by Victor Veliadis

# Accelerating Commercialization of Wide-Bandgap Power Electronics

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. Si 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.

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 system needs. WBG devices have now advanced well past this 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 interest in WBG devices for 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,

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junction barrier Schottky, 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. 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$12–15 million shared between PowerAmerica and the foundry partner. Minimizing capital expenditures by exploiting the mature Si-processing capability lowers fabrication costs, provided the foundry is loaded close to capacity with standard Si processes running on the same line. In addition, aggregating the demand for WBG substrates and epilayers in a few volume foundries contributes to lower material costs. Lower process costs in a fully depreciated and Si+SiC capacity-loaded foundry coupled with decreased material costs lead to significant price reductions for WBG devices. This approach offers a new opportunity for outdated Si foundries that have not kept up with the channel length reductions of the last two decades to continue manufacturing legacy Si parts while ramping up SiC fabrication that requires relatively modest 0.5-$\mu$m design rules.

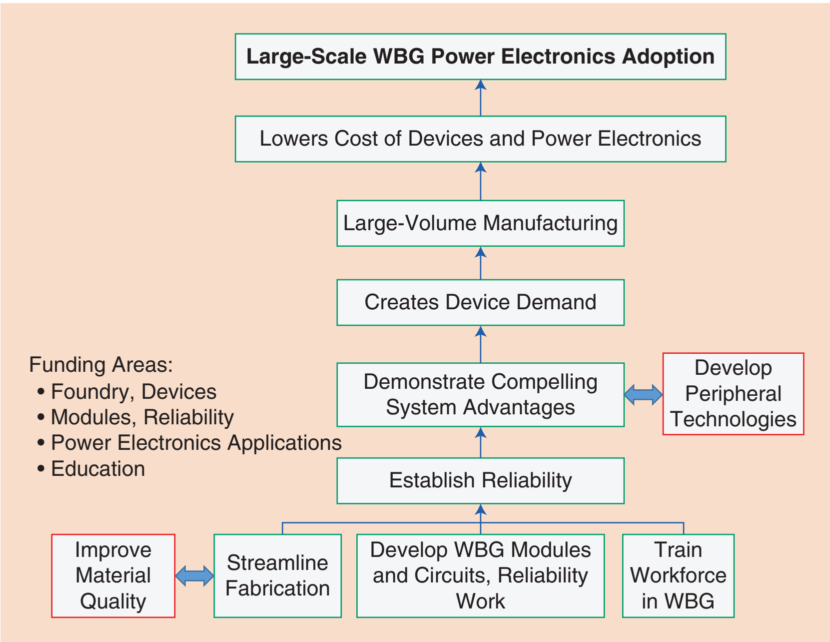


**FIG 1** PowerAmerica funds projects in areas that synergistically culminate in large-scale WBG power electronics adoption (green boxes). The red boxes represent relevant technology areas that are presently outside the PowerAmerica mission.

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.

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, WBG tutorials presented at major conferences, and internship opportunities with WBG-trained students.

Finally, PowerAmerica 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.

Over the past eight years, prices of commercially available SiC MOSFETs have dropped by approximately 80% as a result 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. Also, this is before the efficiency savings over the life of the WBG system are considered.

PowerAmerica is a 46-member-driven institute accelerating the commercialization of WBG power electronics. I am greatly indebted to my team and Department of Energy Technical Manager Al Hefner for valuable technical contributions and generous support.

## About the Author

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