


# PowerAmerica Strategic Roadmap for Next Generation Wide Bandgap Power Electronics

Version 1.0

February 2018

## Table of Contents

## Acknowledgements

This roadmap was developed under the direction of PowerAmerica CTO Victor Veliadis and Rogelio Sullivan. Nexight Group supported PowerAmerica's overall roadmapping processes and prepared this roadmap; Changwon Suh, Sarah Lichtner, Ross Brindle, and Christiana Sherman are the primary contributors. Roadmap development was informed by a variety of stakeholders, including experts from the semiconductor and power electronic industry, academia, national laboratories, and other research organizations. These stakeholders (individuals identified in Appendix A) made vital contributions through workshop participation, working group support, interviews, online surveys, and roadmap reviews.

## About this Roadmap

Collaboration is a key driving force of Manufacturing USA—formerly known as the National Network for Manufacturing Innovation—which aims to establish a public-private partnership network focused on increasing U.S. manufacturing competitiveness. Manufacturing USA has grown quickly, creating synergy between its Institutes and the manufacturing community to pursue the common goal of accelerating development and deployment of advanced manufacturing technologies and processes.

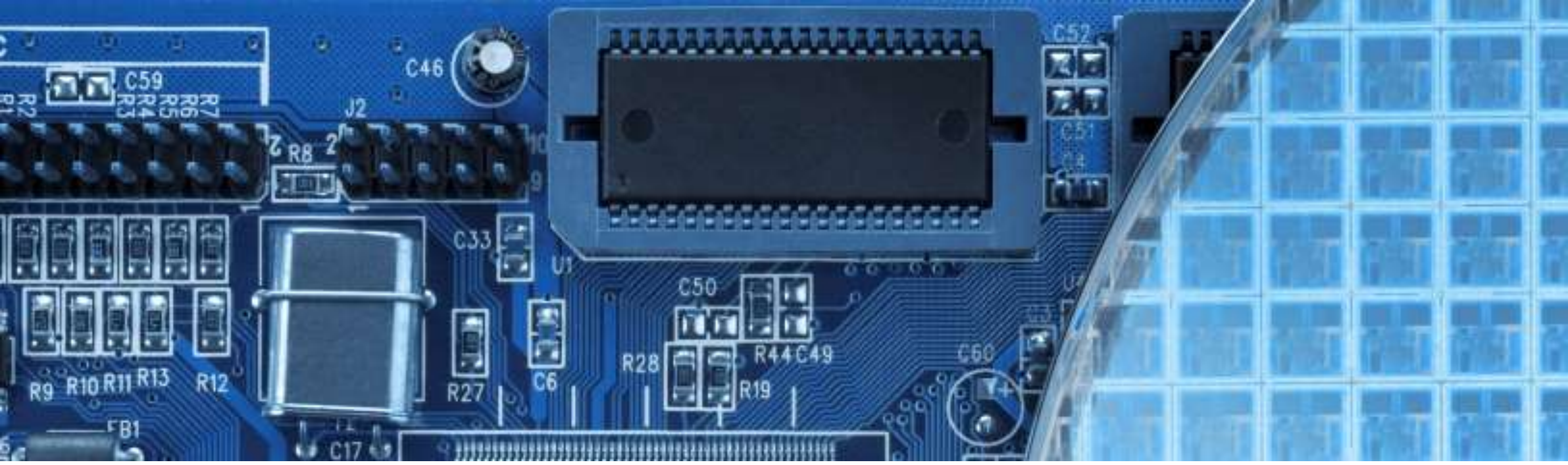
In December 2014, PowerAmerica was established as one of the Manufacturing USA institutes. Led by North Carolina State University, PowerAmerica aims to make wide bandgap (WBG) semiconductor technologies cost competitive with silicon (Si) based power electronics (PE), and to accelerate the adoption of silicon carbide (SiC) and gallium nitride (GaN) based components in markets and applications. PowerAmerica works to develop and implement well-planned but flexible strategies to accelerate this progress and facilitate collaboration across the PE community, including between end users and experts from prominent universities and government agencies.

To ensure the Institute's investments and activities best meet the industry's current needs and anticipated challenges, PowerAmerica has solicited input from semiconductor and PE industry experts to build a near- and long-term technology roadmap. PowerAmerica convened an in-person workshop on June 22, 2016, in Raleigh, North Carolina, and held a second workshop virtually with PowerAmerica working group members on July 27, 2016. 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 roadmap outlines key markets and application areas for SiC and GaN PE, 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. The roadmap activities will guide PowerAmerica's strategic decisions for demonstrating the benefits of SiC and GaN, improving WBG semiconductor device performance, and increasing commercial use of SiC and GaN PE.

## The Need for Advanced Wide Bandgap Power Electronics

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



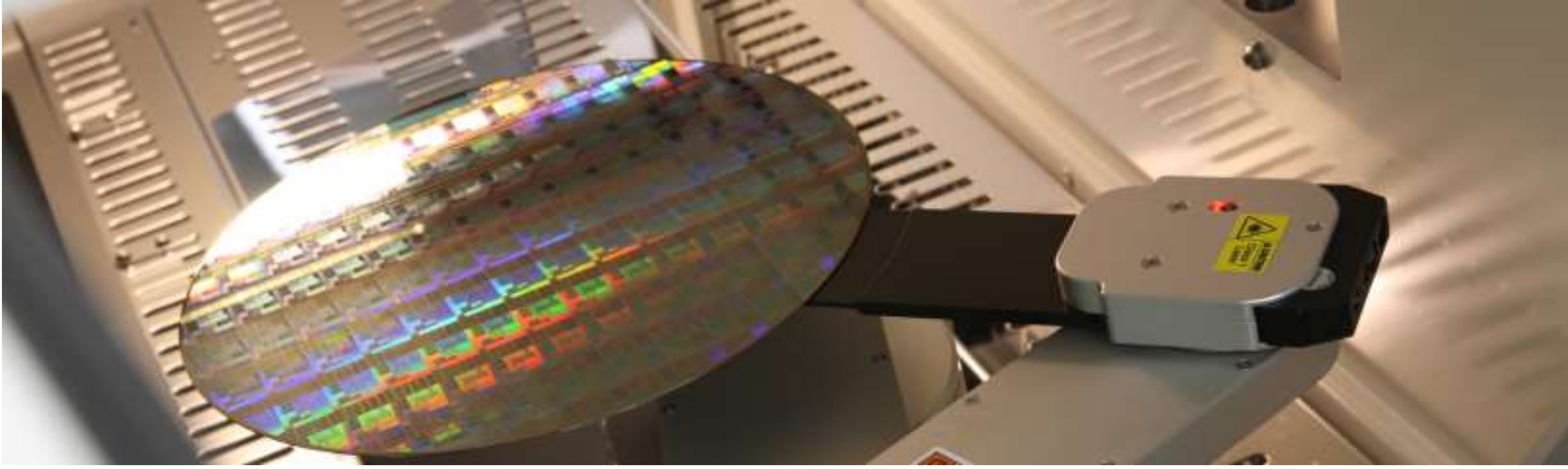
WBG semiconductors hold great promise to significantly outperform and eventually replace traditional Si (bandgap energy [$E_g$]: 1.1eV) based PE technology. While there are R&D efforts in various WBG semiconductors - including diamond, aluminum nitride, and gallium oxide - that could be used in advanced PE, SiC ($E_g$: 3.3eV) and GaN ($E_g$: 3.4eV) have currently reached a level of maturity that allows use in PE applications (see Table 1). 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.

Table 1. Semiconductor Materials and Bandgap Energies

| **Semiconductors** | | |
|---|---|---|
| **Materials** | Chemical Symbol | **$E_g$ (eV)** |
| Germanium | Ge | 0.7 |
| Silicon | Si | 1.1 |
| Gallium Arsenide | GaAs | 1.4 |
| **WBG Semiconductors** | | |
| **Materials** | Chemical Symbol | **$E_g$ (eV)** |
| Silicon Carbide | SiC | 3.3 |
| Gallium Nitride | GaN | 3.4 |
| Zinc Oxide | ZnO | 3.4 |
| Gallium Oxide | $\beta$-$Ga_2O_3$ | 4.8–4.9 |
| Diamond | C | 5.5 |
| Aluminum Nitride | AlN | 6.0 |

Both SiC- and GaN- based power devices have distinct benefits for specific applications: SiC is regarded as a stronger candidate for power electronic applications above 1.2kV, while GaN is ideal for high-frequency applications, and is regarded as highly competitive in applications below 1200V. In particular, device voltage rating 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. Compared with Si devices, GaN-based power devices enable applications with higher electron mobility and lower losses at higher frequencies. This combination can facilitate the development of smaller devices with increased power density.

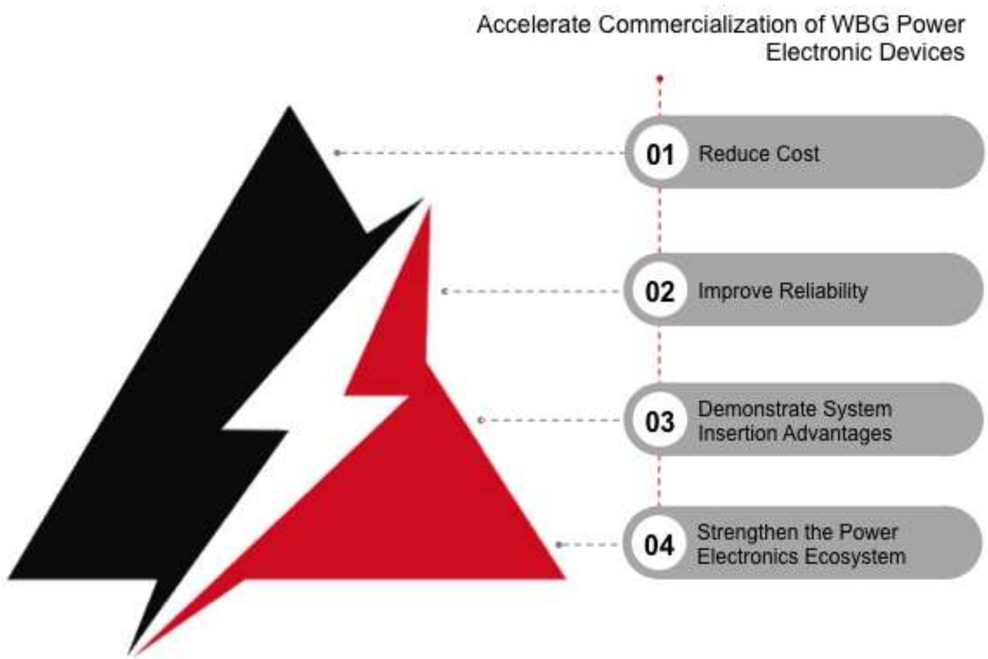
While WBG technologies offer significant capabilities that can advance PE, the industry must overcome numerous technical challenges and reliability concerns. Furthermore, the industry must manufacture devices and insert them in modules and systems at high volumes and low cost. This roadmap aims to provide a deeper understanding of the current state and potential impact of WBG-based PE technologies and outlines collaborative, community-wide activities to accelerate technology development and enhance the PE community's ability to achieve its goals.



## PowerAmerica’s 10-Year Roadmap Strategy

WBG technologies have the potential to reduce energy consumption and emissions in a variety of industries, while also creating manufacturing jobs across the United States. To capitalize on this potential, this roadmap offers a strategy for making WBG semiconductor technologies cost competitive with Si-based PE and for accelerating the adoption of SiC- and GaN-based components in new markets and applications. The roadmap thrusts—Reducing Cost, Improving Reliability, Enhancing Performance Capabilities, and Strengthening the Power Electronics Ecosystem—are intimately connected to form an integrated, collaborative strategy for advancing SiC and GaN technologies for PE.

Figure 1. Overview of PowerAmerica’s Roadmap Strategy




### Thrust 1: Reducing Cost

Reducing the cost of WBG semiconductors is critical to accelerating their adoption. A key driver for successfully reducing costs to levels competitive with Si-based PE is to facilitate high-volume manufacturing, and coordinate efforts in the PE community as a whole to: 1) ensure availability of PE components from materials and wafers to devices and modules; 2) streamline design, manufacturing, packaging, and system integration; and 3) engage stakeholders, from materials providers to manufacturers to end users. This thrust focuses on identifying early adopters, high-volume markets and applications in which there is the greatest need for improved performance and cost-effective manufacturing strategies. Coupled with Thrust 4, it will also be critical to increase the availability of high-quality raw materials and larger area wafers.

## Thrust 2: Improving Reliability

While SiC and GaN devices have demonstrated higher efficiency than Si-based devices in PE applications, reliability concerns still limit the market penetration of WBG technologies. As WBG technologies mature, without strategies to establish their reliability, the PE community cannot gain confidence in their use. Gaining a better understanding of degradation/failure mechanisms under harsh conditions (i.e., stresses such as high voltages and/or high temperatures) is key to designing more robust WBG components. It is essential to consider three issues related to establishing the reliability of WBG technologies: generation of high-quality reliability data from advanced testing methods; standardized reliability assessment; and effective communication about reliability best practices to end users.

## Thrust 3: Enhancing Performance Capabilities

In addition to reducing the cost and establishing the reliability of SiC and GaN devices, the PE community must identify and address technical issues at all levels of design, manufacturing, packaging, and qualification that currently constrain WBG power components capable of higher-temperature, voltage, and frequency operation. Activities to enhance performance capabilities—including best design practices, optimization of structures and exploration of new circuit topologies by the end user—are critical to accelerating commercialization of SiC and GaN technology into a wide range of power electronic products.

## Thrust 4: Strengthening the Power Electronics Ecosystem

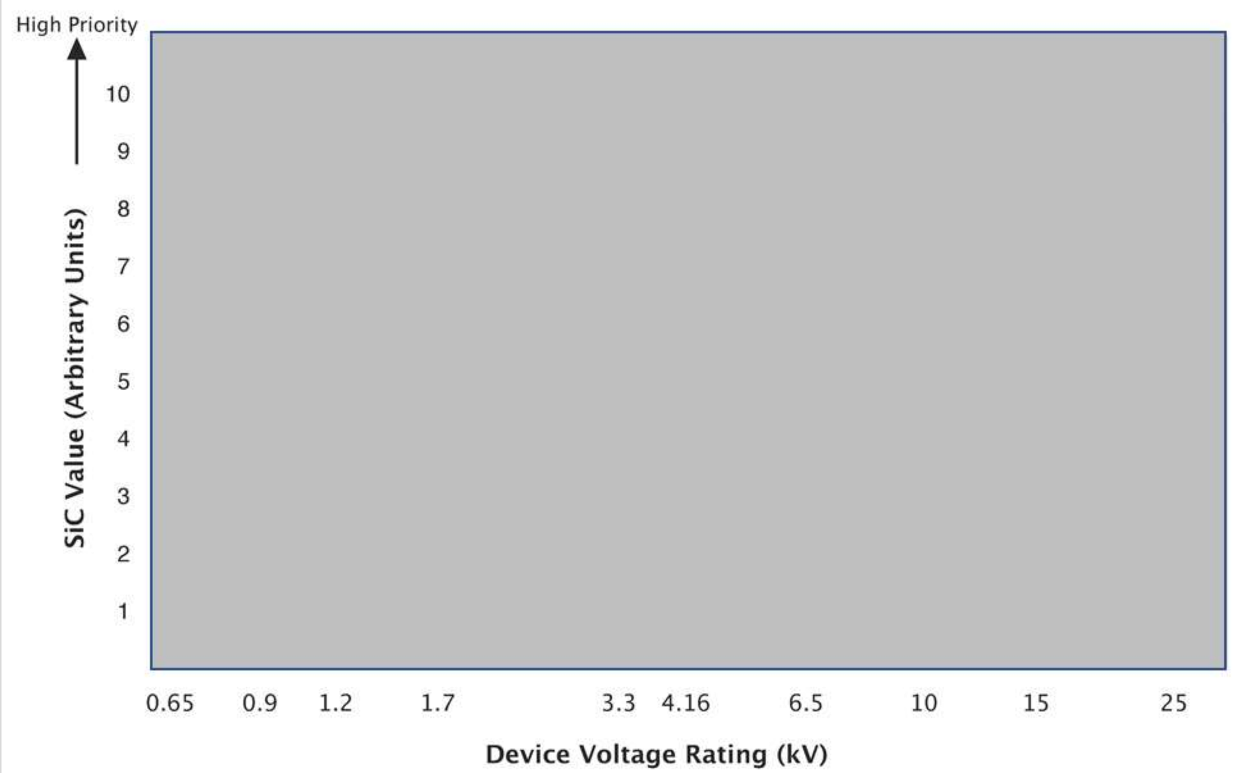
To realize the potential of WBG technologies, the PE community needs to build a network with strong information-sharing capabilities to increase interaction between supply chains, manufacturers, and end users. There is also broad consensus that several additional deficiencies exist across the PE community—including the need for cost-effective U.S. manufacturing capacity, a workforce with a deeper knowledge of WBG PE advances in technologies such as epi-materials, and advanced complementary technologies such as magnetics or vertical GaN devices—that may delay the commercialization of WBG technologies if not addressed concurrently. Although some of these deficiencies (e.g., issues in basic science) are outside the scope of PowerAmerica, the community should monitor and identify national/international activities with the most merit to ensure WBG PE sustainability with further investment. In addition, a robust educational and workforce development program is needed to support this growing industry.

## Key SiC and GaN Power Electronics Markets and Applications

To accelerate widespread adoption of WBG semiconductor components, it will be critical to support their early successful commercialization in high-value markets. For this reason, it is important to identify and prioritize PE markets and applications for SiC and GaN technologies, which are described in this section. Tables of performance targets for key applications, as identified by PowerAmerica roadmapping workshop participants and working group members, accompany the application descriptions.

Figures 2 and 3 show WBG device markets and map the priority of different applications in the next 10 years. The SiC/GaN values on the vertical axes were defined to guide discussions throughout the PowerAmerica roadmapping process. **The values reflect two primary impacts: system impact (efficiency, power density, and cost); and broader economic impact (i.e., size of the market and likely SiC/GaN adoption).** While there are a variety of markets and applications for WBG technologies, this section categorizes key priority markets with respect to SiC/GaN values and distinct voltage ranges.

Figure 2. Primary Markets and Applications of SiC-based Power Electronic Devices/**PowerAmerica Proprietary Information**




| Application | Device Voltage (kV) | Application Voltage Rating (kV) | SiC Value* | Timeline |
|---|---|---|---|---|
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
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| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
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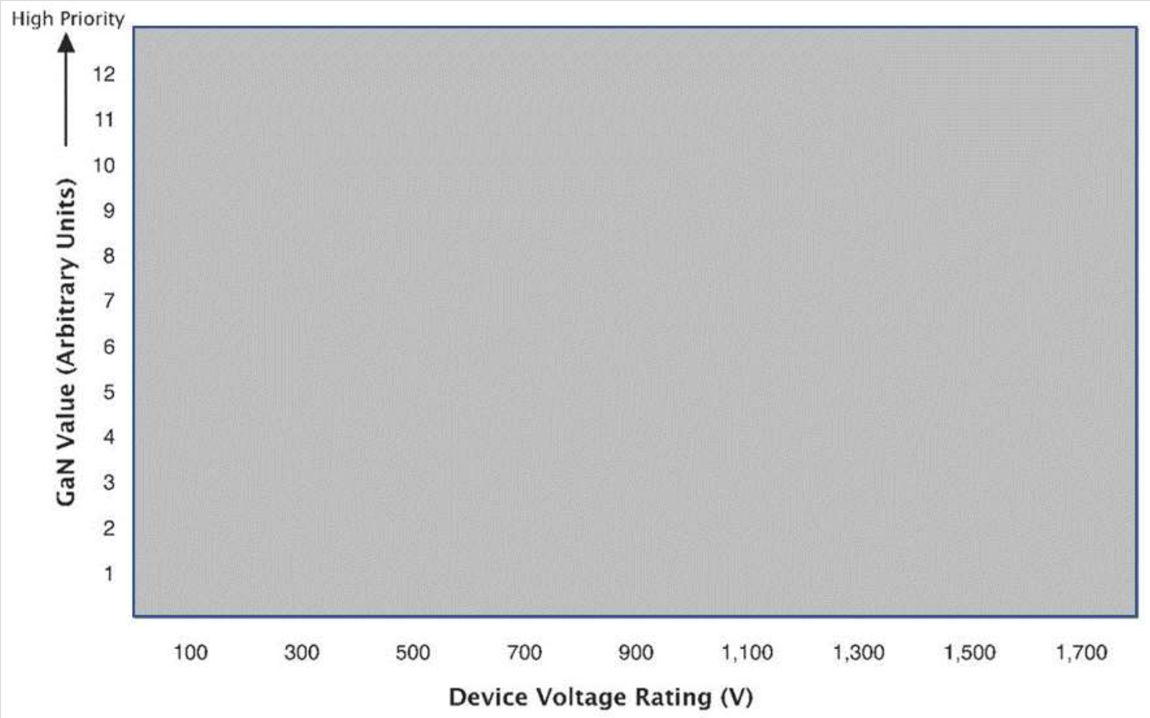
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |
| [redacted] | [redacted] | | [redacted] | [redacted] |

[redacted]

Figure 3. Primary Markets and Applications of GaN-based Power Electronic Devices/**PowerAmerica Proprietary Information**




| Application | Device Voltage (V) | GaN Value | Timeline |
|---|---|---|---|
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |
| [redacted] | [redacted] | [redacted] | [redacted] |

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[redacted]

## Near-term applications with high SiC/GaN values

To accelerate adoption of WBG semiconductors, the PE community must focus on near-term (1-2 years) applications for both SiC and GaN technologies that are most likely to deliver immediate improvements in efficiency and reliability. As shown in Table 2, the majority of key near-term markets or applications with high SiC/GaN values are related to consumer electronics, data centers, and enterprise equipment or to power conversion and control of renewable energy. Chargers, covering device voltages 100/650/900V in GaN and 0.65-1.7kV in SiC, are also near-term crosscutting applications.

Consumer electronics, data centers, and enterprise equipment: The demand for electricity use for consumer electronics (e.g., laptops and smart phones), large-scale data centers, and enterprise equipment (e.g., DC/DC converters and telecom switching stations) continues to rise each year. Power converters that convert AC to DC for consumer electronics use nearly 4% of U.S. electricity. U.S. data centers, which require uninterruptible power supply (UPS) systems as well as power converters, are projected to consume more than 140 billion kilowatt hours annually by 2020. Key enablers for success in this near-term application space include high power density, low switching losses, and high-temperature operation, ultimately increasing system efficiency.

Renewable energy: PE are key for power conversion of renewable energy, particularly for high-efficiency DC-to-AC conversion of photovoltaic (PV) energy generated at solar farms. WBG-based PV inverters and PV systems can convert power more efficiently, yielding significant energy savings. The PE community is looking into WBG to increase the efficiency (e.g., California Energy Commission [CEC] efficiency), power density, reliability, and other requirements (e.g., EMI specification) of power devices for renewable energy systems. Ease of installation and low maintenance costs across the entire grid system are also critical considerations.

Chargers: There is significant demand for advanced chargers for electric vehicles (EVs) and consumer devices such as cell phones. The drawbacks of current EV fast chargers and on-board chargers (OBC) include low efficiency, low power density, and high installation cost. Insertion of SiC in EV chargers could provide a path for addressing these challenges, while also reducing charger size and weight. GaN device technology could enable high-efficiency wired/wireless chargers for laptops, tablets, and mobile devices.

Table 2. Performance Targets for Near-term Applications with High SiC/GaN Value/**PowerAmerica Proprietary Information**

| **Performance Targets** | **Calendar Year** | | | |
|---|---|---|---|---|
| | 2016–2018 | 2019–2021 | 2022–2024 | 2025–2027 |
| **SiC, 650V: Data center** | | | | |
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET Body Diode [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |
| **SiC, 650V: EV onboard chargers** | | | | |
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET Body Diode [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |
| **GaN, Enterprise equipment (e.g., DC/DC converters, data center, HV DC/DC)** | | | | |
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Device Voltage Rating [V] | [redacted] | [redacted] | [redacted] | [redacted] |
| Device Rated Current at 25/150$^{o}$C [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |
| **GaN, Residential PV systems (100/650/900V)** | | | | |
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Device Voltage Rating [V] | [redacted] | [redacted] | [redacted] | [redacted] |
| Device Rated Current at 25/150$^{o}$C [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |

| GaN, Mobile Chargers (wired & wireless laptops, tablets, mobile devices) | | | | |
|---|---|---|---|---|
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Device Voltage Rating [V] | [redacted] | [redacted] | [redacted] | [redacted] |
| Device Rated Current at 25/150$^{o}$C [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |

## Mid-term applications with medium to high SiC/GaN values

As described in Table 3, mid-term (i.e., next 3–5 years) WBG PE applications are related to efficient power transfer and distribution in systems, including EV, traction systems (e.g., EV/PHEV [plug-in hybrid EV] and rail traction), heavy-duty vehicles, and advanced industrial motor drives.

EV, traction (e.g., EV/PHEV and rail traction), and heavy-duty vehicles: As mentioned in the near-term WBG applications section, high demand exists for better EV fast chargers and OBCs for EV/PHEV applications. WBG semiconductor-based devices can enable EV chargers with high power, high conversion efficiency, reduced size and weight, and low installation costs. Integrating WBG PE in heavy-duty vehicle or rail traction systems will be challenging because integration must be achieved with reducing system-level cost and complexity and improved reliability. The reduction in passive components, enabled by WBG devices, is particularly important in these applications.

Industrial motor drives: Electric motor systems are ubiquitous and use nearly 70% of the electricity consumed in U.S. manufacturing to convert electrical power to mechanical energy. WBG PE technologies allow manufacturers to develop energy-efficient motor systems by controlling motor speed to match power requirements.  In addition to the obvious efficiency benefits, this capability can also give plant engineers additional tools for process and control optimization, reduce the cost of expensive gearing systems, and improve capacity utilization.

Table 3. Performance Targets for Mid-term Applications with Medium to High SiC/GaN Values/**PowerAmerica Proprietary Information**

| Performance Targets | Calendar Year | | | |
|---|---|---|---|---|
| | 2016–2018 | 2019–2021 | 2022–2024 | 2025–2027 |
| **SiC, 0.65-1.2kV: EV, traction, charger** | | | | |
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET Body Diode [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |
| **SiC, 1.2-1.7kV: Traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, PV string inverter, circuit protection** | | | | |
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for MOSFET Body Diode [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |

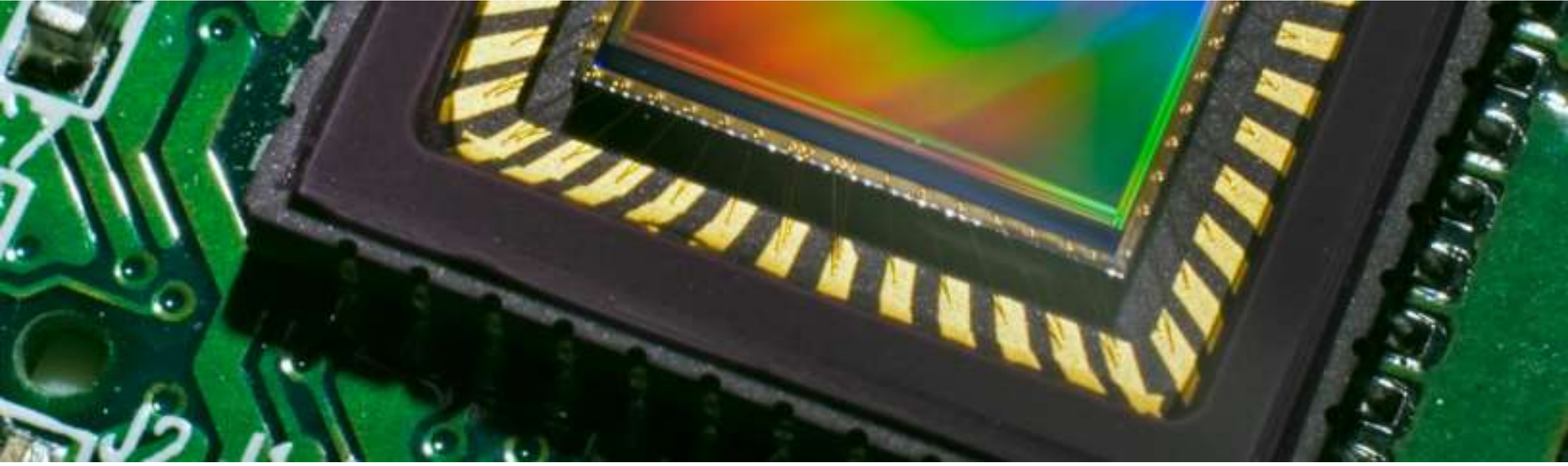
## Long-term applications with low to medium SiC/GaN values

The low- or medium-priority (i.e., low or medium SiC/GaN values) designation of markets at higher device voltages in Table 4 does not mean that these long-term (5-10 years) applications are less important. The low SiC/GaN values of this category are mainly due to the challenge of fabricating devices at high voltage ratings. Table 4 shows performance targets for such long-term applications with low to medium SiC/GaN values.

Medium-voltage (MV) drives: The key focus in this category is advancing medium-voltage (MV) drives focused on the North American standard MV rating of 4.16 kV. A MV drive is used in high-power (i.e., megawatt levels) applications, such as in large-scale pumps, fans, or compressors in power plants and the oil and gas industry. The PE community is currently working to improve these drives by increasing the effectiveness of motor speed controls, reducing energy loss, developing low harmonics for high power quality, and reducing installation costs.

Table 4. Performance Targets for Long-term Applications with Low to Medium SiC/GaN Values/**PowerAmerica Proprietary Information**

| Performance Targets | Calendar Year | | | |
|---|---|---|---|---|
| | 2016–2018 | 2019–2021 | 2022–2024 | 2025–2027 |
| **SiC, 10kV, 15kV: MV drives, MV DC Naval platform, wind, advanced distribution system, solid-state circuit breaker** | | | | |
| Device Type | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for Transistor [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Rated Current for Diode [A] | [redacted] | [redacted] | [redacted] | [redacted] |
| Cost [$/A] | [redacted] | [redacted] | [redacted] | [redacted] |



## Challenges for Volume Manufacturing of SiC and GaN Devices

PowerAmerica recognizes that accelerating large-scale adoption and high-volume manufacturing of WBG semiconductor devices will require a coordinated, interdisciplinary approach involving stakeholders from throughout the PE industry, including large, small, and start-up companies, universities, and national laboratories. With the goals of large-scale adoption and high-volume manufacturing in mind, the four roadmap thrusts discussed in the section on PowerAmerica's 10-Year Roadmap Strategy are not only strategies to pursue, but also the challenges that industry must solve. The following section outlines high-level challenges for achieving large-scale commercialization of both SiC and GaN technologies. Detailed application-specific challenges are included in tables within each thrust section.

### Thrust 1: Key Challenges to Reducing Cost

Although recent advances in WBG-based technologies are rapidly reducing the cost gap between SiC/GaN power devices and Si devices (e.g., 100A), the higher cost of WBG PE devices still makes their market penetration slow and difficult. The cost of WBG devices is mainly linked to the high cost of raw materials, which account for up to 40% of the overall cost of a device. In particular, the GaN community suffers from a lack of low-cost epi-wafers with low defect density, as well as substrates suitable for specific applications. A challenge for the industry is to cost-effectively manufacture WBG devices at large scale (see Table 5).

Table 5. Thrust 1 Challenges—Reducing Cost

| | Application | Thrust 1 Challenges |
|---|---|---|
| SiC | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW) | • High cost of SiC devices compared to 100A Si devices |
| | 0.65–1.2kV: EV traction, charger | - |
| | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection | • High cost |

| | Application | Thrust 1 Challenges |
|---|---|---|
| | 1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | - |
| | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS | - |
| | 10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | - |
| GaN | Enterprise equipment (e.g., DC/DC converters, data center, HV DC/DC) | • High GaN manufacturing cost |
| GaN | Residential PV systems (100/650/900V) | • Need for improved cost and quality of epiwafers; Packaging cost for PV reliability grade devices |
| GaN | Low/Mid-voltage non-traction automotive electronics | • Lack of low-cost epiwafer (<$800 for 150 mm, <$1,400 for 200mm), low defect density $10^6/cm^2$ GaN-on-Si<br>• Need for gate drive design |
| GaN | Mobile chargers (wired & wireless laptops, tablets, mobile devices) and LED driver | • Need for drive Integration, Lower epi cost, reduced cell pitch, improved 2DEG conductivity |
| GaN | EV & HEV charging (wired & wireless) | • Reducing hetero-epitaxy cost and improving yields for large area devices; lower cost reliable packaging |
| GaN | Motor drives for fractional to integral horse-power motors (ind. motion control & robotics, white goods, HVAC) | • Need to lower GaN/Si epitaxy cost with good epi uniformity; thicker epi for higher voltage switches |
| GaN | Military / Aviation | - |
| GaN | Consumer AC/DC | • Need for hetero-epitaxy cost reduction and lowest cost foundry processes |

## Thrust 2: Key Challenges to Improving Reliability

The successful adoption of WBG PE technologies in key markets and applications requires reliable operation of SiC/GaN devices, which necessitates overcoming several challenges (Table 6). The reliable performance of power devices is highly influenced by multiple factors such as their structure, level of defects (e.g., basal plane dislocation [BPD]), processing/manufacturing conditions, packaging, and device degradation from harsh operating conditions (e.g., high-temperature, high-voltage and high-frequency operation). The PE community lacks sufficient reliability data with respect to device performance under different conditions over long periods of time, which is critical for understanding failure mechanisms and defining functions of life-stress relationships. This lack of reliability data is also a result of insufficient standards for reliability testing and measurements.

Table 6. Thrust 2 Challenges—Improving Reliability

| | Application | Thrust 2 Challenges |
|---|---|---|
| SiC | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW) | • Insufficient reliability data |
| | 0.65–1.2kV: EV traction, charger | • Insufficient assurance of reliability for PE in automotive applications/lack of data demonstrating automotive reliability |
| | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection | • Lack of good reliability testing data that demonstrates device performance in different situations over long periods of time |
| | 1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | - |
| | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS | - |
| | 10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | • Need for optimized IGBT buffer-layer and lifetime<br>• Need for low BPD for bipolar operation |
| GaN | Enterprise equipment (e.g., DC/DC converters, data center, HV DC/DC) | • Insufficient standards for GaN reliability |
| | Residential PV systems (100/650/900V) | • Firming up device reliability specifications for PV inverter applications and validating GaN switch reliability |
| | Low/Mid-voltage non-traction automotive electronics | • Need for reliability standards and benchmarking |
| | Mobile chargers (wired & wireless laptops, tablets, mobile devices) and LED driver | • Need for reduced epi layer defects and improved control of interface states<br>• Need for increased system-level testing/reliability (high temperature operating life) |
| | EV & HEV charging (wired & wireless) | • Establishing reliability testing equivalent to AEQ 101, but appropriate for GaN switches, and validating |
| | Motor drives for fractional to integral horse-power motors (ind. motion control & robotics, white goods, HVAC) | • Inadequate consumer and industrial grade reliability for respective segments |
| | Military / Aviation | • Lack of reliability testing capability 100V-200 A/ 540-600V (1700 V)<br>• Lack of system-level testing/reliability |
| | Consumer AC/DC | • Consumer-grade reliability is currently inadequate; very low rates of early failure are acceptable – less than a few ppm |

## Thrust 3: Key Challenges to Enhancing Performance Capabilities

In addition to improving SiC and GaN device cost and reliability, the PE community must solve technical challenges at all levels of PE systems, including challenges related to device performance, module integration and packaging, and qualification standards (Table 7).

Device level challenges: The GaN device community is currently faced with the challenge of developing high-frequency power converters and improved normally-off (i.e., enhancement-mode) devices. Challenges in SiC devices include improving channel mobility with increased channel density and reduced channel lengths; reducing energy losses (e.g., $Q_{rr}$: reverse recovery charge) with reduced parasitics, optimizing gate drivers for specific application environments; and integrating MOSFET with a (Schottky) diode in one chip to lower forward voltage drop and energy loss from the diode.

Module and packaging challenges: Key module and packaging challenges include the need to improve high voltage insulation, thermal management, partial discharge, and EMI to enable high-performance modules (e.g., double-sided cooled power modules operating at a higher junction temperature ($T_{j,max}$: 175°C –200°C), and high-performance discrete packages that can operate at higher temperatures and voltages.

Qualification standards challenges: Because WBG PE technologies are relatively new, there is high demand for qualification standards for PE technologies similar to the Automotive Electronics Council's Qualification (AECQ) standards developed for automotive electronics or the Joint Electron Device Engineering Council's (JEDEC) standards for electronics.

Table 7. Thrust 3 Challenges—Enhancing Performance Capabilities

| | Application | Thrust 3 Challenges |
|---|---|---|
| SiC | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW) | • Need for MOS channel mobility greater than 200 $cm^2/Vs$ to drive cost down<br>• Need for discrete packaging that can operate at higher temperatures<br>• Need for lower gate charge<br>• Need for a gate drive that supports higher-frequency operation |
| SiC | 0.65–1.2kV: EV traction, charger | • Need for cost-effective double-side cooled module technology ($T_{j,\ max}$: 175-200°C) |
| SiC | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection | • Need for AEC-like qualifications, short circuit rating, and/or optimized gate driver<br>• Lack of good high-temperature packaging (e.g., for down hole)<br>• Need for package standardization with dual sourcing<br>• Need for reduced parasitics |
| SiC | 1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | • Need for optimized gate driver in packaging<br>• Need for double plastic coating alternative in packaging |
| SiC | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS | • Difficulty in lowering induction and maintaining good isolation of partial discharge at high voltages (note that this is especially needed for 10kV applications) |
| SiC | 10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | • Need for suitable edge termination (area usage) passivation<br>• Need for advanced gate drivers<br>• MOS and diode integration<br>• Issues in packaging and modules (i.e., inductance, common mode capacitor, HV insulation, and/or partial discharge)<br>• HV system packaging (i.e., voltage insulation, thermal management, and/or EMI)<br>• SOA optimization for IGBT (i.e., SC-SOA and or UIS) |
| GaN | Enterprise equipment (e.g., DC/DC converters, data center, HV DC/DC) | • Lack of high-frequency power converter controllers<br>• Lack of high-speed, low-cost drivers<br>• Insufficient GaN packaging and thermal solutions<br>• Need for appropriate power supply packaging (EMI concerns) |
| GaN | Residential PV systems (100/650/900V) | • Reference designs for the power stages<br>• Need for faster protection hardware<br>• Need for improved capacitors for increased system reliability |
| GaN | Low/Mid-voltage non-traction automotive electronics | • Lack of normally off devices $V_{Th}$>4<br>• Lack of design tools for integrated GaN smart power circuits<br>• Lack of good passivation to achieve low surface state density ($10^{11}$ $cm^{-2}$ $eV^{-1}$)<br>• Need for double-sided cooling (vehicle and vibration) |

| | | |
|---|---|---|
| | Mobile chargers (wired & wireless laptops, tablets, mobile devices) and LED driver | • Need for expanded offering to cover current range<br>• Need to integrate key functions to enable improved soft switching topologies |
| | EV & HEV charging (wired & wireless) | • Reference designs for the several types of systems used for automotive charging |
| | Motor drives for fractional to integral horse-power motors (ind. motion control & robotics, white goods, HVAC) | • Need to begin adoption in areas where performance is more important than cost and volume – such as high-speed machine tools requiring precision speed control, fast compact robotic/motion control systems, etc. |
| | Military / Aviation | • Lower-volume application less likely to be served in the short term |
| | Consumer AC/DC | • Need for reference designs with new circuit topologies showing lower overall system BOM & cost |

## Thrust 4: Key Challenges to Strengthening the Power Electronics Ecosystem

In addition to targeting the above technical challenges, the PE community must also improve collaboration and information sharing by strengthening a PE ecosystem, and must monitor additional technology areas that could result in emerging markets for SiC and GaN devices (Table 8).

Challenges to strengthening an ecosystem for WBG PE technologies: Encouraging a community-driven, integrated framework for collaboration and information sharing across the PE community will accelerate device innovation and adoption. Strengthening this ecosystem, however, is difficult due to the number of industry sectors involved, including wafer suppliers, device design houses, microelectronic fabs, and the multidisciplinary nature of PE challenges. The breadth of the PE community makes it difficult to establish open, shared resources and libraries (e.g., foundries and reliability databases) that can help drive advanced manufacturing and accelerated integration of SiC and GaN devices. The community will also need to work together to solve challenges such as limited supplier availability, and provide workforce training. Multidisciplinary efforts must be made to reduce device cost, enhance reliability, and improve system performance and integration.

Monitoring supplementary technologies: Though the mission of PowerAmerica necessitates focusing primarily on WBG manufacturing and activities between MRL 4 and 7 to maximize energy savings and job creation, the PE community must also monitor emerging, niche, and complementary low-volume PE markets. These areas include novel device design (e.g., vertical GaN) and high-frequency magnetics.

Education and Workforce Development: There is a dire need for a new generation of WBG trained professionals, primarily at the undergraduate and graduate levels, to address the above technical challenges in the near future. Additionally, training working PE professionals in WBG technologies can provide immediate benefits to the WBG Power Electronics Ecosystem.

Table 8. Thrust 4 Challenges—Strengthening the Power Electronics Ecosystem

| | Application | Thrust 4 Challenges |
|---|---|---|
| SiC | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW) | - |
| | 0.65–1.2kV: EV traction, charger | • Trench issues<br>• Need for advanced large area trench<br>• Need for lower gate charge<br>• Issues with short circuit |
| | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection | • Need for improved material quality for 100-200A single chips |
| | 1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | - |
| | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS | - |
| | 10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | • Few sources of epi; need multiple sources that offer low defects, high uniformity, and low costs |
| GaN | Enterprise equipment (e.g., DC/DC converters, data center, HV DC/DC) | • Need for production of integrated magnetics<br>• Insufficient workforce training for GaN and High Frequency Design |
| | Residential PV systems (100/650/900V) | • Need for lower loss and higher-frequency magnetics |
| | Low/Mid-voltage non-traction automotive electronics | • Need multiple approved vendors for epi, devices, and packaging |
| | Mobile chargers (wired & wireless laptops, tablets, mobile devices) | • Need to encourage control IC and magnetics makers to push to higher frequency capability |
| | EV & HEV charging (wired & wireless) | • Need for stronger interaction between battery makers, PE groups, and automobile designers to realize this potential |
| | Motor drives for fractional to integral horse-power motors (ind. motion control & robotics, white goods, HVAC) | • New standards for high-efficiency motors and incentives to motor/drives manufacturers in a very conservative industry |
| | LED driver | • Need to encourage control IC and magnetics makers to push to higher-frequency capability |
| | Military / Aviation | • Lack of epi 200A/270V (1200V) 200V/540V (1700V)<br>• Limited supplier availability and supplier obsolescence |
| | Consumer AC/DC | - |

## Technical Activities to Accelerate WBG Volume Manufacturing

The following section outlines high-level technical activities that will require collaboration across the PE community to achieve PowerAmerica's mission of accelerating high-volume manufacturing and commercialization of both SiC and GaN devices. Detailed application-specific activities are included in tables within each thrust section.

### Thrust 1: Reducing Cost

To increase the availability and accessibility of state-of-the-art WBG power components, the PE community must work to make these technologies cost-competitive with Si technologies. As described in Table 9, these cost savings can be achieved by improving the efficiency and precision of manufacturing processes to create higher-quality, higher-value products that are more reliable, increasing their marketability for demanding PE applications. Increasing manufacturing capacity can also reduce direct manufacturing costs by minimizing the need for outsourcing. To avoid the high initial investment costs of building new WBG foundries, the WBG PE community could leverage mature Si fabrication practices and utilize existing 150- and 200-mm Si foundries to fabricate WBG devices (e.g., SiC MOSFET). This open foundry model could significantly reduce equipment costs and overhead of WBG device manufacturing.

Table 9. Thrust 1 Activities—Reducing Cost

| | Application | Thrust 1 Technical Activities | | | |
|---|---|---|---|---|---|
| | | 2016–2018 | 2019–2021 | 2022–2024 | 2025–2027 |
| SiC | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW)<br>0.65–1.2kV: EV traction, charger | • Conduct application demos (open BoM) comparing Si, SiC, and GaN devices for data centers and EV-chargers, with cost estimates | - | - | - |
| SiC | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection<br>1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | - | - | - | - |
| SiC | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS<br>10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | - | - | - | - |

| | | | | | |
|---|---|---|---|---|---|
| **GaN** | Crosscutting activities | • Identify fabs and conduct cost analysis (overseas vs. US)<br>• Lateral GaN epiwafer cost and quality | - | - | - |

## Thrust 2: Improving Reliability

To increase confidence in WBG devices, the PE community must qualify, validate, and establish the reliability of WBG PE components. To do so, the PE community should increase the quantity and accessibility of reliability data, establish qualification standards for long-term reliability, and develop accelerated reliability testing methodologies for consistent use throughout the industry. Reliability testing and correlation studies are critical to improving the understanding of degradation and failure mechanisms and their impact on the performance of WBG modules, packaging, and integrated systems. Table 10 outlines activities to improve the reliability of WBG PE components for specific applications.

Table 10. Thrust 2 Activities—Improving Reliability

| | Application | Thrust 2 Technical Activities | | | |
|---|---|---|---|---|---|
| | | 2016–2018 | 2019–2021 | 2022–2024 | 2025–2027 |
| **SiC** | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW)<br>0.65–1.2kV: EV traction, charger | • Conduct large-scale reliability testing of SiC and GaN devices | - | - | - |
| **SiC** | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection<br>1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | - | - | - | - |
| **SiC** | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS<br>10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | • Focus on 15kV IGBT buffer layer and lifetime | - | - | - |
| **GaN** | Crosscutting activities | • Conduct reliability benchmarking<br>• Define reliability standards<br>• Provide independent reliability testing labs and service<br>• Support Fab device and test<br>• High frequency magnetics | - | - | - |

## Thrust 3: Enhancing Performance Capabilities

The PE community must demonstrate the advanced capabilities of WBG power devices, which are smaller, faster, and more efficient than Si-based PE in high-voltage, high-temperature, and high-frequency operating environments. To support widespread adoption and large-volume manufacturing of next-generation WBG products, the PE community should pursue technical activities that will increase the efficiency and capacity of manufacturing processes and enhance the performance capabilities of WBG materials, devices, modules, and systems (Table 11). Such activities should include producing reference designs, scaling voltage and power, building WBG gate drives, and improving figures of merits (e.g., on-resistance, leakage, and/or low parasitics). It is important to note that the technical activities for this thrust are not possible without advanced peripheral components, thermal management techniques, gate driver technologies, and innovative EMI/EMC solutions. Technologies like high frequency magnetics are beyond the scope of PowerAmerica, but these technologies should be monitored through Thrust 4: Strengthening the Power Electronics Ecosystem.

Table 11. Thrust 3 Activities—Enhancing Performance Capabilities

| | Application | Thrust 3 Technical Activities | | | |
|---|---|---|---|---|---|
| | | 2016–2018 | 2019–2021 | 2022–2024 | 2025–2027 |
| **SiC** | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW)<br>0.65–1.2kV: EV traction, charger | • Develop circuit design software<br>• Develop thermal design tools<br>• Develop a double-sided cooling package | • Trench MOS channel mobility: 200 $cm^2/Vs$<br>• Planar MOS channel mobility: 200$cm^2/Vs$ | - | - |
| | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection<br>1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | • Develop high power density packaging<br>• Embedded / Surface mount / Small module /Top-cool / Low inductance die attach<br>• Develop improved gate drivers with additional sensing and protection capabilities (e.g., to identify when something is going wrong and when to shut down)<br>• Quantify the impact of combining thermal stresses and coolant (compact SPICE model and electrical/thermal model)<br>• Circuit Modeling<br>• Thermo-mechanical model<br>• Thermal system: air cool, liquid cool | • Develop auxiliary components<br>• Capacitors (all types of parts)<br>• Core-less sensor<br>• EMI/EMC management and shielding<br>• Inductor<br>• Transformer | - | - |

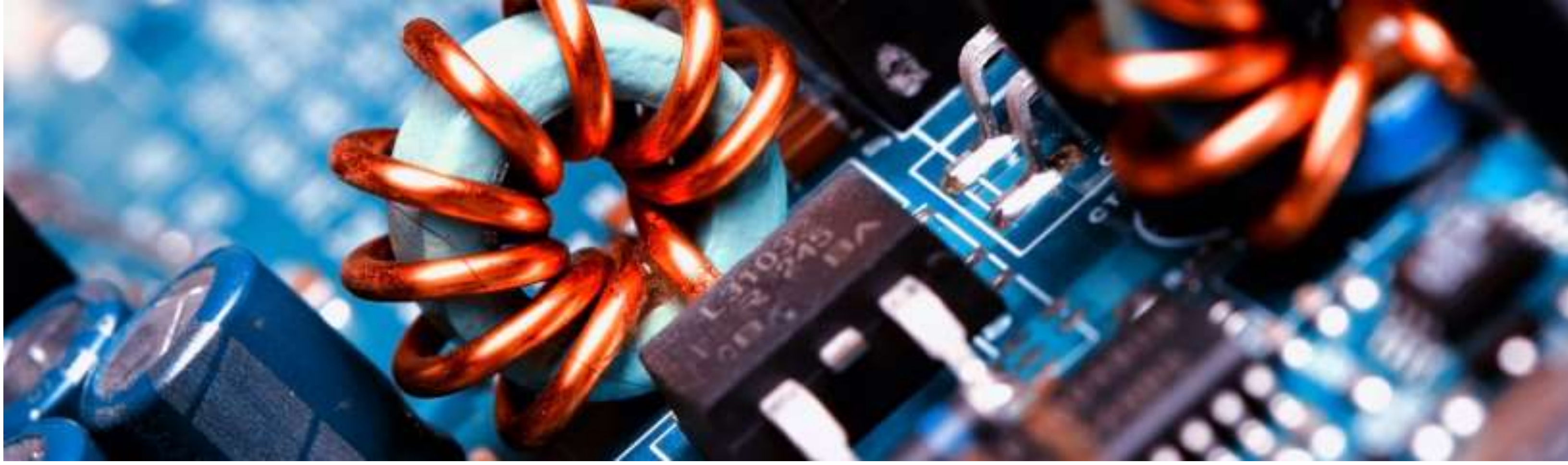
| | | | | | |
|---|---|---|---|---|---|
| | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS<br>10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | • Focus on MV 13.8 kV grid-tie VSC<br>• Develop module packaging<br>• Partial discharge design for HV<br>• Establish DC voltage derating for same FIT rate for HV 10-15 kV MOSFET and IGBT<br>• Compare multi-level MOSFET vs. single IGBT + diode<br>• Consider DC-DC MV converters (e.g., MV-LV: 8-10 kV→800V-1000V and with HF magnetics)<br>• Develop module packaging: insulation degradation at HV and HF operation<br>• Develop IGBT 15 kV edge termination<br>• Develop a 15 kV diode<br>• Focus on MV VSC @ 4.16 kV (compare IGBT vs. MOSFET)<br>• Focus on HV isolated 15 kV (e.g., 20 kV gate driver and SC protect)<br>• Develop module packaging for non-isolated base plate module | - | • Develop HF and high power inductors and capacitors | - |
| **GaN** | Crosscutting activities | • Create lab to provide trusted, third-party testing<br>• Packaging for highly accelerated testing<br>• Application-specific testing<br>• Design tools/models for integrated GaN circuit simulation<br>• Develop reference designs including full systems (vs. evaluation boards)<br>• PV inverter / Data center applications<br>• Spread knowledge about GaN designs (education, workforce, tutorials, etc.)<br>• Develop low-cost, high-speed drivers<br>• Market GaN technology | • Provide a US GaN fab<br>• Ensure GaN fab will maintain processes to support lower-volume military/aviation products<br>• Develop high-frequency, low-cost controllers<br>• Accelerate development over timeframe<br>• Improve E-mode GaN/Si devices | - | - |

## Thrust 4: Strengthening the Power Electronics Ecosystem

Strengthening a collaborative WBG PE ecosystem is critical to accelerating advancement of WBG PE technology and establishing the technology's commercial viability in a variety of applications. To facilitate this collaboration, the PE community should develop a framework for information sharing (e.g., manufacturing reliability data and process recipes), reinforce partnerships across the value chain, and build a more forward-looking and knowledgeable PE workforce. To maintain a sustainable PE ecosystem, the PE community should continuously monitor emerging and complementary technical areas, including work in epi-materials, high-frequency (or very-high-frequency) applications, magnetics, and advanced architectures.

Table 12. Thrust 4 Activities—Strengthening the Power Electronics Ecosystem

| | Application | Thrust 4 Technical Activities | | | |
|---|---|---|---|---|---|
| | | 2016–2018 | 2019–2021 | 2022–2024 | 2025–2027 |
| SiC | 650V: Data center (750W power supply) and EV onboard charging (3/6.6–20kW)<br>0.65–1.2kV: EV traction, charger | | - | - | - |
| | 1.2-1.7kV: PV string inverter, traction (e.g., EV/PHEV and rail), grid-tied energy storage, heavy-duty vehicles, electric aircraft, industrial motor drive, circuit protection<br>1.7-3.3kV: UPS, rail traction, power quality, wind: conventional wind machine with WBG, rail auxiliary power supplies with 1.5kV bus HVDC | - | - | - | - |
| | 4.5kV, 6.5kV: Rail traction, grid-tied charging, UPS<br>10kV, 15kV: MV drives, MV DC naval platform, wind, advanced distribution system, solid-state circuit breaker | • Study HF and HV effect on insulation (for magnetics) | - | - | - |
| GaN | Crosscutting activities | • Develop publications that establish reliability to increase adoption<br>• Webinar, podcasts, social media training<br>• Prove high-frequency magnetics scalability requirements<br>• Fill gaps between feasibility and product of integrated planar magnetics<br>• Promote efforts to improve passives, especially magnetics | • Fund projects to develop more robust enhancement mode devices<br>• Monitor progress in Japan, China, Korea, and ARPA-E switches | • Promote integrated packaging effort | - |



## Path Forward

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 activities needed to overcome those barriers. PowerAmerica's role will be to facilitate coordination across industry, academia, and national labs to implement the priority roadmap activities summarized below and to make strategic investments in technology development, workforce training, and WBG manufacturing.

Reducing Cost

- Lower the $/Ampere of WBG devices and power modules
- Leverage existing Si foundries for WBG fabrication
- 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

- Establish WBG 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 WBG dedicated PE standards

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

Building the Power Electronics Ecosystem

- Facilitate the creation of a "device/module bank" for quick access of next generation devices
- Develop 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

The roadmap provides guidance to accelerate large-scale adoption of WBG semiconductor devices in power electronic systems. Continued and increased investment in R&D, coupled with workforce development and training activities, are critical for maximizing U.S. manufacturing and global competitiveness, and for enabling the PE community to meet increased market demand in the next decade.

# Appendix A. Contributors

## Workshop Attendees

| Name | Affiliation | Breakout Group |
|---|---|---|
| Ayayi Ahyi | Auburn University | SiC |
| Akin Akturk | CoolCAD Electronics LLC | SiC |
| Kevin Bai | Kettering University | SiC |
| Sandeep Bala | ABB | GaN |
| Anup Bhalla | United Silicon Carbide Inc. | SiC |
| Subhashish Bhattacharya | North Carolina State University | SiC |
| Roger Brewer | Lockheed Martin | SiC |
| Stephanie Butler | Texas Instruments | SiC, GaN |
| Thomas Byrd | Lockheed Martin | GaN |
| Julia Casadonte | PowerAmerica | SiC |
| Jeffrey Casady | Wolfspeed / Cree | SiC |
| Bill Castro | Lockheed Martin | SiC |
| Adrian Day | PowerAmerica | SiC |
| Keith Evans | Power Electronics Industry Collaborative | GaN |
| David Fanning | Lockheed Martin | GaN |
| Mehdi Ferdowsi | InnoCit LLC | SiC |
| John Gilligan | North Carolina State University | GaN |
| Neil Goldsman | CoolCAD Electronics LLC | SiC |
| Pawel Gradzki | Booz Allen Hamilton | GaN |
| David Grider | Wolfspeed / Cree | SiC |
| Allen Hefner | NIST | SiC |
| Collin Hitchcock | Rensselaer Polytechnic Institute | GaN |
| Doug Hopkins | North Carolina State University | GaN |
| Ryan Kennedy | Atom Power | SiC |
| Rakesh Lal | Transphorm | GaN |
| Bongmook Lee | North Carolina State University | SiC |
| James LeMunyon | PowerAmerica | SiC |
| Valri Lightner | Adv. Manufacturing Office, Department of Energy | SiC |
| Tim McDonald | Infineon Technologies | GaN |
| Roger McGinnis | Florida State University | SiC |
| Ginny Moser | North Carolina State University | SiC |
| Iulian Nistor | ABB Inc., Corporate Research | SiC |
| Ty Parks | Lockheed Martin | GaN |
| Ed Pascasio | X-Fab Texas | SiC |
| Manyam Pilla | Qorvo | GaN |
| Gregory Romas | Lockheed Martin | SiC |
| Nitesh Satheesh | AgileSwitch, LLC | SiC |

| Name | Affiliation | Breakout Group |
|---|---|---|
| Pourya Shamsi | Missouri S&T | GaN |
| Gene Sheridan | Navitas Semiconductor | GaN |
| Brij Singh | John Deere | SiC |
| Ranbir Singh | GeneSiC Semiconductor Inc. | SiC |
| Srdjan Srdic | North Carolina State University | SiC |
| Rogelio Sullivan | PowerAmerica | SiC |
| Victor Veliadis | PowerAmerica | SiC |
| Jin Wang | Ohio State University | SiC |
| Andy Wilson | X-FAB Texas, Inc. | SiC |
| Wensong Yu | North Carolina State University | SiC |

## Interviewed Subject Matter Experts

| Name | Affiliation |
|---|---|
| Sujit Banerjee | Monolith Semiconductor |
| James Fiorenza | Analog devices |
| Wayne Johnson | IQE |
| Dan Kinzer | Navitas Semiconductor |
| Peter Moens | ON Semiconductor |
| Brij Singh | John Deere |

## Surveyed Subject Matter Experts[1]

| Name | Affiliation |
|---|---|
| Kevin (Hua) Bai | Kettering University |
| Jayant Baliga | North Carolina State University |
| Tom Byrd | Lockheed Martin |
| Jeffrey Casady | Wolfspeed |
| David Fanning | Lockheed Martin |
| Mehdi Ferdowsi | InnoCit LLC |
| Douglas Hopkins | North Carolina State University |
| Sung Joon Kim | Global Power Technology Group |
| Dan Kinzer | Navitas Semiconductor |
| Iulian Nistor | ABB |
| Bruce Odekirk | Microsemi |
| Tyrel Parks | Lockheed Martin |
| Brian Peaslee | General Motors |
| Lal Rakesh | Transphorm |
| Gregory Romas | Lockheed Martin |

[1] Experts who were unable to participate in the interview contributed their insights through the online survey.

## Appendix B. Acronyms

| | |
|---|---|
| **2DEG** | Two-dimensional Electron Gas |
| **AC** | Alternating Current |
| **ACRMS** | Alternating Current Root Mean Square |
| **AECQ** | Automotive Electronics Council Qualification |
| **AlN** | Aluminum Nitride |
| **ARPA-E** | Advanced Research Projects Agency–Energy |
| **BOM** | Bill of Materials |
| **BPD** | Basal Plane Dislocation |
| $C_{gs}$ | Gate-source Capacitance |
| **CMOS** | Complementary Metal Oxide Semiconductor |
| **DC** | Direct Current |
| $E_{AS}$ | Avalanche energy |
| **EMC** | Electromagnetic Compatibility |
| **EMI** | Electromagnetic Interference |
| **E-mode** | Enhancement-mode |
| **EV** | Electric Vehicle |
| **FET** | Field-effect Transistor |
| **FIT** | Failures in Time |
| **GaN** | Gallium Nitride |
| **HEV** | Hybrid Electric Vehicle |
| **HT-DLTS** | High-temperature Deep-level Transient Spectroscopy |
| **HVDC** | High Voltage Direct Current |
| **IGBT** | Insulated Gate Bipolar Transistor |
| $I_o$ | Reverse Leakage Current |
| **JBS** | Junction Barrier Schottky |
| **JEDEC** | Joint Electron Device Engineering Council |
| **LED** | Light Emitting Diode |
| $L_s$ | Source Inductance |
| **MOS** | Metal Oxide Semiconductor |
| **MOSFET** | Metal–Oxide Semiconductor Field-effect Transistor |
| **MV** | Medium Voltage |
| **OBC** | On-board Charger |
| **PE** | Power Electronics |
| **PHEV** | Plug-in Hybrid Electric Vehicle |
| **PV** | Photovoltaic |
| $Q_G$ | Total Gate Charge |
| $Q_{GD}$ | Gate-to-drain Charge |
| $Q_{oss}$ | Output Charge |
| $Q_{rr}$ | Reverser Recovery Charge |

| | |
|---|---|
| **$R_{ds\text{-}on}$** | Specific on-resistance |
| **RF** | Radio Frequency |
| **$R_{jc}$** | Junction-to-case Thermal Resistance |
| **$R_{on}$** | On-resistance |
| **SBD** | Schottky Barrier Diode |
| **SC** | Short Circuit |
| **Si** | Silicon |
| **SiC** | Silicon Carbide |
| **SOA** | Safe Operating Area |
| **$t_f$** | Fall Time |
| **$T_{j,max}$** | Maximum Junction Temperature Rating |
| **$t_{sc}$** | Short Circuit Time |
| **$t_r$** | Rise Time |
| **UIS** | Unclamped Inductive Switching |
| **UPS** | Uninterruptible Power Supply |
| **$V_f$** | Forward Voltage Drop |
| **$V_{gs}$** | Gate to Source Voltage |
| **VSC** | Voltage Source Converter |
| **$V_{Th}$** | Threshold Voltage |
| **WBG** | Wide Bandgap |

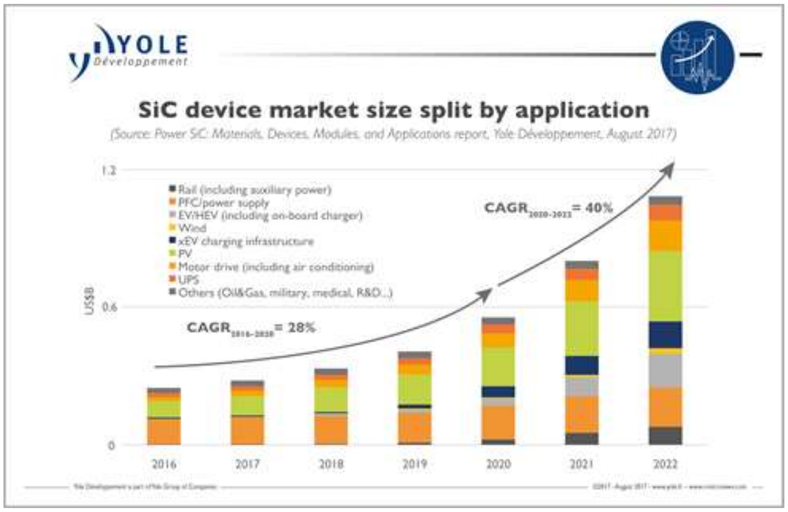
## Appendix C. Application-Specific Performance Targets

Application-specific performance target tables are presented in the following pages. This information is made available to PowerAmerica members only.

## Appendix D. Device Cost Projections

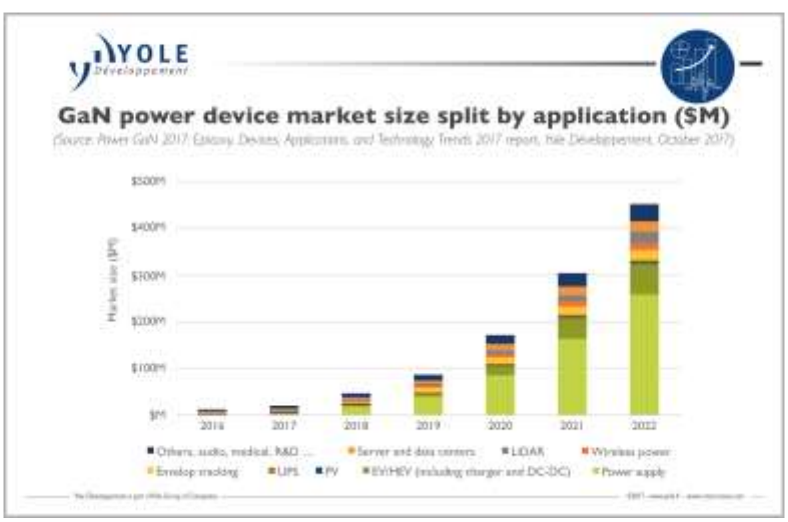
This publicly available information on SiC and GaN device cost is provided as a complement to the technical information contained in this roadmap. These cost projections show aggressive growth over the next four years and agree with forecasts obtained from other sources regarding the Si market. As the global economy continues to grow and the business climate improves due to new tax and fiscal policies, we can expect that the PowerAmerica goals for US job creation, technology advancement, and global competitiveness will benefit.

**For SiC power devices:**




The market for SiC devices is projected to exceed $1B by 2022. It is currently dominated by the PV market, followed closely by power factor correction/power supply applications. The market shares of EV charging infrastructure and on-board chargers is projected to increase significantly after 2020. The voltage ratings for the above applications are 600 V to 1.7 kV, and the current rating for above devices generally requires >100A per single chip.

**For GaN power devices:**



The market for GaN devices is projected to exceed $400M by 2022. The largest market for GaN power devices is power supplies.  The devices are generally <650 V with <15 A current rating, operating at high frequency. The power supply application is expected to continue to dominate the GaN market, with EV systems being the next largest application.