Accelerating Commercialization of Wide-Bandgap Power Electronics – The Power America Manufacturing Initiative

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Abstract

Silicon (Si) power devices have dominated power electronics because of their low-cost volume production, excellent starting material quality, ease of processing, and proven reliability. Although Si power devices continue to make significant progress, they are approaching their operational limits, primarily because of their relatively low bandgap and critical electric field, which result in high conduction and switching losses and in poor high-temperature performance. Silicon carbide (SiC) and gallium nitride (GaN) power devices are revolutionizing power electronics because of their favorable material properties, which allow for highly efficient power devices with a reduced form factor and reduced cooling requirements. In this article, I will outline the strategic efforts of the PowerAmerica Manufacturing Institute to enable U.S. leadership in WBG power electronics manufacturing, work force development, job creation, and energy savings.

INTRODUCTION

Several government-funding initiatives around the world promote the adoption of wide-bandgap (WBG) power electronics to exploit their energy saving and technological innovation promise. In the United States, the Advanced Manufacturing Office of the Department of Energy and North Carolina State University formed PowerAmerica, a National Network for Manufacturing Innovation Institute. PowerAmerica focuses on enabling large-scale production of WBG power electronics with the goal of revolutionizing energy efficiency across multiple application platforms. It started operations in 2015 with a five-year budget of US$140 million and a mission to address manufacturing gaps in WBG power technology to enable U.S. leadership in job creation, energy savings, and technological innovation.

In the United States, the development of advanced WBG crystal growth, wafer fabrication, and device processing technologies owe their beginnings to the support from a number of U.S. government programs. Beginning in the late 1980s, organizations such as the Air Force Research Laboratory, Army Research Laboratory, Office of Naval Research, Missile Defense Agency, and the Defense Advanced Research Projects Agency sponsored hundreds of millions of dollars and decades of work at universities, industry, and government laboratories. Initially, this work focused on proof-of-concept critical enabling technologies such as high-quality substrates, epitaxy, and unit process steps like ion-implantation, implant activation, gate oxidation, and so on, to assure a domestic source for current and future U.S. Department of Defense WBG system needs.

DISCUSSION

WBG devices have now advanced well past the proof-of-concept point with the introduction of the first commercial SiC Schottky diode in 2001. However, widespread commercialization of WBG power electronics has been slow, which is primarily attributed to two factors:

1) high cost: chiefly due to low manufacturing volumes and dedicated foundries that are not fully loaded, WBG devices are more expensive than their mass-produced Si counterparts
2) workforce lacking expertise in WBG technologies: the power electronics industry is traditionally slow to change and adapt to new technologies.

These two factors have limited use of WBG devices in real applications, and the benefits in terms of higher efficiency, reduced weight and volume, and lower overall systems cost have not been ubiquitously quantified. With the value proposition of WBG system integration not being shared in a widespread manner, industry executives have been reluctant to commit internal research and development resources, further hindering large-scale commercialization. In addition, many of the WBG fabrication, packaging, reliability, ruggedness, and system insertion issues that must be resolved for optimal WBG device operation in actual applications are only now being rigorously addressed.

I was named the Deputy Executive Director and Chief Technology Officer of PowerAmerica in 2016 after 21 years in the semiconductor industry, where my technical work included the design, fabrication, and testing of 1–12-kV SiC static induction transistors, JFETs, MOSFETs, thyristors,

junction barrier Schottky diodes, and PiN diodes, as well as GaN radio frequency switches for advanced radar systems on 150-mm GaN-on-Si wafers. In my PowerAmerica role, I manage a budget in excess of US$30 million per year that I strategically allocate to over 35 industrial, university, and national laboratory projects to enable U.S. leadership in WBG power electronics manufacturing, work force development, job creation, and energy savings. My approach for catalyzing the manufacturing of low-cost SiC and GaN power electronics is schematically depicted in Figure 1.

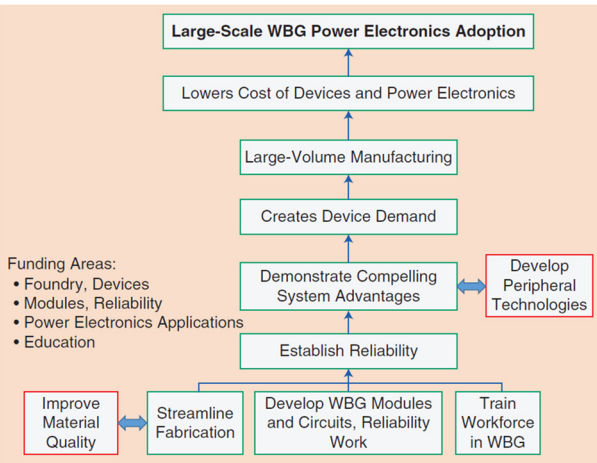

Fig. 1. PowerAmerica funds projects in areas that synergistically culminate in large scale WBG power electronics adoption (green boxes). The red boxes represent relevant technology areas that are presently outside the PowerAmerica mission.

PowerAmerica funds building-block projects in multiple areas of the WBG supply chain that synergistically culminate in large-scale WBG power electronics adoption (green boxes). The red boxes represent technology areas the advancement of which can boost WBG growth but that are presently outside the PowerAmerica mission.

WBG device fabrication in large-volume Si foundries exploits economies of scale and is key in lowering cost. Through repurposing 150- and 200-mm Si foundries in the United States, WBG power devices can be manufactured with the relatively small investments necessary to support unique WBG fabrication steps such as high-temperature implantation and annealing, contact formation, backside processing, and so on. This requires WBG-specific equipment at a cost of US$12–15 million shared between PowerAmerica and the foundry partner. Minimizing capital expenditures by exploiting the mature Si-processing capability lowers fabrication costs, provided the foundry is loaded close to capacity with standard Si processes running on the same line. In addition, aggregating the demand for WBG substrates and epilayers in a few volume foundries contributes to lower material costs. Lower process costs in a fully depreciated and Si+SiC capacity-loaded foundry coupled with decreased material costs lead to significant price reductions for WBG devices. This approach offers a new opportunity for outdated Si foundries that have not kept up with the channel length reductions of the last two decades to continue manufacturing legacy Si parts while ramping up SiC fabrication that requires relatively modest 0.5-µm design rules.

Another area of PowerAmerica's work is WBG device packaging and modules. This is an area in which the United States is highly deficient because semiconductor assembly and packaging was off-shored in the 1970s. Standard Si modules do not allow WBG devices to reach their full performance potential. Thus, WBG devices offer a unique opportunity for industry growth because they require modules with reduced parasitic inductance, reduced thermal impedance, higher-voltage isolation, and higher-temperature capability. PowerAmerica funds WBG modules with special layouts that minimize parasitics, utilize new base-plate materials for lower thermal impedance, allow for double-sided cooling, feature low inductance, and employ new potting compounds for higher-temperature operation.

In addition to better performance, reliability and ruggedness are prerequisites for WBG wide adoption. Improvements in material quality and fabrication contribute to device reliability. Ruggedness is one of the numerous device design tradeoffs. PowerAmerica has funded honest broker ruggedness/reliability testing efforts to build confidence in the use of WBG devices in power electronics applications.

PowerAmerica applications projects highlight the compelling advantages of WBG devices in power electronics systems that include smaller weight/volume, higher efficiency, and a reduced bill of materials. New circuit topologies, novel gate drivers for faster switching and protection, and printed circuit board layouts that minimize inductance and eliminate ringing are among the many demonstrated technological innovations. PowerAmerica projects that prove the WBG power electronics value proposition include laptop adapters, photovoltaic (PV) inverters, uninterruptible power systems, data centers, electric vehicle (EV) fast chargers, EV on-board chargers, solid-state circuit breakers, microgrid power conditioning systems, medium voltage variable speed drives, traction inverters, and auxiliary power converters.

Finally, a workforce well trained in WBG power electronics is key in creating the large device demand that will spur volume manufacturing with its cost-lowering benefits. PowerAmerica hands-on projects, carried out by universities and their industry collaborators, provide upper undergraduate and graduate students with real-world WBG power electronics experience. In the next few years, some of these students will enter the workforce and accelerate the insertion of WBG devices in industrial products. Other students will become faculty members at universities and train a new generation of students creating a WBG education snowball effect. Additional PowerAmerica educational activities include industry-driven WBG short courses that are taught by

world-renown experts from around the United States, internship opportunities with WBG-trained students, and WBG tutorials presented at major conferences. Specifically, tutorial presentations in by Veliadis at the 2017 International Conference on SiC and Related Materials (ICSCRM), the 2018 IEEE Energy Conversion and Congress & EXPO (ECCE), and the 2018 International Symposium on Power Semiconductor Devices and ICs (ISPSD) attracted 410 attendees and promoted the PowerAmerica mission and ecosystem.

The Foundry and Device, Module and Reliability, and Commercialization Applications PowerAmerica projects carried out in the 2017-2018 budget period are listed in Figure 2. As mentioned previously, execution of these projects, which cover multiple areas of the WBG supply chain, and the associated member interactions fostered in the PowerAmerica ecosystem synergistically culminate in large-scale WBG power electronics adoption.

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

Fig. 2. Strategic PowerAmerica 2017-2018 budget period projects synergistically accelerate commercialization of WBG power electronics.

Included in the list of Figure 2 are 19 University applied projects with a combined budget of US$6.5 million. Through these projects, 32 upper undergraduate, 43 graduate, and 4 post-doctoral *full time equivalents* were trained in 2017-2018.

PowerAmerica is a 48-member-driven institute, from all areas of the power GaN/SiC supply chain, accelerating the commercialization of WBG power electronics, Figure 3. PowerAmerica SiC device manufacturing members include the Wolfspeed dedicated vertically integrated foundry. The vertical model is cost efficient as it eliminates stacked margins. In addition, it facilitates technology optimization and improved failure analysis as potential issues can be traced from power module down to the starting device wafer material.

Fig. 3. The 48 PowerAmerica members span all areas of the power GaN/SiC supply chain and synergistically accelerate large-scale adoption of WBG power electronics.

To accommodate the numerous fabless SiC design companies, PowerAmerica collaborated with XFAB to create the first SiC open foundry at the economy scale of silicon. At X-FAB, 150-mm wafer SiC fabrication is fully integrated within a high volume automotive qualified Si foundry. As wafer processing is dominated by fixed overhead costs, the economy scale of Si fabrication enables low cost SiC manufacturing. PowerAmerica members fabricating at XFAB include ABB, GeneSiC, Microchip, Monolith, USCi, Global Power, Sonrisa, SUNY, and NCSU.

The PowerAmerica value proposition provides compelling incentives for membership. PowerAmerica assists its members with device design and cost-effective manufacturing in high volume foundries. To bolster confidence in the use of WBG devices and modules in power electronics applications, Power America continues to support "honest broker" third party reliability/ruggedness evaluation centers. PowerAmerica has established a device/module bank to increase the availability and timely accessibility of pre-production WBG engineering samples for power application development. Through the device bank, members procure long lead-time engineering samples in only a few days. Readily available WBG devices expedite development of member next generation products, and produce valuable user performance feedback to guide manufacturer device optimization.

PowerAmerica provides a wide array of WBG ecosystem benefits such as roadmaps, industry perspectives, promotion of SiC and GaN technology, and ample networking opportunities. PowerAmerica has the reach and depth to connect companies and people across the WBG supply chain. It provides its members with unparalleled opportunities to effortlessly make connections, create partnerships, advance technology innovation, grow their business, and build their brand.

PowerAmerica members have complimentary access to online members-only business and technical content (including market research and presentations), which provides powerful context and data to make sound technical and business decisions. By participating in regularly held member only meetings, individual companies deliver a collective amplified voice on issues that affect the WBG industry thereby influencing its direction and shaping its growth.

PowerAmerica executes "member initiated projects" that are selected by members and financed with membership funds. Working on projects of common interest, and sharing the generated IP, is a cost effective way to spur technology innovation and to overcome barriers that limit industry growth.

Finally, the PowerAmerica education and workforce member benefits include access to industry tailored short courses at reduced cost, specialized tutorials, opportunities for internships and talent recruitment, and interaction with experts across the WBG supply chain.

Over the past eight years, prices of commercially available SiC MOSFETs have dropped by approximately 80% because of an increase in manufacturing volume, technological innovation, and an increase in wafer area to the current 150 mm. Presently, prices of WBG devices are about three to four times higher than those of similarly rated Si components. As PowerAmerica continues to implement its lower-cost WBG manufacturing strategy and with the introduction of 200-mm wafers in the near future, WBG devices are expected to reach a 1.5-times cost parity with Si within five years. It should be noted that device cost is only one element of the system's bill of materials cost. For example, with the system-level simplifications that WBG devices introduce (reduced size and weight of passives, reduced system cooling requirements, and so on), the overall cost of a SiC-based PV system is now comparable to that of its Si-based system counterpart. In addition, this is before the efficiency savings over the life of the WBG system are considered.

CONCLUSIONS

Silicon carbide (SiC) and gallium nitride (GaN) power devices are revolutionizing power electronics because of their favorable material properties. Although these devices have now advanced well past the proof-of-concept point, widespread commercialization of WBG power electronics has been slow primarily due to their high cost and a workforce lacking expertise in these technologies. The U.S Department of Energy launched the PowerAmerica Manufacturing Institute to accelerate adoption of WBG power electronics. PowerAmerica funds building-block projects in device and foundry, reliability and modules, and commercial applications that synergistically culminate in large-scale WBG adoption. It facilitates WBG device fabrication in large-volume open silicon foundries to minimize capital expenditures and exploit economies of scale that lower cost. PowerAmerica supports honest broker ruggedness/reliability testing centers to build confidence in the use of WBG devices in power electronics applications. PowerAmerica has launched numerous education initiatives to train the workforce in WBG power electronics. This is key in creating the large device demand that will spur volume manufacturing with its cost-lowering benefits. Finally, PowerAmerica is a 46 member-driven Institute with a solid value proposition that provides compelling incentives for membership.

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ACRONYMS

JFET: Junction Gate Field Effect Transistor
MOSFET: Metal Oxide Semiconductor Field Effect Transistor