National Network for Manufacturing Innovation

- Flexible Electronics
- Digital Manufacturing and Design Innovation
- Lightweight and Modern Metals Manufacturing Innovation
- National Additive Manufacturing Innovation
- Photonics
- Fiber Textile
- Smart Manufacturing
- Advanced Composites
- PowerAmerica: Next Generation Power Electronics Manufacturing

DOD
DOE
Future
## Technology Readiness Levels and Manufacturing Readiness Levels

| TRL 1: Basic principles observed and reported | MRL 1: Manufacturing feasibility assessed |
| TRL 2: Technology concept and/or application formulated | MRL 2: Manufacturing concepts defined |
| TRL 3: Analytical and experimental critical function and/or characteristic proof of concept | MRL 3: Manufacturing concepts developed |
| TRL 4: Component and/or breadboard validation in a laboratory environment | MRL 4: Capability to produce the technology in a laboratory environment |
| TRL 5: Component or breadboard validation in a relevant environment | MRL 5: Capability to produce prototype components in a production relevant environment |
| TRL 6: System/subsystem model or prototype demonstration in a relevant environment | MRL 6: Capability to produce prototype system or subsystem in a production relevant environment |
| TRL 7: System prototype demonstration in an operational environment | MRL 7: Capability to produce systems, subsystems or components in a production relevant environment |
| TRL 8: Actual system completed and qualified through test and demonstrated | MRL 8: Pilot line capability demonstrated; Ready to begin Low Rate Initial Production |
| TRL 9: Actual system proven through successful mission operations | MRL 9: Low rate production demonstrated; Capability in place to begin Full Rate Production |

*Source: NNMI prelim design report.*
Application Spaces: 1 Volt to 10,000 Volts
Year 2000 compared to 2014

http://www.powerelectronicsworld.net/article/1/19737542-ultra-high-voltage-devices-for-future-power-infrastructure.html
Replacing Si-based Power Devices with SiC Increases Power Density and Relaxes Cooling Requirements

- **Operate w/ Higher Efficiency**: translates to fuel savings + less waste-heat to manage
- **Operate at Higher Temperature**: smaller cooling system + “limp-home” margin
- **Operate at Higher Frequency**: reduce the size of passive circuit components

Courtesy of Dr. T. McNutt, Wolfspeed
Developing advanced manufacturing processes to enable cost-competitive, large-scale production of wide bandgap semiconductor-based power electronics, which allow electronic systems to be smaller, faster and more efficient than power electronics made from silicon.
• Fundamental Principles
  – Cost
    • Cost of devices is tied to Volume. Cost limits adoption.
  – Reliability
    • Industry has to believe WBG Power electronics are reliable.
  – System Value:
    • Size, Weight, Power, Higher Frequency and Efficiency.
  – Training:
    • Graduate Students in WBG
    • Short Courses for Engineers

PowerAmerica

Foundry approach is having an impact for SiC.

GaN foundry approach is less clear. Needs materials investment, but strong industry drivers exist.

Reliability needs to be a community effort. Standards!

Demonstration in applications is important, for proof of concept, but also to obtain confidence in technology.
WBG Ecosystem Spans Numerous Industries

Accelerating WBG adoption requires a clear understanding of industry interplay.

- Wafer Suppliers
- Device Design
- Wafer Fabs
- Reliability and Packaging
- Market Demand Feedback
- OEMs
X-FAB Leverages Si Infrastructure and SiC Tool Investment to Offer SiC Manufacturing Services

SiC JBS diodes, BJTs, and MOSFETs presently fabricated at XFAB

- Leverage Existing investment In Capital Equipment.
- Leverage an existing highly trained workforce
- Benefit from existing experience in offering qualified products
- Increase yield from implementation of quality control.

X-FAB SiC Users: ABB, GeneSiC, Monolith, NCSU, USCi
### SiC Specific Equipment Purchased/Installed in Collaboration with PowerAmerica

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Temp Anneal Furnace</td>
<td>Centrotherm 150-50</td>
</tr>
<tr>
<td>SiC Backgrind Tool</td>
<td>Disco DFG8830</td>
</tr>
<tr>
<td></td>
<td>Capable of thinning to 175um, Installed May 2015</td>
</tr>
<tr>
<td>Backside Metal Deposition Tool</td>
<td>AMAT Endura</td>
</tr>
<tr>
<td></td>
<td>3-chamber tool (Ti/Ni/Ag), Tool installed May 2015</td>
</tr>
<tr>
<td>Backside Laser Anneal Tool</td>
<td>IPG IX-6100</td>
</tr>
<tr>
<td></td>
<td>Backside ohmic contact, Installed Jan 2016</td>
</tr>
<tr>
<td>High Temp Implanter</td>
<td></td>
</tr>
</tbody>
</table>

- **3K – 5K 150mm SiC wafers/month installed capacity**
- **Fab capacity: ~ 30K wafers/month (room to expand)**
  - Currently running 15K to 18K wafers/month of Si
  - Able to increase SiC capacity as market grows
X-FAB / PowerAmerica Manufacturing Vision

- **Open** SiC Foundry fully integrated within a high volume 150mm Si fab
- **Efficiency** through Integrated Manufacturing
  - Converted Si tools to run both Si and SiC wafers. Maximize equipment utilization.
  - Operators run both Si and SiC. Maximize labor efficiency.
  - SiC and Si share manufacturing and quality systems.
  - SiC and Si share overhead. Maximize shared economies of scale.
- **Scalability** through Integrated Manufacturing
  - Additional tools can be converted as SiC demand grows.
  - Additional human resources can be trained for both Si and SiC production as demand grows for SiC.
- **Consolidated** Economies of Scale
  - Aggregated SiC production efficiencies.
  - Aggregated SiC epiwafer purchasing.
SiC Foundry at the Economy Scale of Silicon

Wafer fabrication dominated by fixed O/H costs
- (Management, Quality, EHS, IT)

Economies of scale the greatest factor in reducing cost
- Use the scale established in Si to accelerate SiC
X-FAB Customer Base Increases Through its Open SiC Reduced Manufacturing Cost Offering

43 Si tools converted to handle both Si and SiC wafers
PowerAmerica has Established Baseline Processes for 1200 V MOSFET and Diode SiC Fabrication at XFAB

1.2 kV MOSFET process by NCSU Dr. Jay Baliga and SUNY Dr. Woongje Sung

Unit cell schematic of PA MOSFET (not to scale)

<table>
<thead>
<tr>
<th>Mask</th>
<th>Process steps</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer</td>
<td>N-/N+ substrate</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Alignment Mark</td>
<td>SiC Etch</td>
</tr>
<tr>
<td>2</td>
<td>P-base implant</td>
<td>Oxide dep. Photo, Oxide etch</td>
</tr>
<tr>
<td>3,4,5</td>
<td>N+, P+, JTE implant module</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Gate Poly dep. Photo, Etch</td>
<td>Std process</td>
</tr>
<tr>
<td>7</td>
<td>Oxide dep., Photo, CT Etch</td>
<td>Std process</td>
</tr>
<tr>
<td>8</td>
<td>Ohmic, Schottky metal</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Top Metal, B/S Metal</td>
<td>Std process</td>
</tr>
<tr>
<td>10</td>
<td>Polyimide</td>
<td>Std process</td>
</tr>
</tbody>
</table>

10 Mask MOSFET process includes 4 implant steps
The PowerAmerica Baseline 1.2 kV SiC MOSFET has an Active area of 4.5 mm$^2$ and an $R_{ds,on}$ of 5.5 mΩ-cm$^2$.

The PowerAmerica process yielded 1.2 kV MOSFETs in its first run.

MOSFET Id-Vd, Active area 4.5 mm$^2$

Specific on resistance: **5.5 mΩ-cm$^2$** at 1 A, Vg=20V

BV 1400V, Id@1200V=1uA
The PowerAmerica Baseline 1.2 kV SiC MOSFET has a Threshold Voltage of 2.8 V

MOSFET Id-Vg measured @Vd=0.1V, 25°C

Threshold Voltage: 2.8 V @ Id = 1mA
Monolith Semiconductor Develops High yielding 1200 V Schottky process at X-FAB

Objective: Develop manufacturable, high yielding and low-cost 1200 V SiC Schottky diodes with best-in-class performance and reliability at X-FAB’s 150-mm SiC foundry.
ABB Fabricates 3.3 kV SiC Schottky Diodes and MOSFETs on 150-mm Wafers at X-FAB

Objective: Qualify 150-mm Si foundry for SiC processing

ABB Processes SiC diodes and MOSFETs on 150 mm SiC wafers for the first time:

- Process routers developed in collaboration with XFAB
- 3.3 kV rated SiC Schottky and MOSFET wafers fully processed with encouraging yields (testing underway)
- Pathways determined for cost reduction in future volume manufacturing

Next Steps: Test a statistically relevant number of dies to evaluate yield/performance
USCi Fabricates 1200 V Planar MOSFETs on 150-mm Wafers at X-FAB

Objective: Develop 40mOhm, 1200V planar MOSFET

- Breakdown values on target
- Vth lower than target
- On-state behavior looks good
- Basic TO247 Rel test data looks good – see table
- Basic Switching and UIS tests look good

<table>
<thead>
<tr>
<th>Test</th>
<th>stress condition</th>
<th>duration</th>
<th>sample size</th>
<th>status</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTGB</td>
<td>VGS=+20V, VDS=0, Ta=150C</td>
<td>1000hrs</td>
<td>77</td>
<td>Pass</td>
</tr>
<tr>
<td>HTGBR</td>
<td>VGS=-10V, VDS=0, Ta=150C</td>
<td>1000hrs</td>
<td>77</td>
<td>Pass</td>
</tr>
<tr>
<td>HTRB</td>
<td>VDS=960V, VGS=0, Ta=150C</td>
<td>1000hrs</td>
<td>77</td>
<td>Pass</td>
</tr>
</tbody>
</table>

Ron = 28mΩ at VGS = 20V and RT
Wolfspeed Foundry Fabricates 3.3 kV/40 mΩ SiC MOSFETs and 10 kV/15 A SiC JBS Diodes

Objective: Qualify 3.3 kV/40 mΩ MOSFETs and 10 kV/20 A SiC JBS Diodes

100% Passed 1000 hr HTRB at 175 °C & 2.64 kV (80% 3.3 kV)

100% Passed 1000 hr HTRB at 175 °C & 8 kV (80% 10 kV)
Objective: Develop 3.3 kV SiC Modules

Module Manufacturing Improvements
- Demonstrate Process Automation
- New Equipment Installed & Operational
- Improve Process Yield
- Substrate & Die Attach
- Automate Verification Testing
- Sequential Room Temperature and High Temperature End of Line Testing In-Place

Optimized Module Commercialization
- HT-4201: 1200V / 25 mΩ Full-Bridge SiC Power Module
- HT-3231: 1700V / 8 mΩ Half-Bridge SiC Power Module
  - Gate Drivers, Datasheets, & CAD Models Available

Medium Voltage SiC Packaging & Application Support
- 3.3 kV SiC Module Designed with Customizable Device Configuration
- Companion Form Factor Gate Driver + Power Supply
- Samples Being Fielded to Early Customers
- Datasheets & CAD Models Available
Mission Summary

John Deere Electronic Solutions is Developing WBG Power Electronics with PowerAmerica Support

Objective: Develop a SiC inverter for the JD 644K Hybrid Loader

SiC Inverter Deployed in the JD 644K Hybrid Loader
John Deere Hybrid Loader’s SiC Inverter has Performance Advantages over Conventional Si-IGBT Inverters

Advantages of SiC Inverter

● > 17 kW/L power density as compared to < 9kW/L IGBT inverter

● Up to 25% more work per gallon fuel as compared to a conventional JD 644K Loader

● Suitable for engine coolant operation

● > 95% efficiency as compared to < 95 % efficiency with IGBT inverter

● Systems benefits and advantages: Reduction in engine size as compared to a conventional JD 644K Loader
  ➢ Less fuel consumption during idling
  ➢ Elimination of frequent refueling as compared to a conventional 644 Loader
  ➢ Cost savings: Elimination of inverter coolant loop and inverter operation with engine cooling system
Objective: Build SiC MOSFET/diode based 50 kW commercial PV inverter prototypes. Achieve higher efficiency and lower weight.

Peak Efficiency: 98.39%
CEC Efficiency: 98.2%

SiC MOSFET and diode TO-247 mounted on power board

SiC MOSFET and diode TO-247 soldered onto metal-core PCB

DC/DC Prototype I

DC/DC Prototype II

DC/AC Prototype I

DC/AC Prototype II

Weight of 50 kW PV inverter: 142.77 lbs. / 64.90 kg
Objective: Develop a modular medium voltage Fast Charger using commercial 1200 V SiC MOSFETs/diodes.

- 50 kW, 1200 V MOSFETs and diodes
- 2,400 Vac to 400 Vdc
- $\eta \geq 95\%$, PF $\geq 0.98$, THD $\leq 2\%$
- 10x size reduction
- 4x weight reduction
- Simple install w/o step-down transformer

**MV Fast Charger**

$V = 81.5$ L $\quad m = 60$ kg
$\eta \geq 95\%$

**Commercial Fast Charger**

$V = 1200$ L $\quad m = 400$ kg
$\eta \sim 93.5\%$
NCSU SiC High Fundamental Frequency 3-phase Converter Utilizes 15 kV IGBTs and 10 kV MOSFETs

**Converter Schematic**

- 10 kV/10 A SiC JBS Diode
- 80 mH
- 6 kV
- 60 μF
- 15 kV/20 A SiC IGBT Co-pack module
- 10 kV/10 A SiC MOSFET Co-pack module
- Boost Converter
- Three-Phase, 2-Level VSI
- $f_s = 5 \text{ kHz}$
- $f_s = \geq 10 \text{ kHz}$

**Experimental Results**

**Converter waveforms**

- 5 kV DC bus, 400 Hz Fundamental frequency, 10 kHz switching frequency, 3.7 kW load

**Thermal image of the converter**

- 3 kV DC bus, 1000 Hz Fundamental frequency, 20 kHz switching frequency, 1.45 kW load
PA Provides Value to Members by Accelerating their WBG Concept to Prototype Cycle

PA facilitates members with:

- **Device design to member’s specifications and applications.**
  - PA fabrication processes that can be tailored to member’s devices.
  - Fabrication at X-fab and/or other WBG manufacturing centers.

- **Access to WBG ecosystem**
  - Market direction, industry perspectives, networking opportunities, problem solving, and gaining confidence in a new technology.

- **Develop Packaging Solutions,**
  - Module Assessment, Reliability, Modeling Multi-physics Simulation

- **Workforce training:**
  - Design, fab, test, reliability, packaging, circuit design, module, system to accelerate member’s product introduction to market.
  - Highly WBG trained personnel (graduate students/post-docs) to strengthen member’s workforce.

**PA Industry** members grow their business by accelerated WBG product introduction to market

**PA University** members benefit by collaborating with industry
A Strong Workforce and Education Program

Universities
- Pipeline to M.S and PhD
- WBG M.S. Concentration
- Web Portal Distance Education
- Train the Trainer Community College
- Short Courses

Government
- DoE/DOD National Lab Internships
- NIST Manufacturing Extension Partnerships
- NSF Advanced Technology Education

Industry
- Internships
- Scholarships
- Sponsor Capstone Projects
- Contribute to Short Courses, STEM outreach
- Jobs

Contribute to Short Courses, STEM outreach
Upcoming Announcements

• **PowerAmerica Roadmap**
  • In process of being reviewed, Public Version to be released soon.

• **PowerAmerica Open Process**
  • Initial draft on website, Vanilla 1200 V MOSFET and Diode Process
  • License includes no warranty

• **Device Bank For WBG devices**
  • Industry Member provide engineering samples to PowerAmerica
  • Initial emphasis is on 3.3 kV and 10 kV device die.
  • Not-sold, but provided via Materials Transfer Agreement at Fair Market Cost.

• **Annual Meeting: January 17-19**

• **Presence at more conferences APEX, ICSCRM, ETC.**
Special Thanks to:

Victor Veliadas, CTO PowerAmerica, NC State
Anant Agarwal, DOE
Pawel Gradzki, ARPA-E
Laura Marlino, Oak Ridge National Labs
Valri Lightner, Facilities, AMO
Rob Ivester, Deputy Director, AMO
Mark Johnson, Director Advanced Manufacturing Office
Strategy for Accelerated Large-scale Adoption of WBG Semiconductor Devices

**Strategy**

- **Highlight Performance Advantages of WBG Devices**
  Stress high voltage at low resistance, high temperature, and high frequency WBG device operational advantages over those of Si counterparts

- **Establish Reliability of WBG Devices**
  Leverage Si Reliability best practices in developing WBG reliability standards

- **Demonstrate System Insertion Advantages of WBG Devices**
  - Develop packaging technology that allows for full WBG performance potential
  - Establish WBG PE system smaller weight/volume and higher efficiency value proposition through low additional initial system cost and life of system energy savings

- **Reduce Cost of WBG Devices (TRL 4-7)**
  Leverage mature Si fabrication practices, and qualify WBG specific processes to enable multiple source high-yield volume production

- **Train Workforce in WBG devices/modules/systems**

**Benefits**

Job Creation, Accelerated Technology Innovation, Energy Savings, Smaller Environmental footprint