PowerAmerica's Strategic Roadmap for Next Generation Wide Bandgap Power Electronics

Version 4.1

February 2019

PowerAmerica

Technology Roadmap—Public Version

This roadmap is a public version of the 4.1 version of the PowerAmerica Technology Roadmap of February 2019. As such, it includes the complete Table of Contents of the roadmap so that the public can view its contents in summary form. Also included in this public version are the introductory sections of the roadmap, including executive summary and the background/introduction and market forecast pertaining to silicon carbide and gallium nitride (also referred to as wide bandgap) power electronics.

Acknowledgements

This roadmap was developed under the direction of PowerAmerica Chief Technology Officer (CTO) Victor Veliadis, Program Manager Rogelio Sullivan, Director of Power Device Technology Jon Zhang, and Membership & Industry Relations Manager Jim LeMunyon. Nexight Group supported PowerAmerica's initial roadmapping processes and prepared the initial roadmap; Changwon Suh, Ross Brindle, Jack Holmes, Jackie Bowen, Kendra Chappell, and Lindsay Pack were the primary contributors. Roadmap development and subsequent updates were informed by a variety of stakeholders, including experts from the semiconductor and power electronics industries (especially from PowerAmerica member organizations), academia, national laboratories, and other research organizations. These stakeholders (individuals identified in Appendix A) made vital contributions through workshop participation and subsequent working group support, interviews, online surveys, and roadmap reviews.

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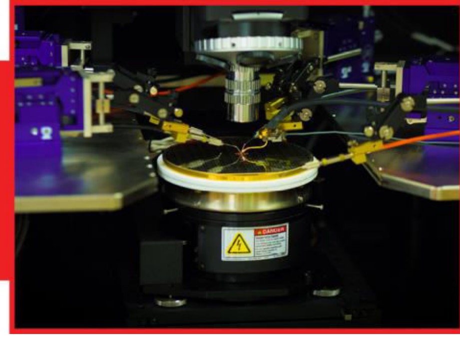
01 About this Roadmap



In December 2014, the PowerAmerica Institute was established through Manufacturing USA—a network of public-private partnerships committed to increasing U.S. manufacturing competitiveness. Led by North Carolina State University in Raleigh, NC, PowerAmerica is a consortium of nearly 50 companies, universities, and federal labs, which aims to accelerate the adoption of wide bandgap (WBG) semiconductor power electronics (PE). By improving technical capabilities, supporting domestic manufacturing, and strengthening the WBG semiconductor ecosystem, PowerAmerica expects to produce energy savings, new jobs, and a strengthened U.S. manufacturing sector.

PowerAmerica focuses specifically on advancing silicon carbide (SiC) and gallium nitride (GaN)—both WBG semiconductors—which offer improved performance across a range of applications. PowerAmerica's member organizations help drive progress and facilitate collaboration across the PE community, including between end users and experts from prominent universities and government agencies. The institute also receives support from the U.S. Department of Energy's Advanced Manufacturing Office (AMO) and the state of North Carolina, as well as investments from industry, academia, and other partners.

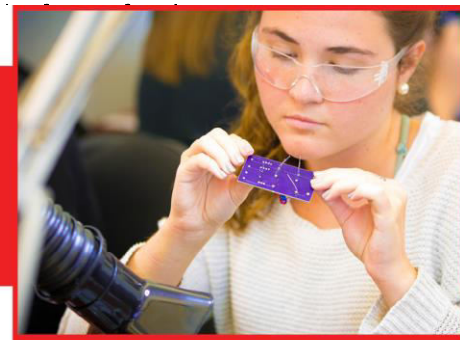
To ensure the Institute's investments and activities best meet the industry's current needs and anticipated challenges, PowerAmerica solicits input from industry experts, especially from PowerAmerica members. PowerAmerica's roadmapping process began in earnest in mid-2016 with the convening of in-person and virtual workshops with members and outside experts. Nexight Group, a consulting company supporting PowerAmerica's roadmapping efforts, also conducted phone interviews with key experts, distributed an online survey to gather additional input, and performed a literature review of relevant resources in this field. This resulted in Version 1.0 of the Roadmap. PowerAmerica members and outside experts also contributed to subsequent updates: Version 2.0 in February 2018, Version 3.0 (interim roadmap update) in July 2018, Version 4.0 in December 2018 and this Version 4.1.

Version 4.0 incorporated updated feedback from the August 2018 roadmapping workshop, where stakeholders discussed the current state of WBG semiconductor technology, ongoing challenges, and key activities to address those challenges. It also included a new market forecast for WBG power electronics, an analysis of SiC and GaN device cost based on market information, and information on PowerAmerica's Device Bank. Results from the mid-2018 survey of members regarding the challenges facing the adoption of WBG semiconductor technology were also incorporated into this version. Version 4.1 is an update that includes several clarifications suggested during a review of the Roadmap at the PowerAmerica Annual Meeting in February 2019. It also includes results from a survey taken at the Annual Meeting in which participants were asked to indicate the highest priority activities that would address industry's challenges.

This roadmap outlines key markets and application areas as well as the performance targets GaN and SiC technologies are expected to meet over time, technical barriers to achieving those targets, and activities needed to overcome those barriers. Roadmapping is an ongoing process that guides PowerAmerica's strategic decisions and provides a common vision of the future for the WBG community to work toward.

Information on contributors, important acronyms, survey results, and the PowerAmerica Device Bank is provided in the Appendices.

02 Executive Summary



This roadmap outlines key markets and application areas for SiC and GaN PE, performance targets for competitive SiC and GaN technologies, technical barriers to achieving those targets, and the PowerAmerica activities needed to overcome those barriers. PowerAmerica's role will be to facilitate coordination across industry, academia, and national labs to implement the priority activities identified in this roadmap and to make strategic investments in technology development, workforce training, and WBG manufacturing. The following high-level recommendations are a summary of the actions found in Section 5: PowerAmerica's 5-Year Roadmap Strategy.

Reducing Cost

- Lower the $/ampere of WBG devices and power modules.
- Support vertically integrated fabrication.
- Support and promote early adopter, high-volume WBG applications.
- Establish SiC and GaN open foundries to scale to high-volume manufacturing.

Improving Reliability and Quality

- Establish WBG PE reliability at system-level and investigate degradation/failure mechanisms of devices, modules, or systems.
- Develop open databases for reliability data.
- Develop capability to perform AECQ or JEDEC standard tests for WBG power devices.
- Set dedicated standards for WBG PE.

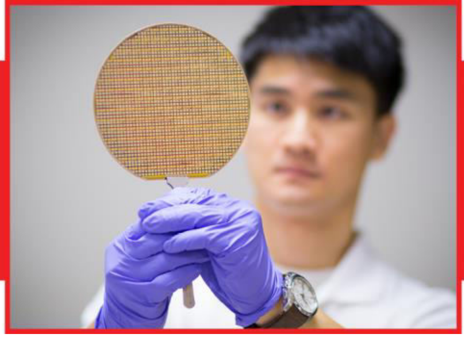
Enhancing Performance Capabilities

- Focus on near-term applications to demonstrate the system-level advantages of WBG power devices.
- Support pathways to commercialization for industry-led projects.
- Promote reference designs, advanced gate drives and modules, and work in advanced peripherals.

Strengthening the Power Electronics Ecosystem

- Continue to offer the Device Bank for quick access to SiC and GaN devices.
- Continue to provide communication mechanisms for different levels of stakeholders, from vendors to end users.
- Train a WBG PE workforce.
- Monitor basic core technologies, state-of-the-art complementary technologies, and long-term applications to identify promising opportunities.

03 The Need for Advanced Wide Bandgap Power Electronics



Background/Introduction

Our society has become increasingly dependent on complex devices, machines, and systems—from handheld electronic devices like smartphones and laptop computers to electric vehicles (EVs) and grid-scale renewable energy systems. None of these technologies would be possible without cross-functional semiconductor power electronics (PE) capable of converting power and controlling electrical energy (i.e., tuning voltage, current, and frequency) from the point of energy generation to distribution.

Semiconductor Materials and their Bandgap Energies (E_g)

WBG Semiconductors:

- *Silicon carbide (SiC): 3.3eV*
- *Gallium nitride (GaN): 3.4eV*
- *Zinc oxide (ZnO): 3.4eV*
- *Gallium oxide (β-Ga_2O_3): 4.8–4.9eV*
- *Diamond (C): 5.5eV*
- *Aluminum Nitride (AlN): 6.0eV*

Conventional Semiconductors:

- *Silicon (Si): 1.1eV*
- *Germanium (Ge): 0.7eV*
- *Gallium Arsenide (GaAs): 1.4eV*

WBG semiconductors hold great promise to significantly outperform and eventually replace traditional Si-based PE technology. While there are research and development (R&D) efforts in various WBG semiconductors—including diamond, aluminum nitride, and gallium oxide—that could be used in advanced PE, SiC and GaN have currently reached a level of maturity that allows use in PE applications. SiC and GaN have enabled the development of compact (i.e., high power density), cost-effective, energy-efficient, and robust power components that operate at higher temperature, voltage, and frequency conditions.

Both SiC- and GaN-based power devices have distinct benefits for specific applications: SiC is generally a stronger candidate for PE above 1.2kV, while GaN is highly competitive for PE below 1.2kV. The device voltage range between 650V and 1.2kV is a competitive space that can be supported by either SiC or GaN technologies. Compared to Si, SiC-based power devices can operate at higher temperatures with higher thermal conductivity, higher breakdown voltage at lower on-stage resistance, faster switching speed, lower conduction and switching on-state loss, and exceptional radiation hardness. Advantages of GaN-based power devices include higher electron mobility and lower losses at higher frequencies, which can enable smaller devices with increased power density.

While WBG technologies offer significant capabilities that can advance PE, industry must overcome numerous challenges including high material and manufacturing costs, reliability perceptions, packaging and performance requirements, and difficulty coordinating efforts across the entire WBG PE ecosystem. Recent progress against these challenges in automotive applications, PV inverters, and power supplies is encouraging; however, SiC and GaN have not taken off as rapidly in traction applications, industrial motor drives, and wind turbines. Further strides are needed to begin manufacturing these devices at high volumes and competitive costs across the full range of useful applications.

Market Forecast

Prices for SiC and GaN devices have been falling rapidly in the last few years, helping fuel recent market growth. SiC metal-oxide-semiconductor field-effect transistor (MOSFET) prices, for example, dropped 50% between 2012 and 2015 (according to IHS Markit). Though prices rose in 2017 due to wafer supply shortages, a growing number of wafer suppliers and improved wafer performance should allow prices to stabilize by 2019 and then continue falling for the foreseeable future. This increasing cost competitiveness has already helped SiC begin to dislodge Si in some applications (e.g., hybrid vehicles) and has enabled mass production of GaN-based end products (mainly in server and telecom rectifier power supplies). In addition, leading manufacturers now have trillions of hours of field device experience to assuage any reliability concerns that might dampen growth.

A recent study by IHS Markit[1] projects annual SiC revenues will reach $10 billion by 2027, with hybrid and electric vehicles making up the vast majority of sales. Annual GaN revenues are projected to top $1.7 billion over the same timeframe, with power supplies, hybrid and electric vehicles, and military and aerospace applications holding the largest shares. In comparison, revenues for SiC and GaN combined were only $210 million[2] in 2015. Across these applications, discrete power devices would account for most of the growth as they are expected to take off faster than power modules and integrated circuits.

A separate forecast from Cree Inc.[3] also predicts EVs will present a tremendous growth opportunity for WBG materials, particularly SiC. To date, automakers have announced plans to spend $150 billion in the EV market.[4] Cree estimates that even modest EV adoption—approximately 10% of total vehicles sales by 2027—could result in SiC revenues of $6 billion. The same forecast places the total SiC PE market at over $5 billion by 2022, largely driven by EV adoption but also industrial and telecom applications. For GaN, telecommunications stand out as an opportunity for strong growth. GaN devices support 10 times faster download speeds and better cellular coverage, which can enable the transition to 5G internet service.

The future is bright for WBG PE technologies. SiC and GaN have already proven their technical advantages over Si, and now decreasing prices are also driving adoption. SiC turned a corner in 2016 and GaN growth should shortly follow. For devices within certain voltage ranges, SiC and GaN will be viable options within the next 10 years and should continue to displace Si in the market.

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[1] Richard Eden, "Market for GaN and SiC power semiconductors to top $10 billion in 2027," https://technology.ihs.com/602187/market-for-gan-and-sic-power-semiconductors-to-top-10-billion-in-2027 (April 24, 2018)

[2] IHS Markit, "Market for GaN and SiC Power Semiconductors to Top $1 Billion in 2020," https://news.ihsmarkit.com/press-release/technology/market-gan-and-sic-power-semiconductors-top-1-billion-2020 (March 9, 2016)

[3] Cengiz Balkas, "Wolfspeed," https://www.sec.gov/Archives/edgar/data/895419/000089541918000019/analystdayfebruary262018.htm (February 26, 2018)

[4] Nic Lutsey et al., "Power Play: How Governments Are Spurring the Electric Vehicle Industry," https://www.theicct.org/sites/default/files/publications/EV_Government_WhitePaper_20180514.pdf (May 2018)