PowerAmerica Manufacturing Institute

DE-E0006521.0011
North Carolina State University Managed Consortium
BP3: July 2017 – June 2018

PI: Prof. Dan Stancil, North Carolina State University
Presenter: Dr. Victor Veliadis, Deputy Director and CTO, PowerAmerica

U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
July 17-19, 2018

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

- The U.S Department of Energy launched the PowerAmerica Manufacturing Institute to Accelerate Adoption of Wide Band Gap Power Electronics.
- PowerAmerica started operations in 2015 with $140M funds over 5 years, and is managed by North Carolina State University in Raleigh, NC USA.
- PowerAmerica addresses gaps in WBG power technology to enable <u>US manufacturing job creation</u> and <u>energy savings.</u>

NC STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY

PowerAmerica Overview

Timeline

- Award issued in 2015
- Projected DOE End date June 2020
- Project 60% complete
- Project fully funded

Barriers

- The Key barrier to increased penetration of wide bandgap semiconductor technologies is high cost. Establishing reliability, and workforce-development/education are needed to create demand, which lead to volume production that reduces cost.

Budget

	FY 15 Costs $	FY 16 Costs $	FY 17 Costs $	FY 18 Budget $	Total $
DOE Funded	16.2 M	14.1M	15.4M	13.2M	58.9M
Project Cost Share	16.6M	19.8M	15.9 M	14.8M	67.1M

Total DOE: $70M

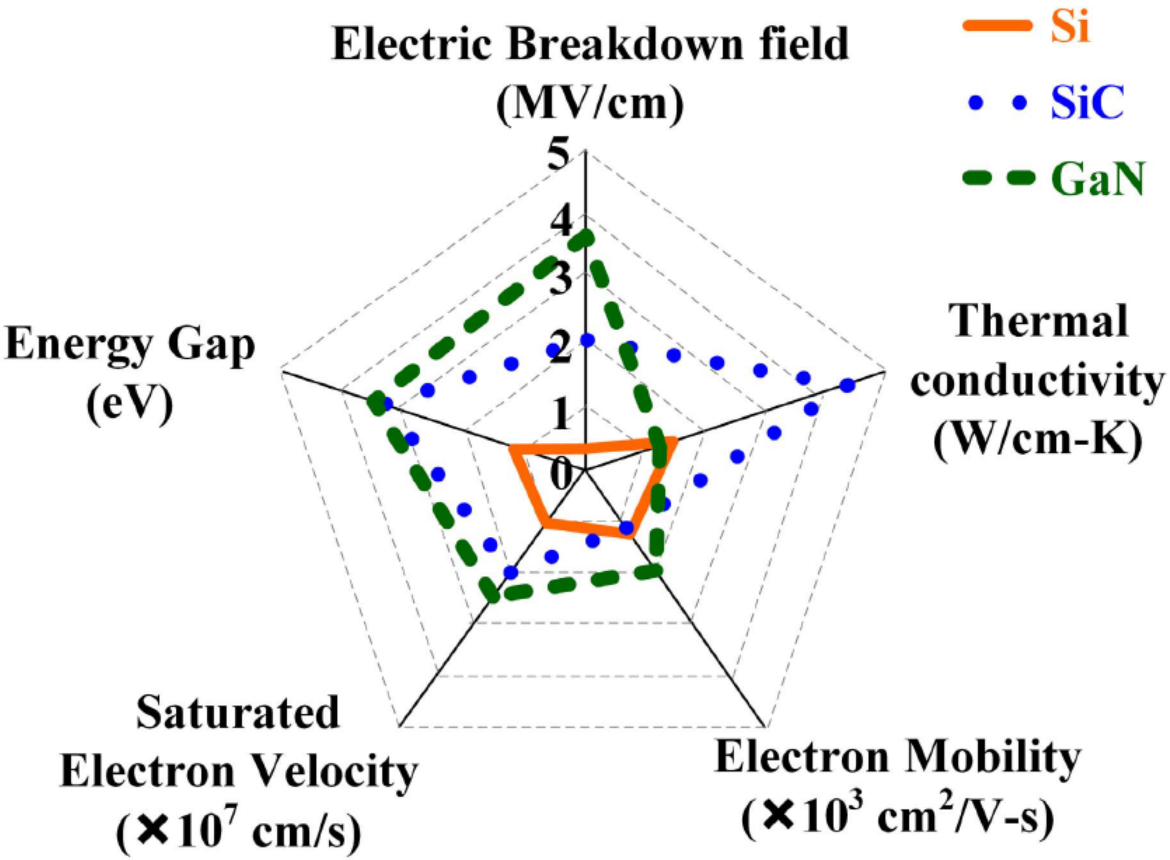
Members

- PowerAmerica is located in Raleigh NC and managed by North Carolina State University.
- PowerAmerica has 46 members who provide key support in technology development, governance, and education
    - 54% industrial, 35% academic, 11% national lab and other consortia
    - Retention year to year at ~90%

PowerAmerica Objectives

- PowerAmerica objectives are to enable US manufacturing job creation and materialize energy savings by volume manufacturing and wide use of Silicon Carbide and Galium Nitride Power Electronics.
- Silicon Carbide and Galium Nitride Power Electronics are far more efficient than their conventional Silicon counterparts allowing for significant energy savings.
- Silicon Carbide and Galium Nitride Power Electronics volume production in the US creates manufacturing jobs.
- Silicon Carbide and Galium Nitride Power Electronics are more expensive than their mature Silicon counterparts and their wide adoption is needed to lower cost through volume production. Workforce training in their use, establishment of their reliability, demonstration of their system benefits, and low cost US manufacturing to compete with Asia are key to success.

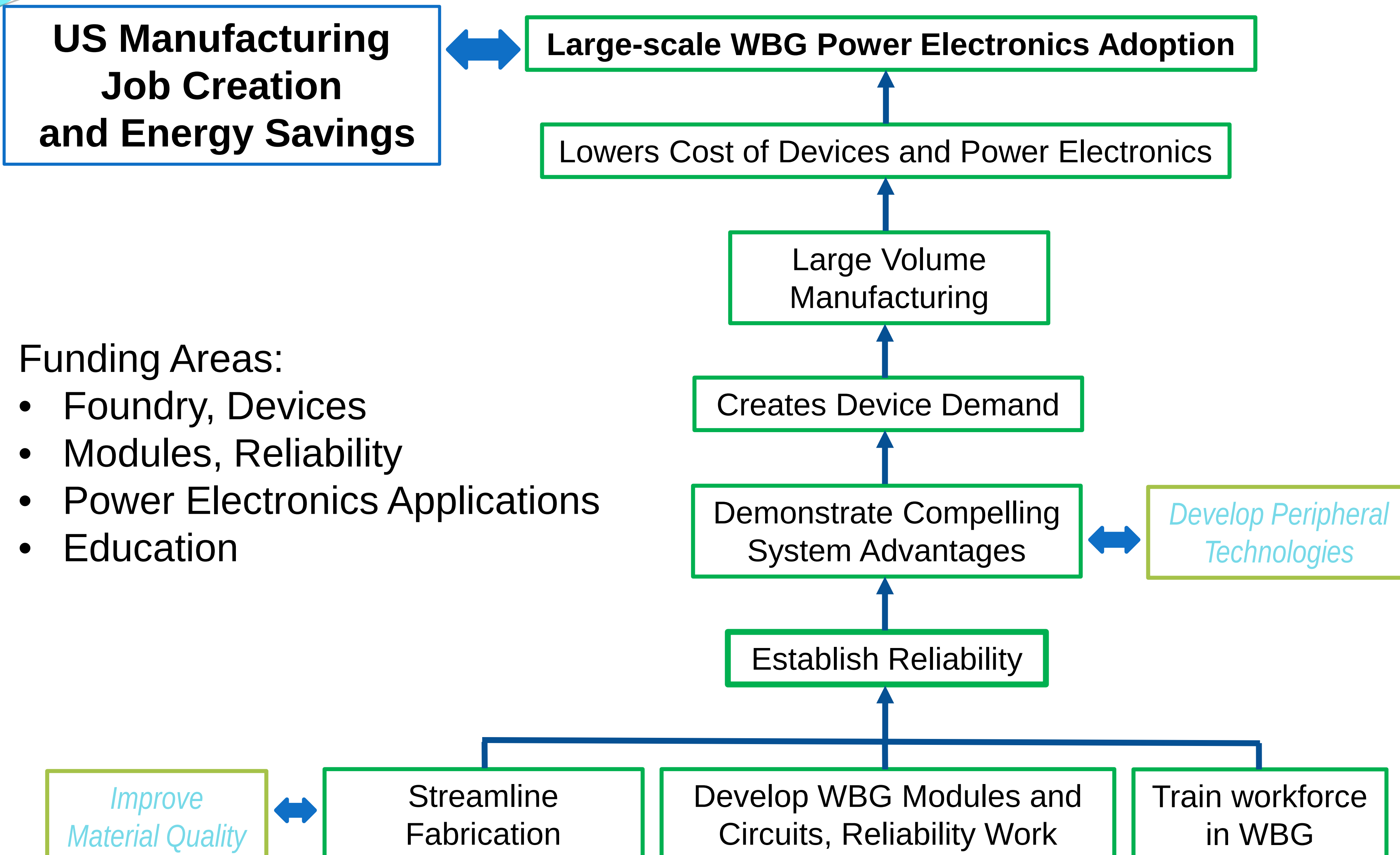
SiC and GaN Power Devices Allow for More Efficient and Novel Power Electronics



$$R_{on\text{-}ideal} = \frac{4\, V_{BR}^{\ 2}}{E_C^{\ 3}\, \mu_n\, \varepsilon_S}$$

WBG power devices offer lower resistance at high voltages, operation at high frequencies, and elevated temperature operation with reduced cooling

PowerAmerica Accelerates Manufacturing of Low Cost SiC and GaN Power Electronics



Funding Areas:

- Foundry, Devices
- Modules, Reliability
- Power Electronics Applications
- Education

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

Funding Period 3: July 2017 – June 2

1 Management and Operations

1.1 Operations and Finance
1.2 Technology Roadmap
1.3 Sustainability
1.4 Device/Module Bank
1.6 Project Portfolio Management
1.7 Membership, Industry Relations and Communications

2 Foundry and Device Development

2.1 SiC Power Device Commercial Foundry Development **X-Fab Texas**
2.3 Development of a Manufacturable Gen3, 6.5 kV/100 mOhm MOSFET **Cree/Wolfspeed**
2.4 Commercialization of 1700V SiC Schottky Diodes **Monolith**
2.8A Lower Cost Foundry Process for 1.2 kV SiC Planar Gate Power MOSFETs and JBS Rectifiers **(Baliga)**
2.8B 1.2kV SiC Shield PowerMOSFETs N
2.14 3.3kV SiC
GeneSiC
2.20 1.7
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ETs:
and
Research
Cost Effective,
V SiC DMOSFETs

GaN 15 -100 MHz DC-DC
ter Integrated Circuit ***Ricketts -***

3 Module Development & Manufacturing

3.1 High Volta
10 kV Pow
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Ma

alf-
USCI

oshiba
with Efficiency
nia Tech
Inverter **FSU**
grid Power Conditioning
S) connector to MicroGrid
arya)
neration 350 kW Three-Phase Medium-
igh-Efficiency EV Fast Charger **NCSU**
)
3 SiC Active Harmonic Filter for Variable Frequency Drives **UTRC + Hopkins + Husain**
4.24 65W High-Efficiency, High-Density Adapter with Improved Manufacturability **Navitas**
4.25 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules **GA Tech**
4.26 High Frequency GaN Power Converter **LMCO + VPT + VA Tech**
4.27 SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck **Bendix Corporation**
4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module **University of Tennessee**
4.29A *Development of Active Harmonic Filter using Interleaved SiC Inverter* ***Husain-OIF***
4.29B *Modeling and Packaging Design of a High Power Density 150A SiC Inverter* ***Hopkins-OIF***
4.30 *High Power Density DC-DC Converter for Auxiliary Power in Heavy-Duty Vehicles* ***Bhattacharya-OIF***
4.31 *A High-efficiency Low-cost 22kW Fast On-board Charger for Electric Vehicles Using Hybrid Switches Combining GaN HEMTs with Si MOSFETs* ***Hella-OIF***

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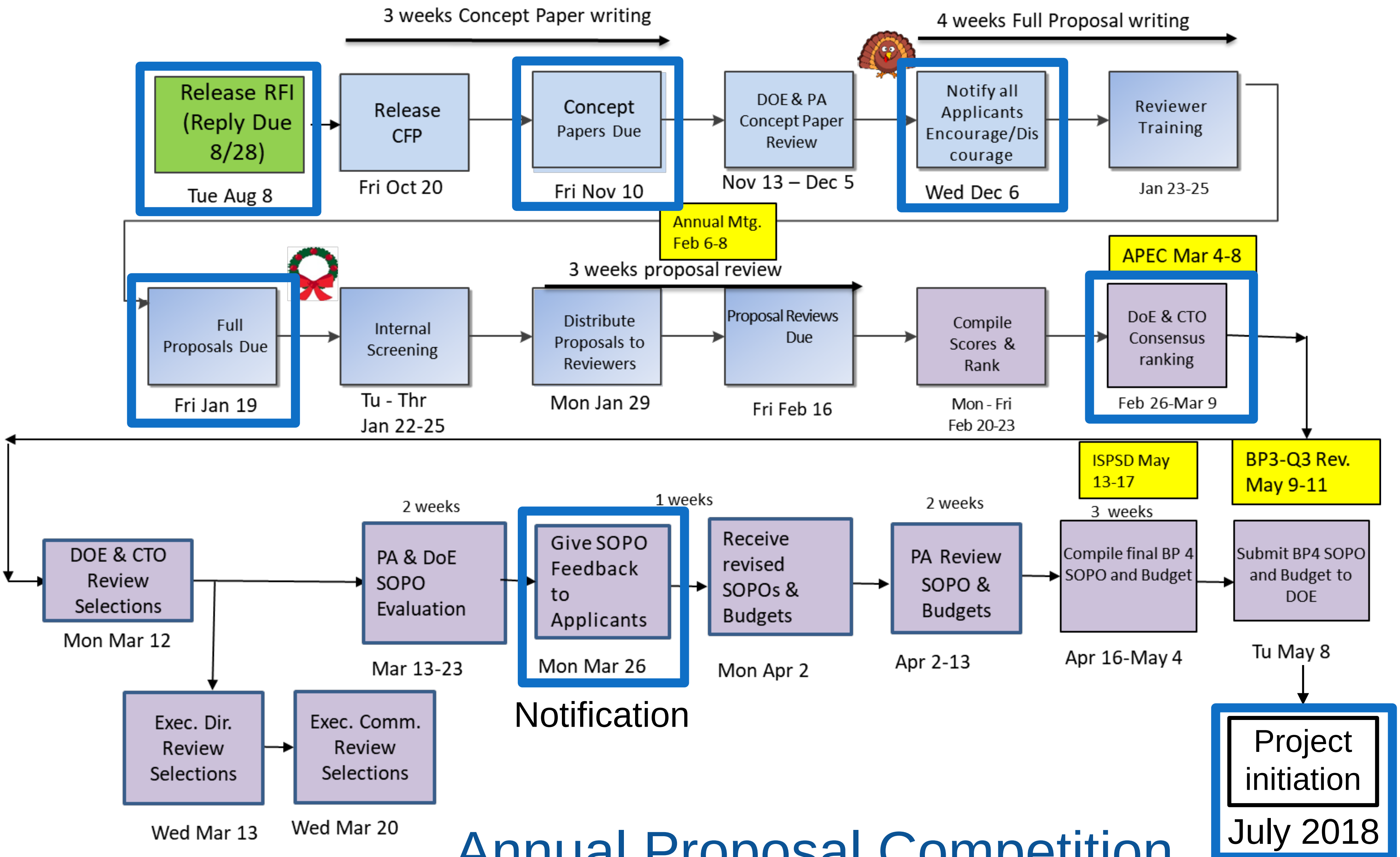
5.1 Education and Workforce Pipeline Development
5.4 Undergraduate Research Scholars
5.5 Pre-College Education **5.6** WBG Short Courses
5.13 Documentation of Design and Process of GaN Power HEMTs **RPI**

33 NEW WBG Projects Annually
Industry/University/National-Lab

V. Veliadis

Carefully Planned RFI/Concept-Paper/Proposal Cycle Selects High Impact WBG Projects



Annual Proposal Competition

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Open Innovation and Member Initiated Projects Strengthen PowerAmerica Technology Portfolio

Open Innovation Projects (Apply anytime)

- Target key time-sensitive gaps in PowerAmerica's portfolio that are too urgent to be postponed until the next annual competition
- Address technology barriers not currently tackled by other PA projects

Member Initiated Projects

- Develop valuable pre-competitive WBG related technologies that members can leverage based on their strengths and technology focus
- Reviewed, selected, and managed by members (with PA in a facilitating role)

46 **Members** from **All Areas** of the WBG Supply Chain Contribute to PowerAmerica Technology Innovation

SiC Foundry

Wolfspeed
X-FAB MIXED-SIGNAL FOUNDRY EXPERTS

SiC Devices Circuits & Modules

USCi United Silicon Carbide, inc.
Wolfspeed
GeneSiC SEMICONDUCTOR
Sonrisa Research, Inc. Creating Progress Through Revolutionary Innovation
ON Semiconductor
AgileSwitch
MONOLITH SEMICONDUCTOR INC.
Microsemi Power Matters.
GlobalPower TechnologiesGroup

GaN Devices & Circuits

Navitas SEMICONDUCTOR
Infineon
HELLA

WBG Systems

GM
TOSHIBA
Raytheon
ATOM POWER
LOCKHEED MARTIN
VPT Power Your Critical Mission Today
JOHN DEERE
ABB
Bendix
United Technologies Research Center
JENOPTIK

Academic

Texas Tech
UC DAVIS UNIVERSITY OF CALIFORNIA
UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA
AUBURN UNIVERSITY
VirginiaTech
Kettering University
Georgia Tech Center for Distributed Energy
M DEARBORN
ASU ARIZONA STATE UNIVERSITY
THE FLORIDA STATE UNIVERSITY
NC STATE UNIVERSITY
Rensselaer
THE OHIO STATE UNIVERSITY
The University of Akron
THE UNIVERSITY OF TENNESSEE KNOXVILLE
SUNY POLYTECHNIC INSTITUTE

Gov. Labs

Naval Research Laboratory Washington, DC
Argonne NATIONAL LABORATORY
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Consortia

PEIC POWER ELECTRONICS INDUSTRY COLLABORATIVE
iNEMI Advancing manufacturing technology

V. Veliadis

PowerAmerica Foundry Projects Enable Low-Cost Large Volume SiC Device Manufacturing in the U.S.

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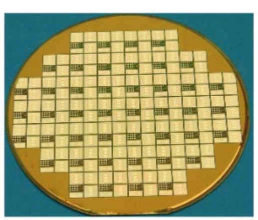

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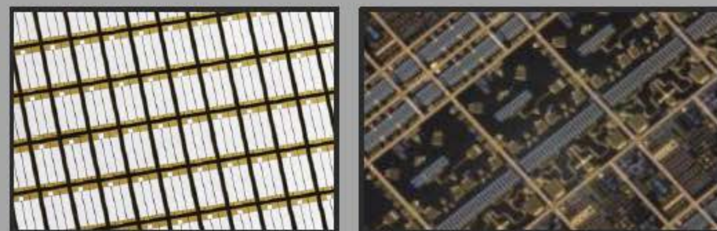
V. Veliadis

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

Wolfspeed

Starting SiC Wafer (100mm or 150mm) → Grow Epitaxial Layer (SiC or GaN) → Fabricate Devices in Wafer Fab



SiC MOSFETs   GaN-on-SiC MMICs

No stacked margins lower cost

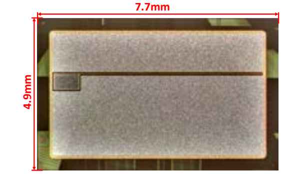
Electrical Test & Saw into Chips → Final Assembly (Pkg. or Module)

Wolfspeed

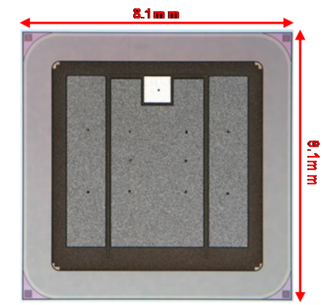
- $171M revenue (FY2016)
- 2240 patents worldwide
- 323,000 sq. ft. of fabrication and office facilities
- Class 10, 100, and 1000 Clean Rooms

Cree-Wolfspeed Manufactures 6.5kV SiC MOSFETs on 150 mm Wafers

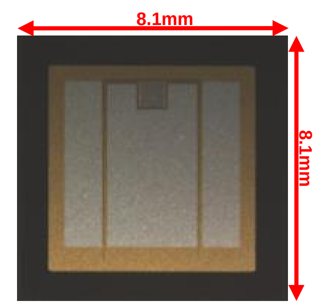
- **2016 – Fabrication & JEDEC Qualification of New Design 3.3kV/45mOhm and 10kV/300mOhm SiC MOSFETs on 100 mm 4HN-SiC Wafers (Extend to BP3)**
  - High Temp Gate Bias (HTGB) - Completed
  - Thermal Shock (TS) - Completed
  - Body Diode Operating Lifetime (BDOL) - Completed
  - Electrostatic Discharge (ESD) - Completed
  - High Humidity High Temp Reverse Bias (H3TRB) - Completed
  - Time Dependent Dielectric Breakdown (TDDB) - Completed
- **2017 – Fabrication & JEDEC Qualification of New Design 6.5kV/100mOhm SiC MOSFETs on 150 mm 4HN-SiC Wafers**
  - Fabrication Lots #1, #2, #3, & #4 – 85 % Complete
  - High Temperature Reverse Bias (HTRB) – Awaiting Devices
  - High Temp Gate Bias (HTGB) – Awaiting Devices
  - Time Dependent Dielectric Breakdown (TDDB) – Awaiting Devices



New Design 3.3kV/45mΩ SiC MOSFET



New Design 10kV/300mΩ SiC MOSFET



New Design 6.5kV/100mΩ SiC MOSFET

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

X-FAB/PowerAmerica Manufacturing Concept

SiC Open Foundry at the Economy Scale of Silicon

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

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

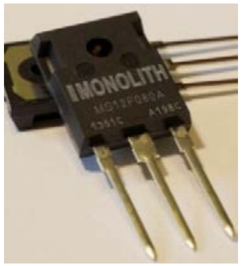
X-FAB/**PA** 9 SiC Users: ABB, GeneSiC, Microchip, Monolith, USCi, Global Power, Sonrisa, SUNY, and NCSU

PowerAmerica Wafer Procurement Planning is Critical in Timely Execution of Device Fabrication Projects

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

Monolith Semiconductor Qualifies 1700V, 10-20-50A SiC Schottky Diode Products at US XFAB High Volume Si CMOS Foundry

Project Title: Enable Commercialization of 1700V SiC Schottky Diodes Manufactured at X-FAB Texas
Objectives: Develop and commercialize 1700V Schottky Diodes
Major Milestones: Developed 1700V, 10A, 15A and 50A SiC Schottky Diodes
Deliverables: Engineering samples to partners



MONOLITH SEMICONDUCTOR INC.

SOPO Task No.:BP3-2.4
TPOC/PI: Kiran Chatty
Email: kchatty@monolithsemi.com
Phone: 802-238-4163

WBG Technology Impact

1. Developed and launched 1200V SiC Schottky diode products manufactured in high volume CMOS fab
2. Key markets: Solar inverters, motor drives, power supplies, automotive.
3. Timeframe for commercialization of 1700V Schottky diodes: 2019
4. 1700V Schottky diodes will enable an improvement in efficiency and cost savings in solar and traction applications

More WBG Impact and Additional impacts

1. Positive impact on local economy via growth and job creation

2. Contributed to creation of semiconductor manufacturing jobs in US

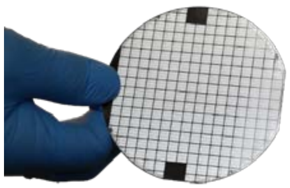
3. Support energy efficiency improvements through use of SiC MOSFETs and Diodes in power electronic systems

3. MRL level: At project start: MRL 5; expected at project completion: MRL 7

Microsemi Selects US XFAB for its Volume SiC Production and Qualifies 1.7 kV and 3.3 kV SiC MOSFETs

Microsemi

- **Objectives**: (a) High volume scale-up Microchip's industry leading 1.7 kV SiC for industrial markets and (b) Develop and optimize 3.3 kV devices
- **Achievements:** Production ready 1.7 kV/50A & 10A SBDs, 3.3 kV SBDs, and 1.7 kV/45 mOhm FETs successfully fabricated, electrical performance better than specs outlined in prelim datasheet and is currently industry leading
- **Impact:**
  - Addresses demand for 1.7 kV and 3.3 kV WBG devices for traction, T&D, Defense and Medical applications
  - One of few US based WBG vendors supplying devices in these voltage nodes, especially critical for Defense applications
  - Production at 6" CMOS fab based in TX, direct impact on increasing US manufacturing capabilities and jobs in hi-tech sector
  - Federal funding assisted Microsemi in accelerating introduction of these voltage nodes in our roadmaps sooner than originally planned



PowerAmerica Foundry and Device Manufacturing Accomplishments

- 150 mm wafer XFAB SiC Open Foundry at the Economy Scale of Silicon for US low cost manufacturing
  - Completed SiC equipment installation and qualification
  - 13 customers with 25 projects (9 PowerAmerica members)
  - 4 customers with 5 products are on track to pass reliability and qualification
  - US microelectronics manufacturing competes favorably with Asia
  - Microsemi selects high volume production at XFAB instead of overseas
  - 150 mm wafer Si US foundry repurposed for low cost SiC production creating/retaining jobs at a time when similar US Silicon foundries close
  - Projects secure US manufacturing leadership in medium voltage market
- CREE-Wolfspeed transitions to 150 mm wafers with PowerAmerica support
  - 6.5 kV MOSFET transition from 100-mm to 150-mm wafers reduces device cost by over 50%
  - Qualification of 6.5 kV MOSFETs maintains US manufacturing leadership and innovation in the medium voltage market
- University foundry projects drive fabrication innovation and train students
  - Develop processes for next generation device manufacturing
  - Educate students and workforce in the manufacturing of wide bandgap devices

Module and Reliability Projects Bridge the Gap Between Device Readiness and Commercial Adoption

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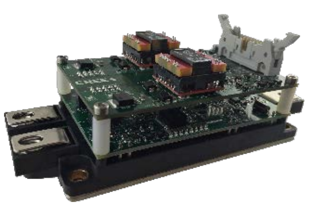

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CREE-Wolfspeed Manufactures and Commercializes Next Generation 6.5 kV & 10 kV Power Modules

Wolfspeed

Objectives:
Improve throughput of 6.5 kV & 10 kV modules, develop commercial tools needed to properly field modules
Significant Equipment Acquisition:
Private $: multiple in-line MFG items (e.g., vacuum potting dispenser)
Deliverables: Released products across current ranges, datasheets, qual report, app notes, & ref designs, circuit simulator models, reporting

*Industry Standard **6.5 kV Modules**, **10 kV Modules,** & HV Gate Drives/PS*

Advanced SiC Module Qualification Testing

WBG Achievements

1. BOM reductions achieved on both modules through strengthening of global supply chain.
2. New domed AlSiC baseplate design for 10 kV power module vs. alternative.
3. ROHS-compliant, lead-free solder substitute identified vs. standard solder for large-area attaches.
4. Optimized module power substrate designs based on application: thermally constrained and mechanically constrained.
5. Optimized $R_{G,int}$ for multiple paralleled 10 kV MOSFETs; 6.5 kV MOSFETs in progress
6. Ultrasonic welding vs. soldering of power and GSK signal leads for improved reliability

More WBG Achievements

7. XHV-9 power module, a miniatured version of the XHV-6, has been developed to address customer multilevel topologies.
8. DIN EN 45545-compliant plastic identified, procured, and tested for housing and lid.
9. Pre-qualification testing (e.g., HALT, HTRB, IOL, PC) with the <u>latest available</u> SiC chip set continues.
10. Continued job creation through MFG and Qualification scaling.
11. Publications on WBG module/system design for industry education; reference designs & bussing hardware for industry-wide understanding of SiC technology / integration / transition.
12. New Student Intern Program recently initiated to prime the WBG workforce pool.

V. Veliadis

Texas-Tech "Honest Broker" Reliability Analysis of Wide Bandgap Commercial Devices Builds Confidence in Their Systems Insertion

Objectives: Conduct long-term reliability testing, accelerated lifetime testing, and failure analysis on WBG devices.

Major Milestones: Testing protocol, electrical characterization and reliability evaluation of devices, failure analysis (SEM-FIB), reliability reports.

SOPO Task No.: BP3-3.7

TPOC/PI: Dr. Stephen Bayne
Email: stephen.bayne@ttu.edu
Phone: 806.834.0526

WBG Technology Impact

1. This work helps to improve the confidence in the long-term reliability of WBG devices, allowing them to be used in more technologies/applications.
2. Reliability data and failure analysis can be used to improve WBG power devices, leading to more robust and cost-effective WBG solutions.
3. WBG power devices are ideal candidates for high-power applications and will be integral to the future of many technologies including renewable energy applications, grid modernization, efficient high-power DC-DC converters and motor drives, etc.

Project Achievements

1. Developed testing protocol
2. Developed testbeds for accelerated and long-term reliability testing, as well as stress testing
3. Electrically characterized and tested SiC MOSFETs from 3 different manufacturers and SiC JBS diodes from 3 different manufacturers
4. Performed failure analysis on devices (including FIB-SEM)
5. Provided reliability reports

PowerAmerica Applications Projects Boost Manufacturing by Showcasing Compelling WBG System Advantages

Funding Period 3: July 2017 – June 2018

1 Management and Operations

1.1 Operations and Finance
1.2 Technology Roadmap
1.3 Sustainability
1.4 Device/Module Bank
1.6 Project Portfolio Management
1.7 Membership, Industry Relations and Communications

2 Foundry and Device Development

2.1 SiC Power Device Commercial Foundry Development **X-Fab Texas**
2.3 Development of a Manufacturable Gen3, 6.5 kV/100 mOhm MOSFET **Cree/Wolfspeed**
2.4 Commercialization of 1700V SiC Schottky Diodes **Monolith**
2.8A Lower Cost Foundry Process for 1.2 kV SiC Planar Gate Power MOSFETs and JBS Rectifiers **NCSU (Baliga)**
2.8B 1.2kV SiC Shielded Trench Gate PowerMOSFETs **NCSU (Baliga)**
2.14 3.3kV SiC MOSFET Development **GeneSiC**
2.20 1.7kV/3.3kV SiC MOSFET Scale-up **Microsemi**
2.21A Development of 3.3kV/6.5kV/10kV SiC MOSFETs, JBS Diodes, and JBS Diode Integrated MOSFETs **SUNY**
2.21B Development of 600V SiC JBS Diodes and MOSFETs **SUNY**
2.23 Advanced SiC Trench MOSFETs: A Path to Record-Low Ron,sp and Record-Low ($/A) **Sonrisa Research**
2.24 Manufacturable, Cost Effective, Low RON-SP 3.3 kV SiC DMOSFETs **Global Power**
2.25** 50 W GaN 15 -100 MHz DC-DC Converter Integrated Circuit **Ricketts - OIF

3 Module Development & Manufacturing

3.1 High Voltage 6.5kV & 10 kV Power Module Commercialization and Manufacturing **Cree Fayetteville**
3.6 Developing a BPD-Free Room Temperature Al Implant and Activation Anneal Process for P-Wells in SiC MOSFETs **NRL**
3.7 Reliability Analysis of Wide Band Gap Power Devices **Texas Tech**
3.8** 100A, 6.5KV Half-Bridge Module **USCI

4 Commercialization Applications

4.1 Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles **John Deere Electronic Solutions**
4.3 SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration **Toshiba**
4.7 100 kW Commercial PV Inverter with Efficiency > 99 % Operating in iTCM **Virginia Tech**
4.10 100 kW Commercial PV Inverter **FSU**
4.11 Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid **NCSU (Bhattacharya)**
4.13 Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger **NCSU (Lukic)**
4.23 SiC Active Harmonic Filter for Variable Frequency Drives **UTRC + Hopkins + Husain**
4.24 65W High-Efficiency, High-Density Adapter with Improved Manufacturability **Navitas**
4.25 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules **GA Tech**
4.26 High Frequency GaN Power Converter **LMCO + VPT + VA Tech**
4.27 SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck **Bendix Corporation**
4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module **University of Tennessee**
4.29A** Development of Active Harmonic Filter using Interleaved SiC Inverter **Husain-OIF
4.29B** Modeling and Packaging Design of a High Power Density 150A SiC Inverter **Hopkins-OIF
4.30** High Power Density DC-DC Converter for Auxiliary Power in Heavy-Duty Vehicles **Bhattacharya-OIF
4.31** A High-efficiency Low-cost 22kW Fast On-board Charger for Electric Vehicles Using Hybrid Switches Combining GaN HEMTs with Si MOSFETs **Hella-OIF

5 Education and Workforce Development

5.1 Education and Workforce Pipeline Development
5.4 Undergraduate Research Scholars
5.5 Pre-College Education **5.6** WBG Short Courses
5.13 Documentation of Design and Process of GaN Power HEMTs **RPI**

V. Veliadis

PowerAmerica Device/Module Bank Eliminates the Long Lead Times of Pre-production WBG Engineering Samples

Device/Module Bank Benefit:

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

Device/Module Bank Fit to PA Mission:

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

Funding Period July 2017 – June 2018 Engineering Devices Available at Onset of Program

Project	Organization/Team	Devices
Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles	John Deere Electronic Solutions (JDES)	No action, During BP3 we plan to work with WolfSpeed to develop Six-Pack SiC power module for John Deere Gen-2 SiC inverter. WolfSpeed team has stated that they have Gen-3 SiC die to pack in the Six-Pack SiC power modules.
SiC Active Harmonic Filter for Variable Frequency Drives (P.400.0481)	United Technologies Research Center	No action, For this project, UTRC will use COTS SiC modules manufactured by CREE-Wolfspeed.
65W High-Efficiency, High-Density Adapter with Improved Manufacturability	Navitas Semiconductor	No action, using their GaN FETs with inegrated gate drives
5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules	Georgia Tech Research Corporation	**25 3.3 kV 15 A SiC MOSFET die which are available now in device bank.**
5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules	Georgia Tech Research Corporation	**30 3.3 kV 15 A SiC diode die**
SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration	Toshiba International Corporation	No action, We use commercial available devices, such as Wolfspeed C2M0040120D and CAS120M12BM2.
High Frequency GaN Power Converter	Lockheed Martin Missiles & Fire Control	No action, EPC Enhancement GaN FET, COTS no lead time
SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck	Bendix, University of Akron	No action, CREE COTS 1200 V 90 A MOSFETs that are readily available: https://www.digikey.com/product-detail/en/cree-wolfspeed/C2M0025120D/C2M0025120D-ND/4807892 modules to be used for testing are: (CAS325M12HM2 (10 weeks lead
100 kW Commercial PV Inverter with Efficiency > 99 % Operating in Interleaved Triangular Conduction Mode (iTCM)	Virginia Polytechnic Institute and State University	No action, 900V and 1700V COTS no need to procure in advance, available from CREE
Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module	University of Tennessee	**60 10 kV MOSFET die**
Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid	NCSU	**Navy, 60 10kV/15A SiC JBS Diode die**
Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid	NCSU	**Navy, 120 10 kV MOSFET die**
Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid	NCSU	**30 10 kV MOSFET die**
100 kW Commercial PV Inverter	Florida State University	No action, CREE COTS 1200 V 90 A MOSFETs that are readily available: https://www.digikey.com/product-detail/en/cree-wolfspeed/C2M0025120D/C2M0025120D-ND/4807892,10 T-type 1200 V SiC MOSFET modules from Wolfspeed wtih a 1 week
Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger	North Carolina State University	**56 10 kV MOSFET die**

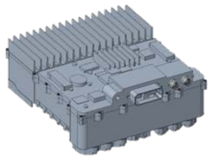
PowerAmerica Device Bank is Critical in Timely Execution of Power Application Projects that require WBG Engineering Samples

PowerAmerica SiC Power Electronics Projects Have Significant US Manufacturing Potential

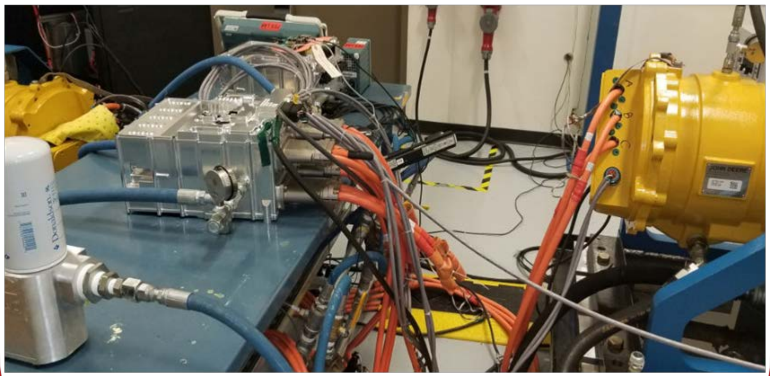
- **Vehicle and motor drive, Low Voltage SiC**
  - Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles *John Deere Electronic Systems*
  - SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck *Bendix Corporation*
  - High Power Density DC-DC Converter for Auxiliary Power in Heavy-Duty Vehicles *NCSU*
- **Power conversion and conditioning, Low Voltage SiC**
  - SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration Toshiba
  - SiC Active Harmonic Filter for Variable Frequency Drives UTRC
  - 100 kW Commercial PV Inverter with Efficiency > 99 % Operating in iTCM Virginia Tech
  - 100 kW Commercial PV Inverter FSU
  - Development of Active Harmonic Filter using Interleaved SiC Inverter *NCSU*
- **High Voltage SiC**
  - Asynchronous Microgrid Power Conditioning System connector NCSU
  - Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger NCSU
  - 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules GA Tech
  - 4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module University of Tennessee

John Deere Design, Fabrication, and Vehicular Testing of Engine Fluid Cooled SiC Traction Inverter for Heavy-Duty Vehicles

Gen-1 SiC Inverter
18 kW/Liter, 105°C Coolant



Gen-2 SiC Inverter
43 kW/Liter, 115°C Coolant



Back-to-Back Motor Dynamometer Driven by High Temperature 200 kW 1050 VDC Gen-1 SiC Inverter

JOHN DEERE

Project Objectives:

- 200 kW 1050 V DC bus SiC dual manufacturing and commercialization
    - WBG technology development and SiC inverter commercialization in heavy-duty vehicles

Achievements:

- Proposed power density of SiC inverter: > 20 kW/Liter
    - **Power density achieved: 43 kW/Liter**
- SiC inverter efficiency: 97%
    - **> 98% efficiency achieved over coolant temperature**
- Develop engine coolant (maximum 115°C WEG coolant) SiC inverter
    - **Gen-2 SiC inverter designed for 115°C WEG coolant**

Project impact:

- Accelerating commercialization of the SiC inverter in heavy-duty off-highway and on-highway vehicles
- Power-dense, engine-coolant, and high-efficiency SiC inverter simplifies vehicle architecture and system level integration

PowerAmerica Support Accelerated Effort by 5 Years

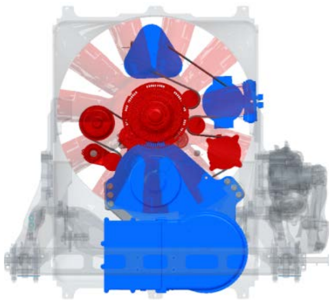
V. Veliadis

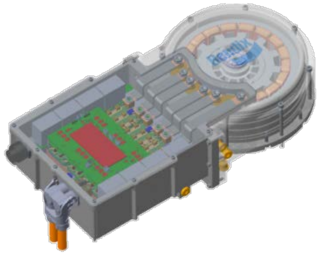
Bendix and Univ. of Akron Develop SiC Based Power Electronic Motor Drive for Class-8 Mild-HEV

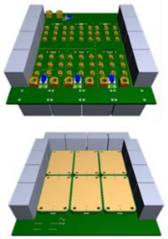
Objectives: To develop an integrated inverter and electric machine (EM) system for accessory drive and energy recovery in a Class-8 truck based on wide band gap power devices.

Major Milestones: 1- Detailed inverter hardware design to meet the size and power requirement
2- Drive and control implementation for rated power level
3- Design gearbox, damper & thermal management system
4- Dyno testing of motor and inverter

Deliverables: 1- Prototypes of the 70 kW SiC inverter, SRM motor, gearbox, clutched damper and thermal management system







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Phone: 330-972-7629

WBG Technology Impact

1. Enabling high frequency and high torque density electric machines for vehicle applications through WBG devices.
2. **Market segments impacted**: Heavy Duty Vehicles, Motor Drives
3. **Timeframe for commercialization:**

   Year 1: Prototype Development and component testing

   Year 2: Vehicle installation and fuel economy testing

   Year 3: Road Tests and Beta Units
4. Improved power density, efficiency and fault tolerance with an integrated motor drive system

Additional impacts

Impact on the cost of WBG compared to Silicon
Approx. 192K (64K X 3) SiC modules will be acquired annually with commercialization of the proposed system

Potential for Job Creation & Economic impact
1- Class 6, 7 and 8 vehicles in inter and intra-city applications **2-** Class 8 vehicles in line-haul applications **3-** Aftermarket retrofit of vehicles. *Capturing 20% of the potential hybrid vehicle segment and 30% of the APU market results in a total market potential of over 64,000 vehicles per year.*

Workforce Development: Engineers, Graduate and Undergraduate students, working on the project will be trained to work with the WBG devices applied to motor drives

Technology Readiness: At project start: TRL4 Expected at project completion: TRL7

V. Veliadis

PowerAmerica SiC Power Electronics Projects Have Significant US Manufacturing Potential

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  - Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles *John Deere Electronic Systems*
  - SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck *Bendix Corporation*
  - High Power Density DC-DC Converter for Auxiliary Power in Heavy-Duty Vehicles *NCSU*
- **Power conversion and conditioning, Low Voltage SiC**
  - SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration Toshiba
  - SiC Active Harmonic Filter for Variable Frequency Drives UTRC
  - 100 kW Commercial PV Inverter with Efficiency > 99 % Operating in iTCM Virginia Tech
  - 100 kW Commercial PV Inverter FSU
  - Development of Active Harmonic Filter using Interleaved SiC Inverter *NCSU*
- **High Voltage SiC**
  - Asynchronous Microgrid Power Conditioning System connector NCSU
  - Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger NCSU
  - 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules GA Tech
  - 4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module University of Tennessee

Toshiba SiC based Hybrid PV Inverter with Li-ion Battery Integration to be Commercialized in 2-3 Years and Manufactured in the US

1. Objectives: Commercialize SiC based hybrid PV inverter with Li-ion Battery Integration.
2. Achievements: built and tested a SiC based hybrid PV inverter.

TPOC/PI: Peter Liu
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Phone: (713)-466-0277 x3554

TOSHIBA

WBG Technology Impact

1. Key CTQ: efficiency, weight and cost.
2. Market segments impacted. Application Spaces: PV Inverter
3. Timeframe for commercialization: Commercialize it in 2-3 years.
4. Higher efficiency, and compatible cost.
5. Toshiba International Corporation commit design and manufacture in US.
6. Large volume of SiC devices will reduce the cost of SiC devices.

Accomplishments

1.Commercialized isolated DC-DC converter using SiC device.

2. The SiC based isolated DC-DC technology will be served as a building block and used in multiple of our products.

3. High-Frequency transformer with high DC voltage and high power is a new requirement after the adoption of SiC devices. We are actively seeking and have built connection with several American vendors which are specialists in H-F transformer. The mass production of H-F transformer can help create U.S. manufacturing jobs.

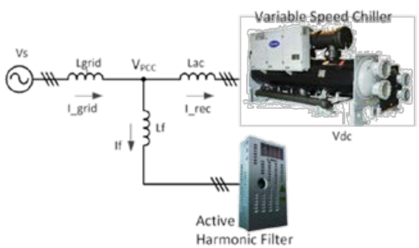
V. Veliadis

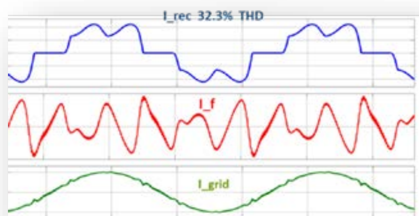
United Technologies SiC Active Harmonic Filter is Manufactured in the US and Has Variable Frequency Drive and Grid Tie Inverter Applications

SiC Active Harmonic Filter for Variable Frequency Drives

Objectives:

- Increase the adoption of WBG devices by developing and demonstrating on a commercial chiller a 150 Amps rated active harmonic filter that is 50% smaller and 20% projected lower cost (TRL 6)

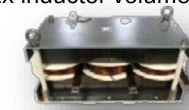




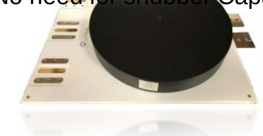
United Technologies Research Center

✓ **2x Higher power density - 1 kW/liter**

- 4x lower inductance value
- 2x inductor volume reduction



- Integrated bus-bar DC Link Capacitor
- 10 nH parasitic inductance
- No need for snubber Capacitors



WBG Technology Impact

This project will accelerate the adoption of wide band gap devices for commercial applications by enabling higher power density and lower cost active harmonic filters that can be used as power quality point of load solution. In addition to active harmonic filter applications, this technology could be used for high speed variable frequency drives and grid tie inverters. Providing a significant market opportunity for the application of WBG devices.

Accomplishments

- ✓ Power stage electrical and mechanical design
- ✓ Implementation of one AHF prototype rated at 150A, 480V and a power density target value of 1.2 kW/liter
- ✓ Signal level verification between the controller and power stage
- ✓ Demonstrate high power test at nominal voltage (480V) and current (150A) according to design specifications with a 40 kHz minimum switching frequency.

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V. Veliadis

PowerAmerica SiC Power Electronics Projects Have Significant US Manufacturing Potential

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  - Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles *John Deere Electronic Systems*
  - SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck *Bendix Corporation*
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- **Power conversion and conditioning, Low Voltage SiC**
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  - 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules GA Tech
  - 4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module University of Tennessee

University of Tennessee SiC Medium Voltage Power Conditioning System has US Manufacturing Partners

Project Objective:

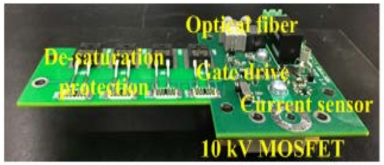
Develop a multi-functional high-efficiency high-density power conditioning system (PCS) module at medium voltage level (13.8 kV AC) using 10 kV SiC power semiconductors, satisfying related requirements (i.e. specific power, power density, efficiency, control bandwidth and grid requirements)

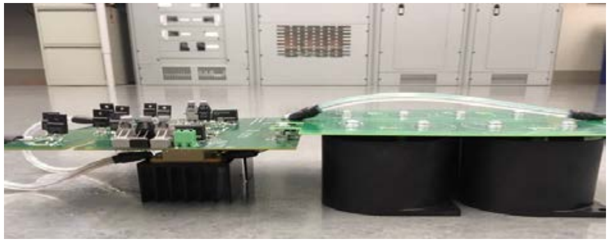
Achievements:

1. Specification and grid requirements determined for the PCS module with help of EPB and SCS
2. Latest generation 10 kV SiC MOSFET characterized, and test report completed
3. PCS phase-leg designed including topology and PWM strategy, passives, cooling, gate drive & isolated power supply
4. PCS controller designed including control and interface board, sensor board and control algorithm
5. 25 kV DC, 35 kW phase-leg prototype and test platform building in progress
6. PCS module controller demonstrated with grid-emulation Hardware Testbed

Impacts on WBG Manufacturing and Jobs

1. Address challenges for MV SiC converter design, and accelerate the commercialization for MV SiC converter
2. Increase the market of asynchronous microgrid with developed SiC PCS, which allows more integration of renewable energy sources
3. With U.S.-based HV SiC device, the project will have a positive impact on U.S. competitiveness and leadership in MV converter, renewable energy and microgrids
4. Collaboration with utility (EPB and Southern Company) and manufacturing partners (EPC Power) will help the product transition to market, creating a complete chain and more jobs from converter manufacturing to grid integration

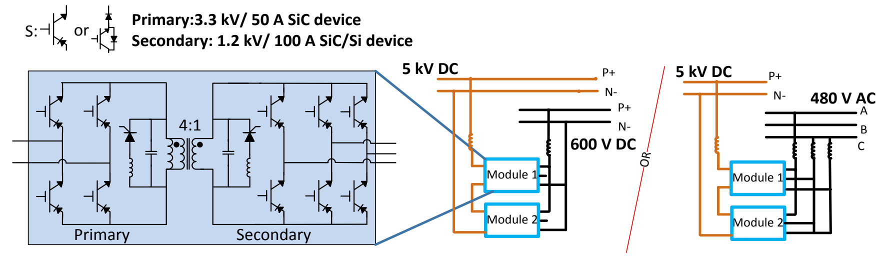




V. Veliadis

Georgia Tech SiC Based 5 kV DC to LV Microgrid Power Conditioning Module Has Industrial Plant and Naval Applications

Project Title: 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules
Objectives: Develop a MVDC to LVDC/LVAC SiC based module that can serve as the building block for a DC distribution network.
Major Milestones: 3.3 kV SiC based 2.5 kV DC to LV DC/AC module operating at 25 kW, 98 % eff, 25 kHz, and low dv/dt.
Deliverables: 50 kW 5 kV DC to 480 V AC/600 V DC single stage converter with 98% efficiency , 25 kHz switching freq and low dv/dt.



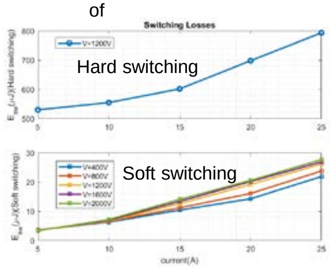
Topology of the proposed MVDC to LVAC / LVDC (600 V DC) single stage four quadrant converter module.
Proposed prototype: 50 kW 5 kV DC to 480 V AC/600 V DC, Fsw = 25 kHz

Accomplishments

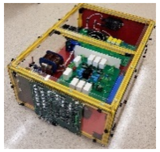
1. Demonstrated the advantage of using 3.3 kV SiC devices under soft switching - Low dv/dt and 95 % lower losses compared to hard switching
2. Novel control method to address voltage scaling issues verified through simulations
3. 25 kVA 5 kV to 600 V DC module designed and fabricated
4. Two under graduate and two graduate students are being trained

3.3 kV SiC custom module from CREE

Characterization results of



25 kVA 5 kV Dc to 600 V DC Building Block Based on 3.3 kV SiC current Switch



WBG Technology Impact

1. Compared to Si based approach the proposed solution results in reduced size and complexity through
   a) single conversion stage with high frequency isolation
   b) Low dv/dt and > 25 kHz switching freq -> small filters
2. Market segments impacted: Micro grids, distribution systems, industrial plants, naval ships and aircraft.
3. Timeframe for commercialization: 2-3 years
4. Si based approach limits Fsw to 1 kHz, resulting in large filters. Proposed SiC based approach allows Fsw > 25 kHz.

V. Veliadis

PowerAmerica GaN Power Electronics Projects Have Significant US System Integration Manufacturing Potential

High Frequency GaN

- 65W High-Efficiency, High-Density Adapter with Improved Manufacturability *Navitas*
- High Frequency GaN Power Converter *LMCO* + *VPT* + *VA Tech*
- A High-efficiency Low-cost 22kW Fast On-board Charger for Electric Vehicles Using Hybrid Switches Combining GaN HEMTs with Si MOSFETs *Hella*
- 50 W GaN 15 -100 MHz DC-DC Converter Integrated Circuit *NCSU*
- Documentation of Design and Process of GaN Power HEMTs *RPI*

Navitas GaN Adapter has High Efficiency and Addresses Large Consumer Electronics Market

Navitas

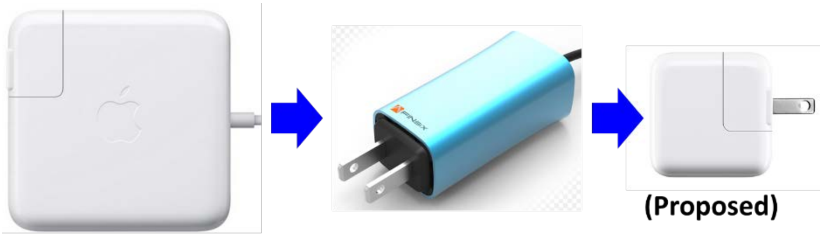
Project Title: 65W High-Efficiency High-Density Adapter with Improved Manufacturability

Objectives: Create a commercially compelling platform that sets an industry standard in energy efficiency, power density & is manufacturing proven & volume ready (TRL≥8) for US OEMs.

Major Milestones: Aug – 1st proto, Nov – eval & optimization, Feb– final design, May – mfg validation & release

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

65W High-Efficiency High-Density Adapter



7W/in^3 | 17W/in^3 | (Proposed) 25W/in^3

SOPO Task No.: **BP3-4.24**

TPOC/PI: Dan Kinzer
Email: dan.kinzer@navitassemi.com
Phone: 408-386-8041

WBG Technology Impact

1. Advances over silicon or conventional approaches: *Advancement & commercialization of Navitas GaN power ICs*
2. Markets impacts: *mobile chargers, travel adapters (consumer electronics)*
3. Timeframe for commercialization: *Q3 2018*
4. Quantitative benefits over state-of-the-art: *50% higher density, 30% improved energy efficiencies, improved manufacturability at a lower cost per watt*
5. Impact on the cost of WBG compared to Silicon: *A high-volume platform that demonstrates WBG superiority over silicon in performance and cost*
6. Potential for Job Creation Economic impact: *Significant job creation for US manufacturing partner(s) & US OEMs*

WBG Technology Impact (Cont.)

7. Workforce Development and Education: *All R&D and manufacturing is 100% based in the US with significant workforce development and education with Navitas, suppliers, partners and customers*

Accomplishments

1. Verified high-efficiency (>92.5%) high-density (>25W/in^3) system design
2. Improved manufacturability (higher automation, improved quality)
3. Technology adopted in world thinnest 45W PD adapter
4. Technology feedback to academia (Virginia Tech)

V. Veliadis

Lockheed Martin Industry/University High Frequency GaN Power Converter has Wide Commercial Applications

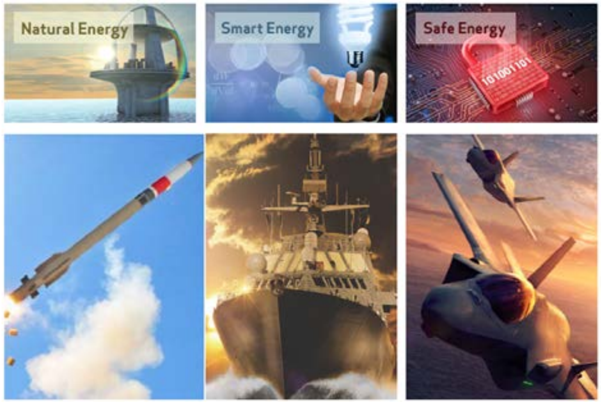
LOCKHEED MARTIN

Project Title: High Frequency GaN Power Converter

Objectives: Increase Power Performance for the 1/2 Brick Module, 550W/in^3 to 750W/in^3

Major Milestones:
- Commercial Module Requirement
- Power Converter Design Review
- Power Converter Modules and testing

Deliverables: Prototype Module, Performance Data, Commercialized GaN converter module



PI:	Tom Byrd	Dr. Fred Lee	Leonard Leslie
Email:	tom.e.byrd@lmco.com	fclee@vt.edu	lleslie@vptpower.com
Phone:	972-603-7009	540-231-7716	540-552-5000 x7533

WBG Technology Impact

1. Increased 1/2 Brick Module Power from 650W to 1kW; Power Density from 450W/in3 to 750W/in3
2. Telecommunications, Automotive, Aerospace, and Industrials
3. Timeframe for commercialization: 2 to 3 years
4. State of the Art: Silicon MOSFET based, ½ Brick modules producing 650W or less and 94% efficiency
5. Project results in GaN MOSFET based, ½ brick modules producing in excess of 1kW and 95% efficiency

Additional impacts

1. Impact on the cost of WBG compared to Silicon:
   Expect to have a higher performing module that replaces two Silicon based modules at a cost less than 2X the current modules.
2. Potential for Job Creation & Economic impact:
   Provides capabilities for module manufacturers, desing focus for domestic manufacturing
3. Workforce Development and Education:
   LM HF GaN Training Course training for Lockheed Martin Power Engineers
4. TRL level: At project start: TRL-3
   Expected at project completion: TRL-5

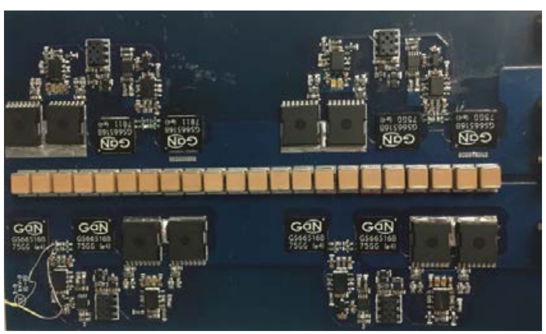
V. Veliadis

HELLA 22 kW Fast On-board EV Charger Uses Hybrid GaN/Si Power Switches for High-efficiency at Low-cost

Project Objective:
Bring a 650V/60A GaN HEMTs based, 97%-efficiency, 22kW battery on board charger (OBC) to market with a cost effective implementation of GaN devices.

Achievements:
Initial test results have indicated that the proposed hybrid solution which uses Si in parallel with GaN is a promising way to exploit the high performance of GaN while keeping costs low with inexpensive Si parts.

Manufacturing:
- Success with this project provides a means to accelerate the adoption of GaN-based automotive products by OEM customers.
- This product will be made in HELLA's U.S manufacturing facility for a global customer base.



GaN/Si On-board charger

HELLA Corporate Center USA Plymouth, MI

HELLA Electronics Corp. Flora, Illinois

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Strategic **University** PowerAmerica Projects Provide Hands-on Training to the Next Generation of WBG Engineers

Funding Period 3: July 2017 – June 2018

1 Management and Operations

1.1 Operations and Finance
1.2 Technology Roadmap
1.3 Sustainability
1.4 Device/Module Bank
1.6 Project Portfolio Management
1.7 Membership, Industry Relations and Communications

2 Foundry and Device Development

2.1 SiC Power Device Commercial Foundry Development **X-Fab Texas**
2.3 Development of a Manufacturable Gen3, 6.5 kV/100 mOhm MOSFET **Cree/Wolfspeed**
2.4 Commercialization of 1700V SiC Schottky Diodes **Monolith**
2.8A Lower Cost Foundry Process for 1.2 kV SiC Planar Gate Power MOSFETs and JBS Rectifiers **NCSU (Baliga)**
2.8B 1.2kV SiC Shielded Trench Gate PowerMOSFETs **NCSU (Baliga)**
2.14 3.3kV SiC MOSFET Development **GeneSiC**
2.20 1.7kV/3.3kV SiC MOSFET Scale-up **Microsemi**
2.21A Development of 3.3kV/6.5kV/10kV SiC MOSFETs, JBS Diodes, and JBS Diode Integrated MOSFETs **SUNY**
2.21B Development of 600V SiC JBS Diodes and MOSFETs **SUNY**
2.23 Advanced SiC Trench MOSFETs: A Path to Record-Low Ron,sp and Record-Low ($/A) **Sonrisa Research**
2.24 Manufacturable, Cost Effective, Low RON-SP 3.3 kV SiC DMOSFETs **Global Power**
2.25** 50 W GaN 15 -100 MHz DC-DC Converter Integrated Circuit **Ricketts - OIF

3 Module Development & Manufacturing

3.1 High Voltage 6.5kV & 10 kV Power Module Commercialization and Manufacturing **Cree Fayetteville**
3.6 Developing a BPD-Free Room Temperature Al Implant and Activation Anneal Process for P-Wells in SiC MOSFETs **NRL**
3.7 Reliability Analysis of Wide Band Gap Power Devices **Texas Tech**
*3.8 100A, 6.5KV Half-Bridge Module **USCI***

4 Commercialization Applications

4.1 Design, Fabrication, and Vehicular Testing of SiC Inverter for Heavy-Duty Vehicles **John Deere Electronic Solutions**
4.3 SiC Device based Commercial Hybrid PV Inverter with Li-ion Battery Integration **Toshiba**
4.7 100 kW Commercial PV Inverter with Efficiency > 99 % Operating in iTCM **Virginia Tech**
4.10 100 kW Commercial PV Inverter **FSU**
4.11 Asynchronous Microgrid Power Conditioning System (Microgrid PCS) connector to MicroGrid **NCSU (Bhattacharya)**
4.13 Next Generation 350 kW Three-Phase Medium-Voltage High-Efficiency EV Fast Charger **NCSU (Lukic)**
4.23 SiC Active Harmonic Filter for Variable Frequency Drives **UTRC + Hopkins + Husain**
4.24 65W High-Efficiency, High-Density Adapter with Improved Manufacturability **Navitas**
4.25 5 kV DC to LV DC or 3 Phase AC Microgrid Power Conditioning Modules **GA Tech**
4.26 High Frequency GaN Power Converter **LMCO + VPT + VA Tech**
4.27 SiC Based Power Electronic Motor Driver for Class-8 Mild Hybrid Truck **Bendix Corporation**
4.28 Multi-functional High-efficiency High-density Medium Voltage SiC Based Asynchronous Microgrid Power Conditioning System Module **University of Tennessee**
4.29A** Development of Active Harmonic Filter using Interleaved SiC Inverter **Husain-OIF
4.29B** Modeling and Packaging Design of a High Power Density 150A SiC Inverter **Hopkins-OIF
4.30** High Power Density DC-DC Converter for Auxiliary Power in Heavy-Duty Vehicles **Bhattacharya-OIF
4.31** A High-efficiency Low-cost 22kW Fast On-board Charger for Electric Vehicles Using Hybrid Switches Combining GaN HEMTs with Si MOSFETs **Hella-OIF

19 University applied projects provide real world experience to the next generation of WBG Engineers: $6.5M, 31.5 undergrad, 42.5 grad, and 4 Post-doc full-time (FTE) trainees

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PowerAmerica Member Universities Educate the Next Generation of Wide Bandgap Power Engineers

481 Graduates in Power Electronics courses

244 Undergraduates in Power Electronics courses

83 graduates and 30 undergraduates involved in hands-on training in power electronics

94 WBG lectures have been integrated into power electronic programs

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

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PowerAmerica Wide Band Gap Short Course Trains Existing Workforce

SCHEDULE

Day 1 8- 8:30 a.m. Registration
8:30 a.m-5:30 p.m. Class and Laboratory

Day 2 8 a.m.-5 p.m. Class and Laboratory

Day 3 8 a.m.-12 p.m. Class and Laboratory

COURSE OUTLINE

Opening session: Executive Overview

Power GaN Transistor Design Fundamentals and Application

- Where is the state-of-the-art today
- Gate drive requirements and considerations
- Layout techniques for high frequency switching
- Paralleling GaN transistors
- Dead-time requirements
- Thermal management
- High speed measurement techniques
- Design Examples

Practical Implementation of SiC MOSFETs for Power Converter Design

- Si IGBT's and SiC MOSFET's similarities and differences overview
- Gate driver design and pcb layout
- EMI effects and control
- Thermal design and packaging
- Real world design example of an EV charger
- Long term reliability and design margin

Introduction to WBG Module Packaging and Impact on Circuit Design

- Electrical design challenges for WBG devices
- Packaging processes, materials and design requirements
- Advanced packaging technologies
- Full design case study, design creation and hands-on lab experience
- Common failure mechanisms and reliability testing
- System level considerations of WBG power modules

Application of WBG Power Electronics: Power Converters, Electric Vehicles and Motor Drives

MV Fast Charger System Specification and Design Requirements

- Converter topology selection
- Device selection and characterization
- System modeling and simulations
- Control system specification
- Prototype development and testing
- Schematics and PCB design, hardware assembly and testing
- Control code development and debugging
- System optimization to meet the design requirements
- Demo of MV SiC fast EV charger

WBG SiC Converter for Electric and Hybrid Vehicles

- EV Powertrain system modeling and simulation
- WBG EV traction inverter
- Power stage, gate driver, and controller
- WBG Circuit Design for high frequency, high temperature operation and EMI suppression
- Passive Component sizing and selection
- System benefits of WBG insertion

HV SiC Power Device Characterization and Converter Applications

- High voltage SiC device characterization
- Gate Drive isolation, short circuit protection and switching performance
- Power converter design considerations
- High frequency magnetics
- Solid state transformers and MV motor drives

WBG Power Devices and Foundry Tour

- SiC device design and fabrication fundamentals
- WBG devices roadmap, cost model, and projections
- WBG devices characterization: tools and techniques
- High Voltage device testing lab tour
- NCSU foundry tour

SOLD OUT

Industry Driven Short Course Content

2.5 day duration
Nov. 7-9, 2017

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PowerAmerica Wide Bandgap Conference Tutorials Educate Participants and Promote Mission and Sustainability

2017-2018 PowerAmerica WBG Tutorial pres…
conferences:

- ✓ "SiC Processing - An Exercise in Si F… Veliadis 225 attendees, *Internat… ICSCRM Sept. 2017*
- ✓ "SiC power device … … Power Converters" … *…Energy Conversion and Co…*
- ✓ "… …ng the transition from Silicon," *…posium on Power Semiconductor …*

410 Tutorial Attendees in 2017-2018

PowerAmerica SiC and GaN Technology Roadmaps Are Being Updated by Members for 2018

- GaN devices, SiC devices, and Power Electronics Applications working groups were formed and member leaders were selected:
  - Rakesh Lal (Transphorm): GaN devices
  - Harish Suryanarayana (ABB): SiC devices
  - Nitesh Satheesh (Agileswitch): Applications
- Experts in SiC and GaN Power Electronics have been identified for feedback

	SiC Working Group		
	Name	Affiliation	Email
Lead	**Harish Suryanarayana**	**ABB**	**harish.suryanarayana@us.abb.com**
Member	David Divins	Infineon	david.divins@infineon.com
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External Expert	Pawel Gradzki	DoE Contr.	pawel.gradzki@ee.doe.gov

	GaN Working Group		
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Member	Dan Sable	VPT	sable@vptpower.com
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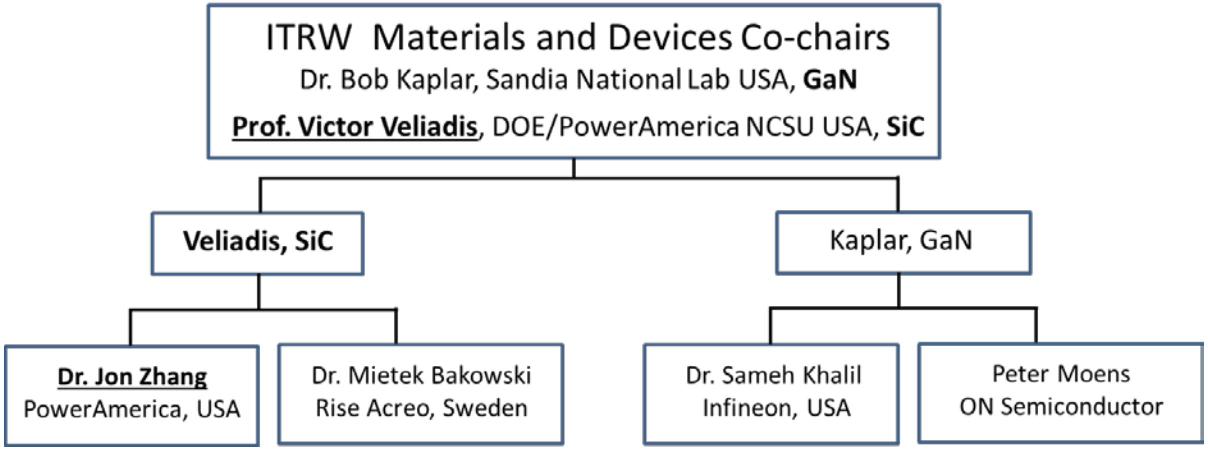
External Expert	Miguel Hinojosa	SiC testing	miguel.hinojosa4.civ@mail.mil
External Expert	Marian Kazimierc	AF	marian.kazimierczuk@wright.edu

PowerAmerica Roadmap guides solicitation and funding decisions

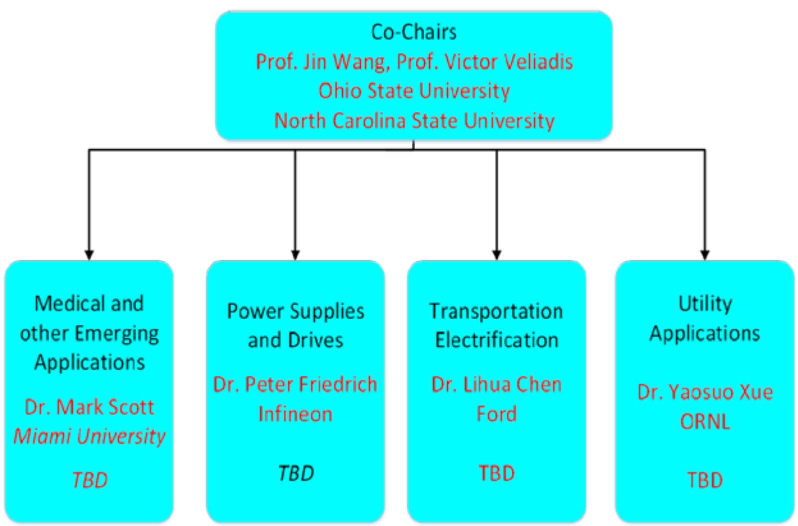
V. Veliadis

PowerAmerica Co-chairs 2 of the 4 IEEE "*International Technology Roadmap for Wide-Bandgap Power Semiconductors* (ITRW)" Working Groups

ITRW SiC/GaN Materials and Devices Working Group Organization Chart



ITRW SiC Applications Working Group Organization Chart



Other IEEE ITRW Groups:

- Modules & Packaging
- GaN Applications

Future Strategic DOE/PowerAmerica Funding Alloca
Will Commercialize WBG Power Electronics

New Funding Period: July 2018 – Ju

27 WBG Projects
Industry/University/National-Lab
July 2018 – June 2019

1 Management and Operations

1.1 Operations and Finance
1.2 Technology Roadmap
1.3 Sustainability
1.4 Device/Module Bank
1.6 Project Portfolio Management
1.7 Membership, Industry Relations and Communications

2 Foundry and Device Development

2.1 SiC Power Device Commercial Foundry Development **X-FAB**
2.3 Development of Manufacturable Gen3 3.3 kV/50 mOhm MOSFET Fabricated on 150 mm 4HN-SiC Wafers Along With HTRB, HT BDOL, TS, ESD, and TD Reliability Qualificati **Cree/Wolfspeed**
2.14 6.5 kV S Developm **Gene**
2.

3 Module Develo Ma

edium

or Utility-
iC MOSFET

age DC Power
Center **VA Tech/Li+**

rmerless Medium Voltage Central
ter **FSU/Li+GEAS**
Asynchronous Microgrid Power
onditioning System **NCSU/Bhattacharya**
4.23 High Speed Energy Efficient HVAC Drive **UTRC**
4.15 Isolated, Soft Switching SEPIC with Active Clamp for 480 V AC to 400 V DC Rectifier for Data Centers **ASU/Ayyanar**
4.28 Multi-functional High-efficiency High-density MV SiC Based Asynchronous Microgrid Power Conditioning System Module **UTK/Wang**
4.32 GaN-based High Efficiency Multi-Load Wireless Power Supply **UTK/Costinett**
4.33 Dual-Inductor Hybrid Converter for Direct 48V to sub-1V PoL DC-DC Module **U-CO/Maksimovic**
4.34 Introduction of WBG Devices for Solid State Circuit Breaking at MV **UNCC/Manjrekar**
4.36 600V GaN Bi-directional Switch **Infineon**

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elopment

Education and Workforce Pipeline Development
5.4 Undergraduate Research Scholars
5.5 Pre-College Education
5.6 WBG Short Courses
5.13 Documentation of Design and Process of GaN Power HEMTs **RPI/Chow**
5.14 WBG Power Converter Design Space Exploration **NCSU/Lukic**
5.16 Universal Platform of Education, Research, and Industrial Rapid Prototyping of High Power WBG Applications **NCSU/Husain**
5.17 Graduate WBG Semiconductor Power Device Lab **NCSU/Pavlidis**
5.18 Power electronics teaching lab incorporating WBG switches and circuits **UNCC/Parkideh**

NEW
shown i

PowerAmerica is Transitioning to a "Member Governed" WBG Power Technology Manufacturing Institute

Executive Committee: consists of 10 experienced industrial, academic, and government leaders, in an advisory role

Member Advisory Committee (MAC): Consists of all members, has an elected chair and vice-chair, meets quarterly. PA uses MAC input to:

- Develop initiatives to address member needs
- Create WBG Tutorials to train the workforce
- Integrate member ideas into PA programs
- Enhance PA value proposition for members
- Formulate post-DoE funding sustainability
- Review and provide revisions, if necessary, to PA by-laws including:
    - Intellectual Property rights
    - annual dues and benefits for each membership level
- Define Executive Committee composition

PowerAmerica Provides Value Beyond DOE Funding and Will Continue to Accelerate WBG Technology Manufacturing

- **Networking**
  - Summer/Winter member meetings
  - Summary presentation of all PA projects at meetings
  - Long networking breaks at meetings
- **Access to Universities and recruitment**
  - Student presentations, internships
  - Job opportunities posted on website
  - Collaborative research projects
- **Education and Workforce Development**
  - WBG short course offering with industry driven content
  - Tutorials presented at major WBG conferences
- **Timely access to PowerAmerica device bank engineering samples**
- **WBG ecosystem benefits** such as roadmaps, industry perspectives, technical consulting, member initiated projects, and promotion of SiC and GaN power technology

ASU Arizona State University
Auburn University
Kettering University
NC State University
Rensselaer
UC Davis University of California
Virginia Tech Invent the Future
The University of Tennessee Knoxville
SUNY Polytechnic Institute
Georgia Tech Center for Distributed Energy
The Florida State University
M Dearborn
The Ohio State University
The University of Akron 1870
UCSB University of California Santa Barbara
Texas Tech University
UNC Charlotte EPIC

Questions?

PowerAmerica

Thanks for your attention!