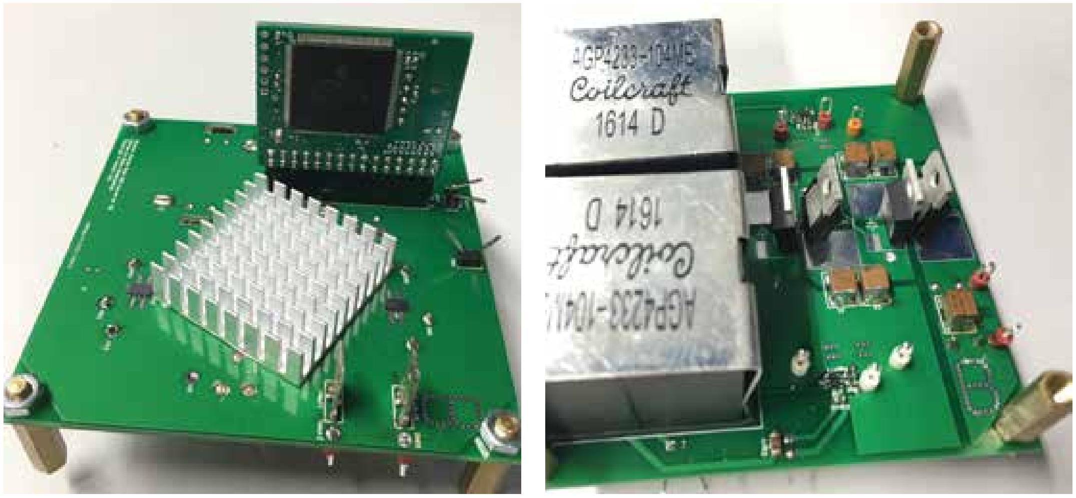
Deliverables

- 100kW SiC PV inverter hardware achieving world-record efficiency and power density
- Control software and hardware
- Design guidance for passive components
- Thermal design report
- Four journal papers and three conference papers
- Two invention disclosures
- Two Master theses

Impact/Benefits

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

Hybrid Micro Converter



DCP HVG Converter (Left: Top; Right: Bottom)

Technology Gap/Need

Lack of power electronic engineers experienced in working with wide bandgap devices.

Project Summary

The Hybrid Micro (HybMic) Converter is suitable for AC, DC, and hybrid applications. It links an individual solar panel (20~30-VDC) to a 240-V, single-phase AC grid or a 400-V DC power distribution system. This converter is comprised of a high voltage gain DC-DC converter cascaded with a DC-AC inverter. The voltage of the DC link is 400 V. Therefore, the HybMic converter can be used to tie solar panels to DC microgrids, energy storage, and UPS systems. While taking advantage of the physical properties of wide bandgap devices, the proposed HybMic converter addresses the main market pain points which are the efficiency, reliability, and cost effectiveness of solar power generation.

Accomplishments

Development of GaN gate drivers; successful heatsink design; achieving a CEC efficiency of 97%; 500 hours of beta testing.

Deliverables

Four hardware prototypes, one conference paper and one journal manuscript.

Impact/Benefits

The 400-VDC output can be used to form a local DC distribution system serving local DC demands. Wiring of such a DC system requires less copper. It also takes a much shorter time; therefore, installation costs are reduced by 50%. Distributing power in DC form has several advantages over an AC system. For example, common loads such as computers, monitors, and light - emitting diodes are all DC in nature. Variable-speed motors run on AC power but there is a DC link in their structure. Therefore, motor drives can directly benefit from a DC distribution network. Also, energy storage systems such as batteries and ultra-capacitors are DC. Plug-in vehicles can also be considered as DC loads. Sources such as PV panels and fuel cell are DC as well. In a microgrid environment (e.g. a large building or a small neighborhood) with a considerable renewable generation capacity, it is more efficient to avoid excessive AC-DC rectification and DC-AC inversion by using a DC distribution system.

InnoCit

InnoCit LLC in collaboration with the Missouri University of Science and Technology

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PowerAmerica Roadmap Targets

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Manufacturing, Testing, and Heavy-Duty Vehicle Deployment of 200 kW 1050 VDC SiC Dual-Inverter

JOHN DEERE

John Deere Electronic Solutions Inc. (JDES), a subsidiary of Deere & Company

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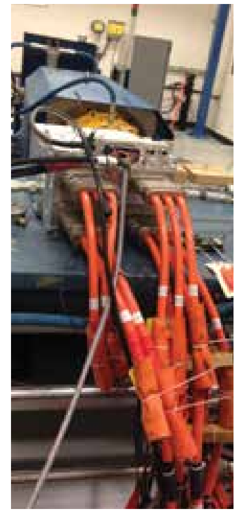


John Deere is testing a SiC inverter in its 644K Hybrid Loader.

Technology Gap/Need

The high power density SiC inverter is a suitable candidate for heavy-duty off-highway vehicle applications. This is because a heavy-duty vehicle is conducive to exploiting all unique properties of the SiC material. Prior to the start of this project, no example of a SiC inverter application in a heavy-duty off-highway vehicle existed.

A power-dense, robust, reliable, and engine coolant-capable SiC inverter will make the vehicle platform simpler due to the elimination of the dedicated cooling circuit required today with IGBT inverter technology. This will address industry needs and could accelerate the adoption of high-performing hybrid technology to promote US manufacturing.

Project Summary

John Deere Electronic Solutions Inc. (JDES), a subsidiary of Deere & Company, is designing a 200 kW 1050 VDC SiC dual inverter to manufacture. Key attributes of the final version of this inverter are: vehicle radiator coolant (max temperature 115°) power electronics, high power density (> 20 kW/L), and high efficiency (> 97%) over a wide range of torque and speed of heavy-duty electric vehicles. The identified application of the dual inverter is the JD 644K Hybrid Loader. JDES has deployed the Gen-0 and Gen-1 SiC inverter in the JD 644K Hybrid Loader and named the vehicle as the JD 644 WBG Loader. The Gen-0 SiC inverter have been thoroughly tested in the 644 WBG Loader. The Gen-1 SiC inverter is designed to operate with the engine coolant, which is, 105°C Water Ethylene Glycol (WEG) coolant. The Gen-1 SiC inverter has been tested in a 644 WBG Loader while the inverter is cooled with engine coolant.

Accomplishments

The project met and often exceeded project milestones. Engine coolant capable Gen-1 SiC inverter has been deployed in a JD 644 WBG Loader and inverter operation has been demonstrated to DOE and PowerAmerica personnel. A commercialization path has been developed and upcoming budget periods will be used to work on the commercialization pathway so that adoption of WBG power electronics takes place in John Deere and the OEM platform supported by JDES power electronics.

Deliverables

The final result of the project was the successful vehicle demonstration of the Gen-1 SiC inverter in a JD 644 WBG Loader.

Impact/Benefits

The application of a WBG inverter in heavy-duty off-highway hybrid vehicle platforms.

Comparing SiC and GaN Electric Vehicle Chargers

Technology Gap/Need

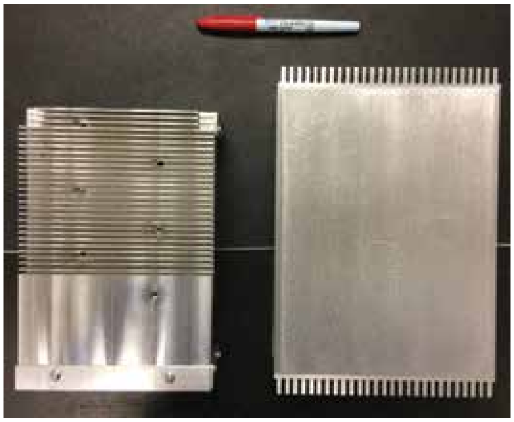
- Low-voltage (<1200V) SiC devices are quite new, which has not been reported on the EV charger applications yet.
- A head-to-head comparison of SiC and GaN is rarely seen given these two different technologies used to take care of different voltage ratings.
- A soft-switching control within whole battery-voltage range is rewarding to maximize the potential of WBG devices.

Project Summary

Based upon the previously developed Level-2 battery charger using top-cooled E-modeGaN HEMTs, Hella, UM-Dearborn and Kettering University adopted 650V SiC MOSFETs for the charger and did a head-to-head comparison between two WBG technologies, including the efficiency, power density, thermal performance and cost. Both chargers reached >97% efficiency and >3.3kW/L power density, superior to the 94%-efficiency and <2kW/L chargers on the market.

Accomplishments

- Generated two much smaller and lighter EV chargers for automotive OEMs (3~4kW/L of WBG devices vs 1kW/L of Si version);
- Processed a head-to-head comparison of GaN and SiC in WBG community, including the efficiency, thermal, power density and cost;
- Tested two different SiC devices in the charger. One is 650V/93A, the other is 900V/160A;
- Involved six undergraduate co-op students, three graduate students, and two engineers to build a strong pipeline of power electronics expertise;
- Investigated and implemented multiple novel control strategies for EV chargers. All are able to secure the soft switching within the wide battery-voltage range (200-450V).



GaN charger (left), 4 kW/L vs. SiC charger (right), 3.3 kW/L.

Deliverables

- One SiC charger and one GaN charger. Both were comprehensively tested and reached >97% efficiency with >3kW/L power density;
- One journal paper "Comparison of SiC MOSFETs and GaN HEMTs Based High- efficiency High-power-density 7.2kW EV Battery Chargers," was submitted and under review;
- One short course, "Applying Wide-bandgap Devices to EV Battery Chargers" was delivered online through VTS (http://resourcecenter.vts.ieee.org/vts/product/webinars/VTSWEB0013).
- One short course was delivered to Hella Electronics Global.

Impact/Benefits

This project provided the electric vehicle industry two highly efficient and highly compact EV battery chargers. Meanwhile, a direct head-to-head comparison of SiC and GaN devices was carried out, demonstrating the effectiveness of WBG devices on shrinking the size and increasing the efficiency of EV battery chargers. The whole project involved two engineers from one company, as well as three graduate students and six undergraduate students from two universities, building a strong pipeline of power electronics expertise.

Kettering

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GaN RF DC-DC Converter Design

NC STATE UNIVERSITY

LOCKHEED MARTIN
We never forget who we're working for®

North Carolina State University, Lockheed Martin

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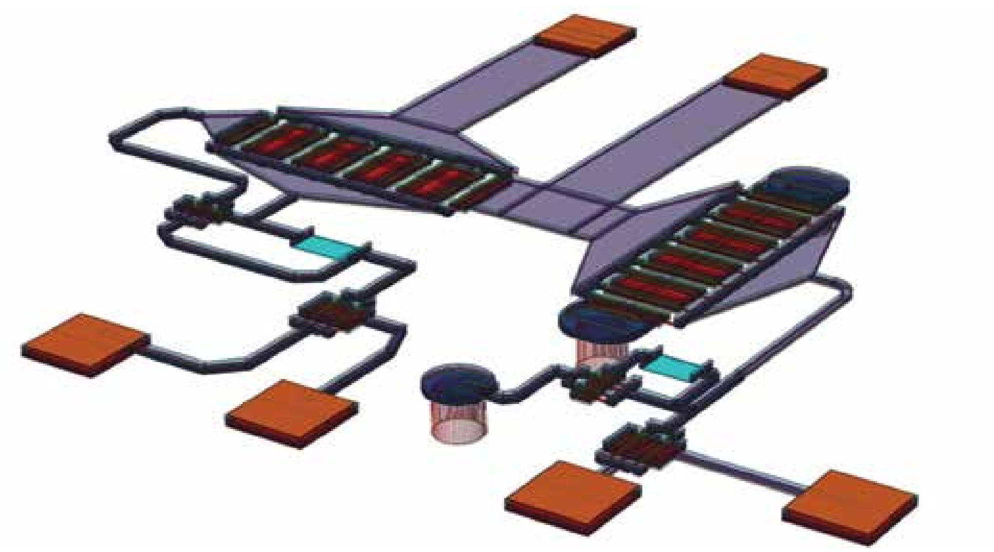

Integrated design layout.

Technology Gap/Need

Previous DC-DC based designs have used discrete GaN to achieve high-power and efficiency. In this project we seek an integrated design with ultra-low parasitics and high-speed devices that can exceed switching speeds of 100 MHz.

Project Summary

This task seeks to reduce energy consumption through the development of a high-speed DC-DC GaN converter. Using integrated GaN, a high-speed DC-DC converter will be investigated with bandwidths exceeding the current bandwidth of cellular and other wireless technologies. This will enable GaN to replace linear amplification currently used in wireless systems, such as telecom base-stations, which currently use 60 TWh/a. Power is dominated by linear power amplification.

Accomplishments

We have demonstrated a GaN DC-DC converter design that surpasses state-of-the-art performance in transient speed.

Deliverables

At the completion of the project, the team will have a manufacturing specification to build a high-speed DC-DC converter achieving the project goals of < 10 ns rise time.

Impact/Benefits

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

Integrated Intelligent Gate Driver and Interface System for Medium Voltage Applications

NC STATE UNIVERSITY

North Carolina State University

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Technology Gap/Need

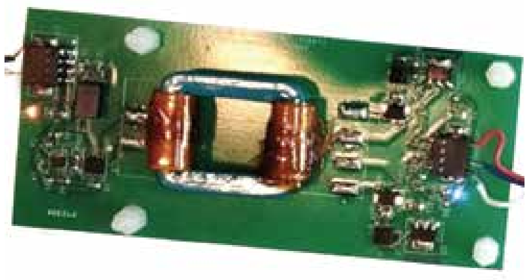
Successful implementation of 10kV SiC MOSFETs in medium voltage converter is greatly dependent upon reliable gate driving technology. High voltage swing on the gate driver output ports requires high common mode transient immunity of the gate driver channel as well as high voltage isolation of the DC power supply. Presently, no gate driver for 10kV SiC MOSFETs is available commercially. The 10kV SiC MOSFETs are still in the development stage, and are prone to failure in harsh operating conditions. A prognosis and diagnosis feature embedded in its gate driver can help in understanding the failure mechanisms. The short circuit protection of the MOSFETs is an inherent requirement for reliable operation of the converter enabled by these MOSFETs. Active gating can significantly reduce the switching losses of these MOSFETs, and thus, increasing the power handling capability of the converter cooling system. In this project, all the aforementioned features have been incorporated in the gate driver, which is validated with suitable test-benches.

Project Summary

The goal is to design, develop, validate and optimize a 15 kV isolated gate driver (GD) for SiC MOSFETs suitable for operating at 10 kHz to 20 kHz with integrated diagnostics, active gate driving capability, software programmable gate resistance selection, and with data acquisition and protective features. The objective is also to work with industry partners to optimize and package the gate driver; to commercialize isolated GD for HV SiC 3.3kV to 10 kV MOSFETs.

Accomplishments

- Developed isolated DC-DC converter with <1.5pF coupling capacitance and >15kV DC isolation.
- The gate driver, qualified in boost, buck-boost and boost-buck converter at 5kV DC bus, 10A current and 10 kHz switching frequency.
- Short circuit protection up to 6kV DC bus and 224A short circuit current with trip time less than 2.4μs.
- Active gating scheme.
- Monitoring of voltage and current of the MOSFET for its prognosis and diagnosis.
- An interface board for communication of 12 intelligent gate drivers, required in 3-level 3-phase voltage source converter with 12 switches.
- Demonstration of high frequency 3-phase voltage source converter using 10kV SiC MOSFETs for 1 kHz fundamental frequency, 3kV DC bus, 20 kHz switching frequency and 1.45kW load.
- Series connection of 1.7kV SiC MOSFETs for 1.8kV DC bus in an H-bridge converter with 76kVA load, 10 kHz switching frequency and 150A peak current.



15kV Isolated DC-DC power supply for the medium voltage gate driver.

- Report on detailed specifications of the medium voltage gate driver, insulation requirements and the various packaging goals and the models.

Deliverables

- 15kV isolated DC-DC power supply with <1.5pF coupling capacitance
- Intelligent medium voltage gate driver suitable for 6kV DC bus, 10A and 10 kHz switching frequency operation with short circuit protection feature.
- Interface system for the gate drivers.
- Test setups for qualification of the gate driver.
- 3-phase 5kV DC bus 500Hz fundamental frequency 3-phase voltage source converter.
- Report on detailed design and application of the GD for series connection of low voltage devices
- Report on design considerations and test results of the medium voltage high frequency converter for high-speed machines at 8kW output power.

Impact/Benefits

Usage of SiC devices in high speed medium voltage electric machines will obviate the need of costly gear boxes in high speed gas compressor systems for oil and gas production platforms. The solid state transformer is another promising application of 10kV SiC MOSFETs. Feasibility of medium voltage asynchronous grid connecter depends upon these 10kV MOSFETs. The gate driver is the only interface between the converter designer and the power device designer. If a suitable gate driver with sufficient reliability is available for use, the converter designer will see the power device as a switch only, making the design process for the converter easier. Availability of these gate drivers with appropriate protective features promises wide application of 10kV SiC MOSFETs in medium voltage applications.

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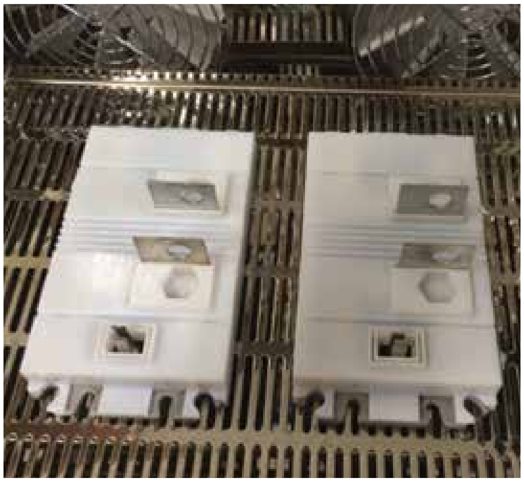
PowerAmerica Roadmap Targets

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

Demonstration of a Medium Voltage Power Module for High Density Conversion



Left: Fully packaged PREES 6.5kV/100A SuperCascode Module (w/ unbent terminals). Right: Internal view of the PREES 6.5kV/100A SuperCas-code Module.

Technology Gap/Need

Package and module manufacturing capabilities are needed to support WBG manufacturing.

Project Summary

This project develops and demonstrates the first 6.5kV/100A SiC Super Cascode Power Module (SCPM) as a Single-Switch in a compact standard L3/57-Pack. Design and preliminary testing shows operation in the 10's of ns with high electrical efficiency. The module is designed for upgrade to 6.5kV/200A when SiC JFET devices become available.

Along with the modules, a 1.25MW/5kV/100kHz continuous power test platform has been designed. The test platform recirculates power. Hence, only a low power source is required. The testing results can directly show switching energy, on-state loss, and thermal performance. The setup is designed as a stand-alone tester for future high performance medium voltage module evaluations.

Accomplishments

We have designed and built custom stressing and aging systems used for the reliability tests of the commercial HEMTs. Before stressing, we performed full static, dynamic, and temperature characterization on the approximately 150 commercial devices (of four varieties) included in this study. Decapsulation of failed test devices and analysis of failure mechanisms is underway.

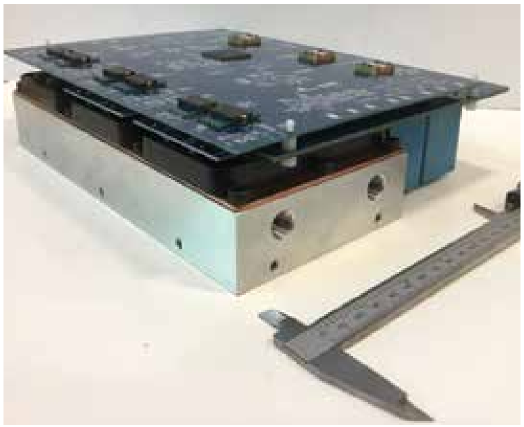
Deliverables

Demonstration of a 6.5kV/100A SiC Super Cascode Power Module (SCPM) as a Single-Switch in a compact standard L3/57-Pack. Along with the modules, a 1.25MW/5kV/100kHz Continuous-Power test platform has been constructed.

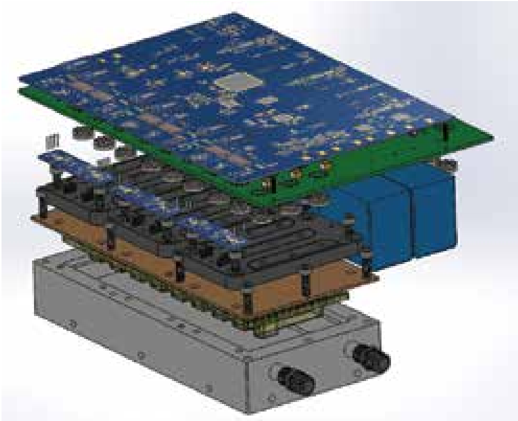
Impact/Benefits

Medium voltage systems, such as medium voltage drives, and smart grid solid-state transformers.

100kW SiC Inverter for Electric Vehicle Traction Drive



100 kW EV inverter for traction drive.



Architecture of the 100 kW EV inverter.

Technology Gap/Need

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

Project Summary

The goal of this project is to design, fabricate, and test a 100 kW automotive electric vehicle (EV) traction inverter using SiC power devices. The inverter has been designed to have a high power density (19.3 kW/L) as well as high efficiency (99% peak) utilizing a two-stage topology which incorporates an interleaved-boost front end and a three-phase voltage source inverter (VSI) connected via a DC-bus of 1 kV.

Accomplishments

- Traction drive inverter has been designed, fabricated, and tested with a peak power capability of 135 kW with 1 kV DC-link voltage.
- Planarized design with high voltage and high current PCB-based bus bar provides low power-loop inductance (<13 nH).
- Developed innovative heavy duty connectors for interfacing the modules with the PCB bus bar.
- Ultra-low-profile (4 mm) gate driver provides 70% height reduction compared to the commercially-available solution.
- Inverter-only volume is 3.9L (yielding 35 kW/L power density), while the overall system volume (with boost converter and VSI) is 7 L (yielding 19.3 kW/L power density).

Deliverables

135 kW (peak) SiC traction inverter with a power density of 35 kW/L was successfully built and tested at 40 kW and 100 kVAR.

Impact/Benefits

The high-power density inverter can provide significant reduction in overall traction drive volume and weight. Coupled with an electric machine utilizing the high DC-bus voltage, the overall system efficiency can also be increased. This can enhance the fuel economy of electric vehicles thus extending the drivable range while reducing CO_2 emissions which would help the auto industry meet the aggressive corporate aggregate fuel economy (CAFE) requirements.

The features of the SiC inverter like low profile gate driving circuitry, high voltage and high current PCB bus bar etc. can be extended to other applications like active harmonic filtering.

A companion "Technology Transition" project was also successfully conducted. This project paired engineering and business school students to analyze the potential market, voice of the customer, manufacturability, large volume manufacturing cost, and commercialization pathways, to lay the groundwork for commercialization of this product.

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North Carolina State University

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PowerAmerica Roadmap Targets

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

Development and Deployment of a Wide Bandgap Medium-voltage Electric Vehicle Fast Charger

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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Comparison of SOA Fast charger and WBG MV Fast Charger.

The WBG MV Fast charger inside view.

Technology Gap/Need

Commercially available fast chargers connect to a 3-phase 480V/208V/400V service, typically supplied to industrial loads. As a result, the installation site requires access to a service transformer with 50kVA or more spare capacity. The need for a service transformer affects the overall size, weight and the installation cost of the system, which can be especially problematic in densely populated areas, where electric vehicles are likely to be adopted. Further, the system efficiency of the state of the art fast chargers is approximately 93% when the efficiency of both the charger and the service transformer are considered. Our approach is to connect the fast charger directly to the medium-voltage (MV) line, thus eliminating the service transformer. This approach can significantly reduce installation costs while halving power conversion losses.

Project Summary

In this project we developed an electric vehicle charger that is 6-10 times smaller than existing chargers, and wastes half as much power during charging. The prototype replaces a conventional 50kW charger, and the associated service transformer required to connect the charger to the distribution system. The charger is designed to be modular, allowing for higher voltage and power chargers to be constructed by simply adding additional modules to the system. The project demonstrates that wide bandgap technology enables converters with better efficiency and power density.

Accomplishments

Demonstrated the 50 kW, 2.4 kV AC input, and 250-450 V DC Medium-Voltage Fast Charger in operation. The charger exceeds 95% efficiency, 1 kW/L power density, and current total harmonic distortion of less than 2% at full load. The designed system is modular, which allows the system scaling in voltage and power with minimal additional development.

Filed a provisional patent protecting IP generated in designing the fast charger.

Deliverables

Demonstrated the 50kW medium-voltage electric vehicle fast charger in operation, charging an electric vehicle.

Impact/Benefits

Our medium-voltage electric vehicle fast charger can be used to supply power to most electric vehicles on the market today. The design can also provide DC service to other kinds of high-power DC loads and sources, including industrial loads and DC data centers.

A companion "Technology Transition" project was also successfully conducted. This project paired engineering and business school students to analyze the potential market, voice of the customer, manufacturability, large volume manufacturing cost, and commercialization pathways, to lay the groundwork for commercialization of this product.

Medium Voltage Gate Drive with Comprehensive Protection Functions

Technology Gap/Need

Applications of medium voltage SiC devices in multi-level converters present great challenges in the gate drive system design.

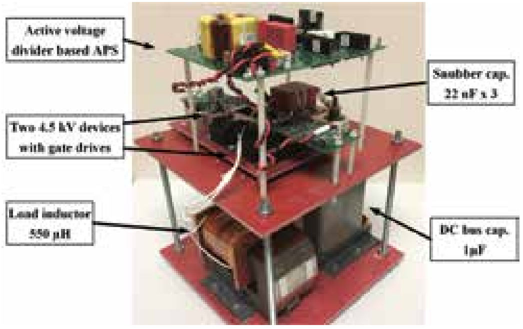
- Medium voltage SiC devices, compared to Si devices or SiC devices with lower voltage rating, have higher switching speed, but are more vulnerable to faults, such as short circuit and overcurrent. These devices require their gate drive to have higher common-mode transient immunity and more robust protection functions.
- In multilevel circuits, gate drive auxiliary power supplies usually get their input power from sub-module DC buses. The emerging 10 kV or higher voltage rated SiC devices will make the sub-module DC bus voltage reach 7 kV and higher. The lack of feasible solutions for auxiliary power supply with high input voltage is one of the main barriers for applying medium voltage SiC devices in high voltage applications.

Project Summary

The main task of this project is to develop a gate drive system for medium voltage silicon carbide devices, which will enable their implementation in multi-level converters for high voltage applications. The developed gate drive system includes a medium voltage gate drive circuit and an associated auxiliary power supply. The gate drive circuit features a high common mode transient immunity (> 200 Giga Volts per second) and comprehensive protection functions, including overcurrent protection, isolated gate drive failure protection, PWM overlap protection, undervoltage lockout, soft turn-off, and fault report. The associated auxiliary power supply is based on the concept of active voltage divider. It utilizes a 7 kV DC bus to generate a 15V output with simple circuit structure and robust control schemes.

Accomplishments

- A 15 kV rated test platform has been designed and fabricated for evaluation of medium voltage SiC devices and their gate drive systems.
- A medium voltage SiC device gate drive system, which includes a medium voltage gate drive circuit and an associated auxiliary gate drive power supply, has been developed and fully tested. All designed functions have been fully validated with the following tests.
- The functions of the auxiliary power supply have been tested with a 7 kV input. The circuit passed 10 kV insulation test, demonstrated robust automatic start-up function and has very stable voltage output at step load change.



Medium voltage SiC device evaluation setup with the developed gate drive system.

- Three conference papers have been submitted and journal publications are in preparation. A patent application is in progress
- Six graduate and four undergraduate students were involved in this project.

Deliverables

- Evaluation platform for medium voltage SiC devices and their gate drive systems
- Medium voltage SiC device gate drive circuit with high common mode immunity (> 200 kV/µs) and comprehensive protection functions
- A high-reliability auxiliary gate drive power supply with 7 kV input, 15 V output and 10 W power rating
- Demonstration of developed gate drive system in booster converters built with 10 kV SiC MOSFETs

Impact/Benefits

Technical Benefits
The developed gate drive system has high common mode noise immunity, comprehensive protection functions, and high reliability. The auxiliary power supply, which directly takes input power from > 7kV DC bus, is a key technology that enables applications of SiC devices in high voltage (>100 kV) applications including high voltage DC transmission and large-scale integration of renewable energy.

Educational Impact
Six graduate and four undergraduate students have participated in this project. The outcome of the project has been integrated into OSU's high voltage engineering class (ECE5047) as a case study and demonstration. This gives students exposure to safety requirements for high voltage power electronics, advantages and challenges of SiC devices, basic principles of gate drive circuits, double pulse tester and associated measurement instruments.

The Ohio State University

The Ohio State University

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PowerAmerica Roadmap Targets

IMPROVING RELIABILITY

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

SiC Device-based Small Commercial PV Inverter

TOSHIBA
Leading Innovation

Toshiba Internal Corporation

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PowerAmerica Roadmap Targets

REDUCING COST

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Technology Gap/Need

The first technology gap is to evaluate SiC devices' performance and determine the appropriate match for new products. The portfolio of available SiC devices has changed and performance has improved very quickly in the last several years. Making a good decision on device selection is crucial for a good product design and a solid supply chain.

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

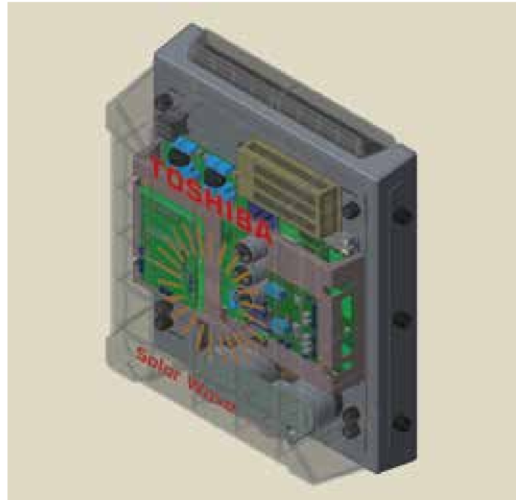
Project Summary

This project aims to design, develop, release and manufacture SiC-based small commercial photovoltaic (PV) inverters (10kW to 99kW) with higher efficiency, smaller size, lighter weight and higher reliability. The deliverable is the 50kW SiC device based PV inverter.

The most important critical to quality (CTQ) feature for a PV inverter is the inverter's efficiency, since a return on investment (ROI) of a PV inverter is directly proportional to the inverter's efficiency. The second important CTQ is the inverter's size and weight, which is particularly important for small commercial PV inverters. Costs of installation, transportation and inventory of small commercial inverters accounts for a large proportion of their life-cycle cost.

By using a SiC MOSFET inside the PV inverter, 98+% CEC efficiency has been achieved and the core portion of the inverter is less than 65 kg.

We successfully developed the SiC device-based 50kW PV inverter which has 98+ % CEC efficiency and the core portion of the inverter is less than 65 kg.



Product mechanical design.

At the same time, we have educated power electronics engineers, supply chain engineers and industrial engineers on the application of new SiC devices in new product design and manufacturing.

Deliverables

The SiC device based 50kW PV inverter has been developed and tested. The CEC efficiency is 98+ % and the core portion of the inverter is less than 65 kg.

Impact/Benefits

The global market for PV inverters has been predicted to be more than 56.23 GW per year. More than 21% of PV inverters will be small commercial PV inverters with power ratings from 10 kW to 99 kW. Small commercial PV inverters will be a large market segment with a high growth rate.

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

Open-Source Compact Transformerless Grid-Tied 3kW GaN PV Inverters

MPPT Board.

Transphorm, Inc.

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PowerAmerica Roadmap Targets

REDUCING COST

IMPROVING RELIABILITY

ENHANCING PERFORMANCE CAPABILITIES

Technology Gap/Need

GaN power switches are much faster than conventional silicon power switches such as IGBTs (> 10x) and have very low reverse recovery charge. That enables designers to increase power density of systems and improve energy conversion efficiency at the same time. A major hurdle to widespread acceptance of the new technology has been the shortage of designers who are familiar with high-speed power electronics design and the concomitant dearth of reference designs with GaN power switches. This project addresses that need in one area, namely residential grid tied PV inverters.

Project Summary

This project is on prototyping a compact open source PV inverter with GaN power switches so that the development time at PV inverter companies can be halved from about 36 months to 18 months.

The 3 kW inverter comprises of:

- Two maximum power point trackers that utilize two-phase interleaved modulation to give efficiency greater than 98.5% over a large power range (0.5 to 2 kW) and peak efficiency exceeding 99% in the upper quarter of the power band.
- A high efficiency inverter with peak efficiency about 99% through 75% of the output power level.
- A DSP controller board for modulation and overall control.

All subsystems have been prototyped and tested, including the complete system grid tied to a grid simulator. The final single board design is being completed and will be available to the user community as an open source design in Q3 2017.

Accomplishments

In the course of this project we have been able to prototype the following:

- A compact & efficient two phase interleaved CRM boost converter prototype made with GaN power switches;
- A compact grid tied inverter made with GaN power switches;
- A complete 3 kW grid tied inverter.

Both the boost converter and the inverter can be used as building blocks in other power electronics systems and therefore separate applications notes and reference designs will be made for them.

Deliverables

A complete open-source design of a 3 kW grid tied PV inverter with detailed documentation so that solar inverter companies can readily adapt the design to make inverters in the 1.5-5 kW power range to suit their product portfolios. Higher power levels can be obtained by paralleling the 5 kW design. All reference designs will be available through the PowerAmerica and Transphorm websites.

Impact/Benefits

Transphorm's GaN-on-silicon switches enable compact power electronics systems to be made. They reduce device power losses by half, and conserve metals (such as aluminum for heat sinks; copper, nickel & moly in inductors; tantalum in capacitors, etc) and are therefore very cost effective. The real world impact of this state-of-the-art design will be more efficient conversion of solar energy to electricity with very light & compact systems that are easy to install and which help conserve material resources. The new technology will also facilitate American solar inverter manufacturers to become more competitive with Chinese manufacturers.

EMI Mitigation and Containment in SiC-Based Modular UPS for Commercial Applications

Virginia Tech, Center for Power Electronics Systems (CPES)
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PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Technology Gap/Need

- There are few SiC modules in three-level configuration, which limited the range of possible topologies and imposed hard barriers on the UPS module design.
- The packaging of SiC modules is still strongly based on Si designs, which imposes a limit on the maximum performance attainable with these devices.
- There are no commercial gate drivers suitable for controlling the four MOSFET devices in the three-level modules.

Project Summary

This project devised a mitigation and containment strategy for the conducted electromagnetic interference (EMI) noise generated by uninterruptible power supply (UPS) modules using silicon carbide (SiC) devices. Specifically, the project targeted the design, construction and testing of the UPS module, EMI filters, the development of an active PWM control strategy to minimize EMI emissions, and the design of the UPS module physical layout to direct the EMI noise generated away from all critical components. In addition, the project evaluated alternative circuit topologies for the power conversion stages, selecting a three-level neutral-point-clamped (NPC) topology for the ac and dc-dc converters. This allowed the maximization of efficiency exceeding 99% for each stage. Lastly, a UPS module rated at 20 kW, 480 V ac, 800 V dc, and switching at 60 kHz was built for validation purposes demonstrating the effectiveness of the EMI containment strategy developed.

Accomplishments

- Developed a three-terminal common-mode circuit model of the UPS module to capture the EMI emissions and propagation paths of the AC-DC-AC (three-phase grid-load interface) and DC-DC (battery charger) stages.
- Developed an active EMI suppression strategy for the operation of the grid and load side three-phase converters reducing the noise generated by 30 dB.
- Developed an active EMI suppression strategy for the three-level buck DC-DC converter that theoretically eliminates all CM voltage from its operation.
- Developed a comprehensive noise mitigation strategy qualifying its operation against the EMI commercial UPS standard IEC 62040-2.
- Demonstrated a three-level 20 kW, 480V AC, 800V DC, 60 kHz, full-SiC UPS module achieving 98% efficiency AC-to-AC, with a 99% efficiency per stage.

Three-phase three-level AC-DC-AC 20 kW, 480 V, 800 V DC, SiC-based UPS module with integrated three-level DC-DC battery charger under test.

Deliverables

- Design files for SiC gate-driver NPC phase-leg, UPS module and EMI filter.
- Active EMI suppression PWM schemes for three-phase three-level AC-DC-AC converters and three-level DC-DC buck converter.
- EMI mitigation and containment strategy ensuring the operational integrity of the SiC-based UPS module.
- Three-terminal CM voltage circuit model of the SiC-based UPS module.

Impact/Benefits

- Three terminal model of UPS can predict the DC-DC stage effect on the EMI generated, providing a guideline for EMI filter design.
- Proposed active PWM scheme reduced EMI emissions by up to 30 dB.
- EMI mitigation and containment strategy based on impedance-channeling technique ensured the operational integrity of the UPS module eliminating the “EMI unknown” factor for nuisance tripping.

DC Data Center with High Frequency Isolation

Technology Gap/Need

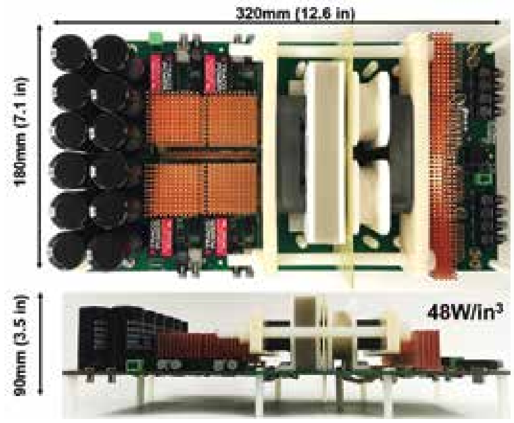
• High frequency solid state transformer (SST) with medium voltage isolation. Most of the SST demonstrations around the world are using silicon IGBTs with a switching frequency of less than 20 kHz. Even with silicon carbide MOSFETs, the highest switching frequency reported is still less than 50 kHz – resulting in very bulky passive components. In order to shrink the system volume and weight, we propose to use Silicon Carbide MOSFETs and operate the SST at an unprecedented 500 kHz, which is at least 10 times higher than others. However, with such high frequency, the transformer isolation becomes very challenging and needs to be addressed.
• High frequency SST with 98% efficiency. With 10 times switching frequency, the device switching loss and transformer AC winding loss can be overwhelming. Advanced techniques like soft switching have to be adopted to help achieve 98% efficiency.

Project Summary

The focus of this project is a three-phase AC/DC power conditioning modular building block converting medium voltage directly into a 380VDC. For each phase, five cascaded H-bridge converters together with CLLC isolated resonant converters are employed. The inputs of the H-bridges are in series to handle the medium voltage and the outputs of the CLLC converters are connected in parallel to handle the large power and provide isolation. For each module, the power level is 15-20kW and with five modules in each phase, the total system capacity can reach 300kW. The proposed cascaded SST system is modularized and scalable, and is able to be easily extended from 4.16 kV AC line to 13.8 kV AC line and from the data center to a broad range of applications, such as an electric vehicle charging station, energy storage systems, photovoltaic farms and other micro-grid related applications.

Accomplishments

• Different transformer core materials were evaluated and 3F36 was selected due to its superior performance under high frequency. A sectional winding structure was proposed so that the leakage inductance of the transformer could be greatly reduced.
• A transformer loss model was proposed including core loss and high frequency winding loss. A transformer design procedure was given so that the lowest loss can be achieved under a given transformer volume. The resulted transformer loss was only 74W, which is 0.5% of the total system power.
• Isolation materials were selected that could handle medium voltage. The proposed transformer was tested under the required voltage and satisfied the IEEE std. C57.12.01 for 4.16kV operation.



500kHz 15kW DC/DC module with medium voltage isolation.

• A 15kW 500kHz modular building block with CLLC bi-directional resonant converter was built using SiC devices with 98% efficiency and 48W/in3 power density.
• The entire system simulation model was built with cascaded H-Bridge (CHB) converter as AC/DC stage and CLLC resonant converter as DC/DC stage. When the CHB converter works in rectifier mode, three-level capacitor voltage balance control is adopted to keep DC capacitor voltage balanced. When the CHB converter works in inverter mode, power control is adopted to achieve bidirectional power flow. In addition, fault detection was implemented into the simulation, including under/over voltage protection and over current protection.

Deliverables

• A 15kW modular building block with CLLC bi-directional resonant converter was built with 98% efficiency and 48W/in3 power density.
• The whole system simulation model was built with CHB converter as the AC/DC stage and CLLC resonant converter as the DC/DC stage.

Impact/Benefits

For the traditional AC data center power architecture, multi-megawatts of power are taken from the high-voltage lines and converted to 480VAC through a bulky 60Hz transformer. Followed by it are multiple conversion stages, resulting in very low efficiency. By converting medium voltage directly to 380V DC using a high frequency solid state transformer, redundant stages are removed and the system efficiency can be improved by over 10%. Also, by eliminating the bulky 60Hz transformer, the total system volume and cost can be greatly reduced.

VirginiaTech

CPES

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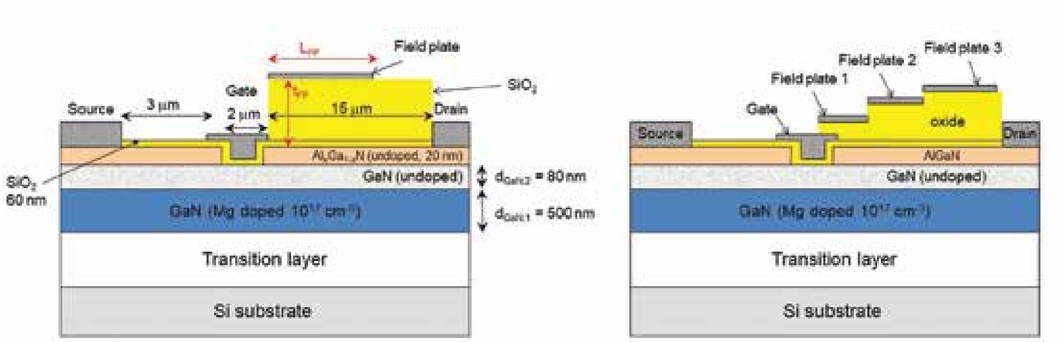
PowerAmerica Roadmap Targets

IMPROVING RELIABILITY

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Curriculum Development on Modeling, Simulation, and Design of Wide Band Gap Semiconductor Devices



Before you make it, simulate it! Power devices are expensive to fabricate. To make sure the design fits the needs of the customer, computer simulations are becoming an important component in any fab today.

Florida State University

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PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Technology Gap/Need

The existing undergraduate curriculum contains courses on fundamentals of semiconductor devices, power electronics, system electronics, and power distribution systems. What is missing however is an important component about the fundamentals and computer simulation of power devices. This component is important for preparing students to understand how semiconductor devices (i.e. diodes, transistors, etc.) operate in order to be able to better design power circuits and systems.

Project Summary

The project introduces aspects of modeling, simulation, and design of wide bandgap semiconductor devices into the undergraduate curriculum of the Department of Electrical and Computer Engineering (ECE) at the Florida A&M University-Florida State University (FAMU-FSU) College of Engineering. The objectives of the project are to integrate techniques for the analysis and simulation of WBG semiconductor devices in two undergraduate courses and create multiple opportunities for undergraduate students to learn new concepts and pursue research activities in the area of WBG semiconductors. Fundamentals of WBG semiconductor devices will be introduced in the two courses by adding a two-week course module with focus on WBG semiconductors and by designing course projects that offer more in-depth education in this area.

Accomplishments

We developed a 2-week module (4 lectures) on the modeling and simulation of power semiconductor devices. Students were taught key topics on power semiconductor devices (bandgap, impact ionization, special types of power devices) and how to use Synopsis-Sentaurus, which is the state-of-the art simulator for power devices.

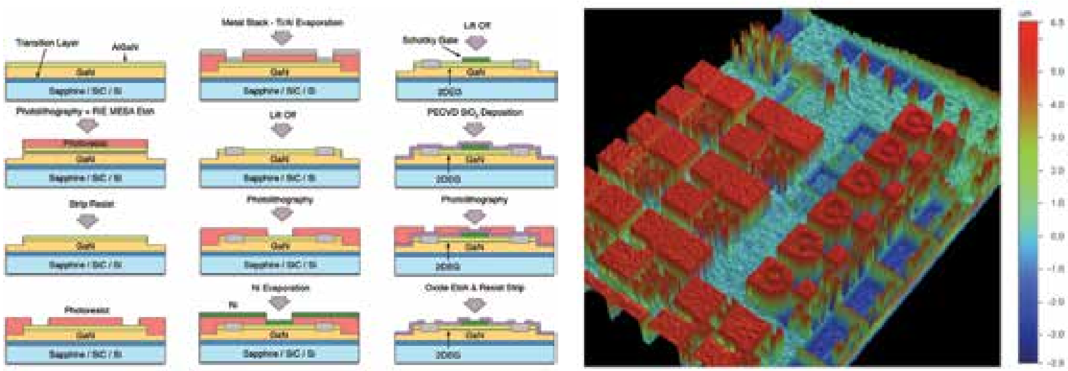
Deliverables

In-class lectures and lecture notes.

Impact/Benefits

The project has a broader impact on student education and preparing them to enter the workforce with more valuable skills.

WBG Workshop Development and Teaching Modules for GaN Transistor Fabrication



Left: GaN transistor processing schematic sequence. Right: GaN transistor simulation.

Technology Gap/Need

The project offers the opportunity to run a 3-day workshop to teach device fabrication to those individuals with no background in semiconductors or device fabrication. Additionally, the project provides the means to introduce GaN transistor fabrication in undergraduate and graduate level courses.

Project Summary

The goal of this project is to develop new opportunities for training of undergraduate and graduate students as well as engineers on processes used in manufacturing of wide bandgap devices. Here, the target group is engineers, who join the workforce without proper training on device fabrication. As such, this project is focused on workforce development, a key component of the PowerAmerica mission.

The overarching goal of this program is to establish a process sequence for GaN transistor fabrication, which can be used in undergraduate and graduate courses or accelerated workshops. It is desirable to have this process sequence be simple enough to be executed in a typical university cleanroom while including many of the standard processes used in device fabrication. GaN (instead of SiC) was deliberately chosen as the semiconductor material since the fabrication equipment needed to execute the steps were readily available in the NCSU cleanroom. On the other hand, SiC devices typically involve very high temperature processes that require special furnaces, which are not available in a typical university cleanroom. The project also included preparation of teaching materials to be used in such courses and workshops. These materials will be available to the public through PowerAmerica.

This program also provided the funds for the acquisition of a GCA stepper for projection lithography as well as an Oxford reactive ion etching system for GaN etching. These tools will not only help our teaching mission but they will also be extremely useful in our WBG research efforts.

Accomplishments

- A simple, hands-on GaN transistor fabrication module for education purposes
- A 3-day workshop has been delivered to a group of undergraduate students
- Developed educational materials for graduate or undergraduate level courses
- Acquisition of a GaN reactive ion etching system

Deliverables

GaN Transistor Fabrication Process, 3-Day Workshop, Educational Materials

Impact/Benefits

Introduction of semiconductor fabrication (with emphasis on GaN transistor fabrication) to an audience with little or no background in the field.

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PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Documentation of Design and Process of GaN Power Devices

Rensselaer

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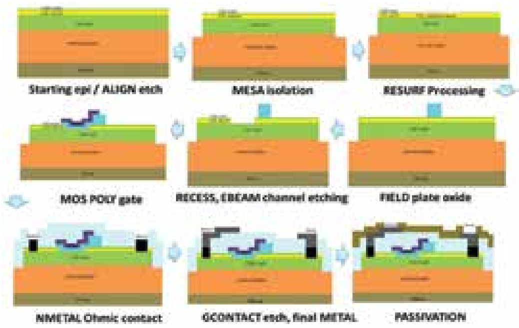
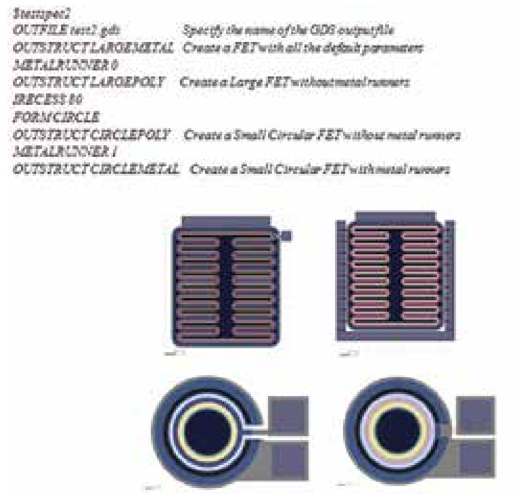
PowerAmerica Roadmap Targets

ENHANCING PERFORMANCE CAPABILITIES

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE



Four MOS HEMT layouts and the specfile which generates them.



GaN MOS HEMT processing summary.

Technology Gap/Need

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

Project Summary

Drawing on our research group's 10 years of experience designing and fabricating gallium nitride MOS HEMTs, we select the best-practice architecture and design for full documentation. In addition to comprehensive documentation we provide an automated layout tool to generate mask layouts from a concise set of design parameters.

Accomplishments

We have documented our verified GaN HEMT design and provided a fully documented automated layout tool for PowerAmerica member use.

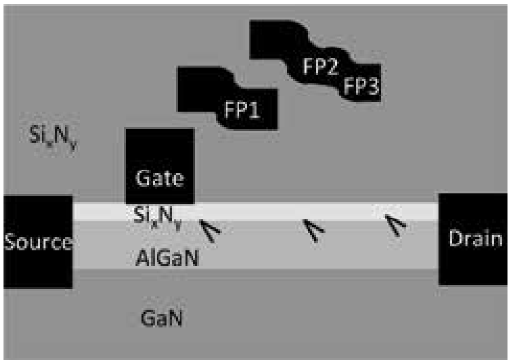
Deliverables

Full documentation of our process architecture and flow along with a fully documented, relatively user-friendly layout tool has been submitted to Power America. Future deliverables include inclusion of more high-level parameters incorporating design synthesis into our current layout tool with the aim of producing a fully turn-key design tool.

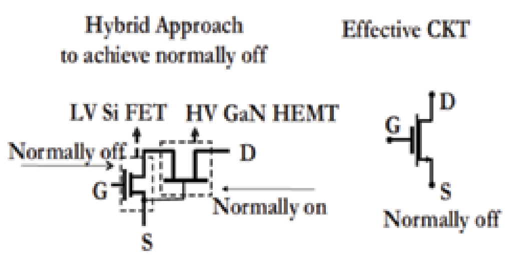
Impact/Benefits

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

Development of Complete Documentation on Fabrication of GaN HEMTs (600V-1.1KV)



Schematic of 600V lateral GaN HEMT with 3 field plates designed for field management.



Cascode normally off GaN HEMT allows for standard silicon-based drive circuits while delivering the high voltage performance of GaN devices.

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PowerAmerica Roadmap Targets

ACCELERATING DEVELOPMENT OF AN ADVANCED MANUFACTURING WORKFORCE

Technology Gap/Need

Power conversion losses are endemic in all areas of electricity consumption, including motion control, lighting, air conditioning, and information technology. Si, the workhorse of the industry, has reached its material limits. Increasingly, the lateral AlGaN/GaN HEMT based on gallium nitride (GaN-on-Si) is becoming the device of choice for medium power electronics as it enables high-power conversion efficiency and reduced form factor at attractive pricing for wide market penetration. Prior to our effort to document GaN power device development using practical knowledge and experimental approach, there were no handbooks or documentation available to an end-user to 'make' their device. This effort has bridged the gap between an engineer who understands basic device fundamentals and processing and GaN device experts.

Project Summary

Create complete documentation of design and fabrication of GaN HEMTs to disseminate the knowledge and understanding of its design and processes and create a chapter handbook based on this information.

Accomplishments

Publishing a document in the form of a book with Springer Publications is a key accomplishment which will enable the proliferation of GaN-based power electronics.

Deliverables

A handbook documenting fabrication and testing of medium power GaN HEMTs
Chapter 1. Material growth
Chapter 2. Design of medium voltage (600V-1.1kV) HEMTs using 2D-drift diffusion models and discussion of the various parameters influencing its performance
Chapter 3. Device fabrication and processing
Chapter 4. Device characterization
Chapter 5. Failure analysis and reliability

Impact/Benefits

Developing a platform that documents the current GaN transistor fabrication process that can be used as a handbook by students and engineers to fabricate 600V GaN Power HEMTs.

The two key outcomes are:

- Widespread GaN HEMT fabrication know-how will lead to multiplying efforts and ultimately creating more market acceptance of the technology.
- Training the next generation workforce will be a key outcome of this document.

Join us

Become a part of a network of Industry visionaries and lead the revolution. Get access to ground-breaking research, proven processes, and an educated workforce to help **grow your business.**

PowerAmerica

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