Quadrennial Technology Review 2015

Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing

Technology Assessments

U.S. DEPARTMENT OF ENERGY

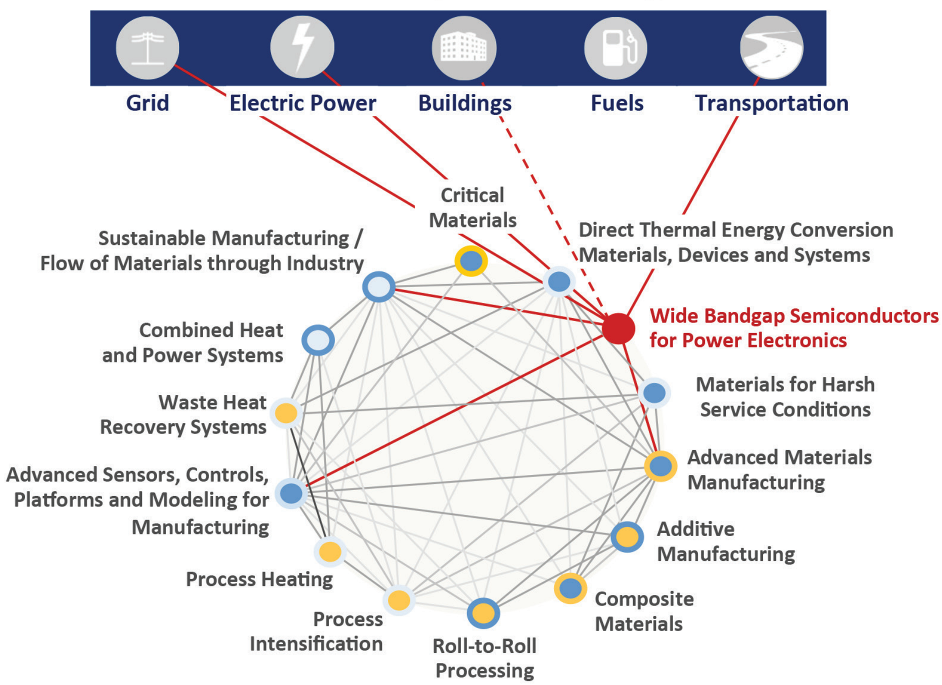
Quadrennial Technology Review 2015

Wide Bandgap Semiconductors for Power Electronics

Chapter 6: Technology Assessments

NOTE: This technology assessment is available as an appendix to the 2015 Quadrennial Technology Review (QTR). ***Wide Bandgap Semiconductors for Power Electronics*** *is one of fourteen manufacturing-focused technology assessments prepared in support of Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. For context within the 2015 QTR, key connections between this technology assessment, other QTR technology chapters, and other Chapter 6 technology assessments are illustrated below.*

Connections to other QTR Chapters and Technology Assessments



Representative Intra-Chapter Connections	Representative Extra-Chapter Connections
■ **Sustainable Manufacturing:** smaller-footprint electronics with reduced cooling requirements ■ **Advanced Sensors, Controls, Platforms, and Modeling for Manufacturing:** variable frequency drives and motor speed control ■ **Advanced Materials Manufacturing:** low-cost, commercial-scale production methods for wide bandgap devices	■ **Grid:** solid state transformers for power flow control; inverters for renewable energy ■ **Electric Power:** inverters for photovoltaic and wind power systems ■ **Buildings:** variable speed drives for HVAC systems; AC-to-DC and DC-to-AC adapters ■ **Transportation:** Power electronics for electric vehicles

Introduction to the Technology/System

The field of power electronics focuses on the use of solid-state electronic devices for the conversion, control, and processing of electricity and electric power. Silicon (Si) semiconductors have traditionally been employed in fabricating these power circuits. However, as devices and equipment evolve and become more powerful, existing Si power electronics are losing the ability to keep pace with increasing performance demands. This is primarily attributed to the fact that traditional Si device technology has matured to a point where it is pushing the fundamental limitations of this material system.

Wide bandgap (WBG) semiconductors have shown the capability to meet the higher performance demands of the evolving power equipment, operating at higher voltages and temperatures and enabling switching frequencies with greater efficiencies compared with existing Si devices. Along with performance improvements, WBG-based power electronics can be fabricated with a much smaller footprint (reduced volume) compared with comparable Si devices due to decreased cooling requirements and smaller passive components, contributing to overall lower system costs.

Reducing energy consumption is critical to U.S economic, environmental, and security interests. In 2014, U.S. industrial plants accounted for 955 billion kWh of electricity consumption—over a quarter of end-use electrical consumption in the United States.[1, 2] It is projected that this consumption will grow by 26% to 1270 billion kWh between 2014 and 2040.[3] Motors and generators are critical in industrial applications, driving equipment such as fans, pumps, compressors, and conveyer systems. To that end, increasing the efficiency of power electronics is imperative. The use of WBG semiconductors in variable frequency drives (VFDs) controlling these machines can result in significant levels of energy reduction as well as enabling substantial decreases in the weight and volume of the drive electronics. For example, one estimate stated that the heat sink size for the variable speed drive of a 10 horsepower (hp) industrial electric motor could be reduced by 66% if WBG-based power electronics were used.[4] Other applications where WBG power electronics could achieve appreciable energy savings include hybrid and electric vehicles, lighting, data servers, AC adapters, solar inverters, power supplies, charging circuits, and grid control.[5] Energy savings opportunities are quantified for many of these applications in the *Case Studies* at the end of this technology assessment.

Two major WBG materials with the potential to enable significant advances in power electronics are silicon carbide (SiC) and gallium nitride (GaN). To date, the predominant use of SiC in electronics is as a substrate for GaN light emitting diodes (LEDs). While SiC currently has limited use in power electronics, its role is expected to grow as it becomes the prevailing WBG replacement for Si in applications requiring device ratings in excess of 600 volts.[6] A major challenge to widespread adoption of SiC power electronics devices is the high cost of substrates and epitaxial materials. These high costs are tied to small production volumes and high manufacturing costs. Significant markets are expected for SiC devices in hybrid and electric vehicles as well as solar inverters and power supplies. SiC diodes are already used with companion Si transistors in photovoltaic (PV) inverters and hybrid vehicle chargers. Their greatest revenue-generating applications are expected to be in industrial motor drives[7] and hybrid and electric vehicles.[8]

GaN is currently widely used in LEDs and radio frequency (RF) amplifiers, and its emergence in power electronics is relatively recent.[7] Challenges for GaN-on-Si semiconductors, the current most cost-effective method for fabricating GaN power devices, are mostly related to their lack of maturity. Issues include overcoming material challenges, such as the high lattice strain at the GaN and Si interface owing to mismatches in the coefficient of thermal expansion. GaN high-electron-mobility transistors (HEMTs) are expected to be the dominant WBG semiconductor replacement for Si in applications requiring device ratings less than 600 volts,[6] whereas impacts have already been realized in RF and power-supply applications.[7]

There is much discussion about how the high frequency capabilities of WBG semiconductors might benefit imaging and sensing devices[9] or how smaller WBG LEDs might improve minimally invasive surgical probes, among other applications.[10] For example, magnetic resonance imaging (MRI) equipment generates significant noise because the gradient coil vibrates due to the Lorentz force. GaN-based devices could enable MRI systems to operate at higher frequencies, thereby reducing noise. These innovations are also targeted to save space by integrating the control equipment, which is currently placed in a separate room, into the MRI system.

The size reductions made possible by WBG devices could also enable a wider array of implantable medical devices. For cutting and coagulation of tissue in electrosurgical units, GaN-based devices can be used at higher frequencies of 500,000 to 3,000,000 Hz.[11] This is important to minimize nerve and muscle stimulation, which occurs at electrical frequencies below 10,000 Hz.[12] In addition, an exciting area has been in devices that power themselves through energy harvesting, such as self-powering pacemakers.[13] The improved efficiencies that WBG power electronics allow could mean that devices with even higher power requirements could eventually be made to last longer and be more compact by eliminating the need for batteries.

Currently, the United States is among the leading countries developing WBG technologies. Retaining and strengthening the WBG industry have been deemed priorities by the U.S. government for energy savings, economic development, and national security reasons.[14, 15] As such, there is a great deal of momentum behind public/private partnerships in this space. One major federal investment is in the Next Generation Power Electronics National Network for Manufacturing Innovation Institute (PowerAmerica), led by North Carolina State University.[16, 17] PowerAmerica was announced in January 2014, with a stated goal of making WBG power electronics cost-competitive within five years. Previously, progress had been made over the past 20 years in the material quality of SiC substrates, SiC epitaxy, and GaN/SiC and GaN/Si epitaxy with Department of Defense funding. PowerAmerica is, therefore, focusing its activities on device manufacturing, WBG-specific power module development, and electronics to leverage the attributes of WBG devices rather than on fundamental materials work. Individual states are also showing growing interest in investing in this area of research. For example, New York is supporting the New York Power Electronics Manufacturing Consortium (NY-PEMC), which is a partnership of over 100 private companies, including General Electric (GE) and IBM.

Going forward, the most important function of public/private partnerships will be to establish a technology and business development ecosystem for continued advancement of the WBG power electronics industry.

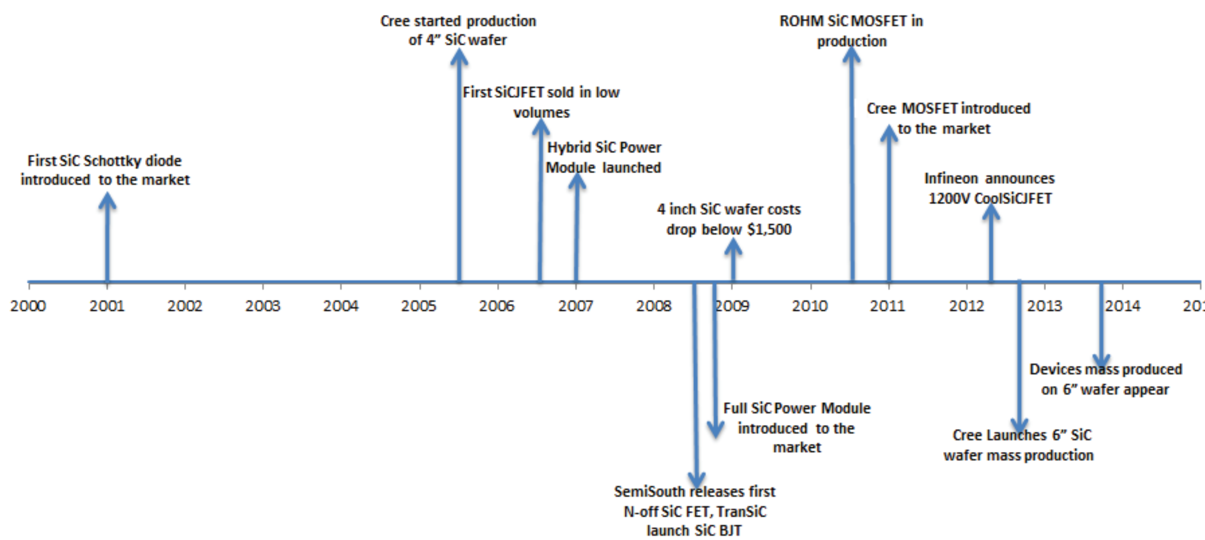
Technology Assessment and Potential

Performance Advances in SiC

SiC power semiconductors are a relatively new entrant in the commercial marketplace, with the first SiC Schottky diode introduced in 2001.[7] This milestone and others in the history of SiC power electronics are noted in Figure 6.N.1. Despite the relatively recent emergence of SiC power devices, significant advances have been made. Six-inch SiC wafers are currently in production—they were first announced by Cree, Inc., in August 2012[18]—though they are not yet commonly used to produce power electronics devices. Wafer quality has also improved. The most common defects in SiC wafers have historically been "micropipes," which are crystallographic defects resulting from the propagation of screw dislocations through epitaxial layers during wafer growth. The densities for these defects were in the range of 5–10/cm^2 in 2006,[19] improving to 0.75/cm^2 in 2014.[20] Japanese manufacturer Showa Denko has claimed even lower defect densities of 0.25/cm^2 in their six-inch wafers, announced in September 2014.[21]

Figure 6.N.1 Milestones in SiC Power Electronics Development[7]

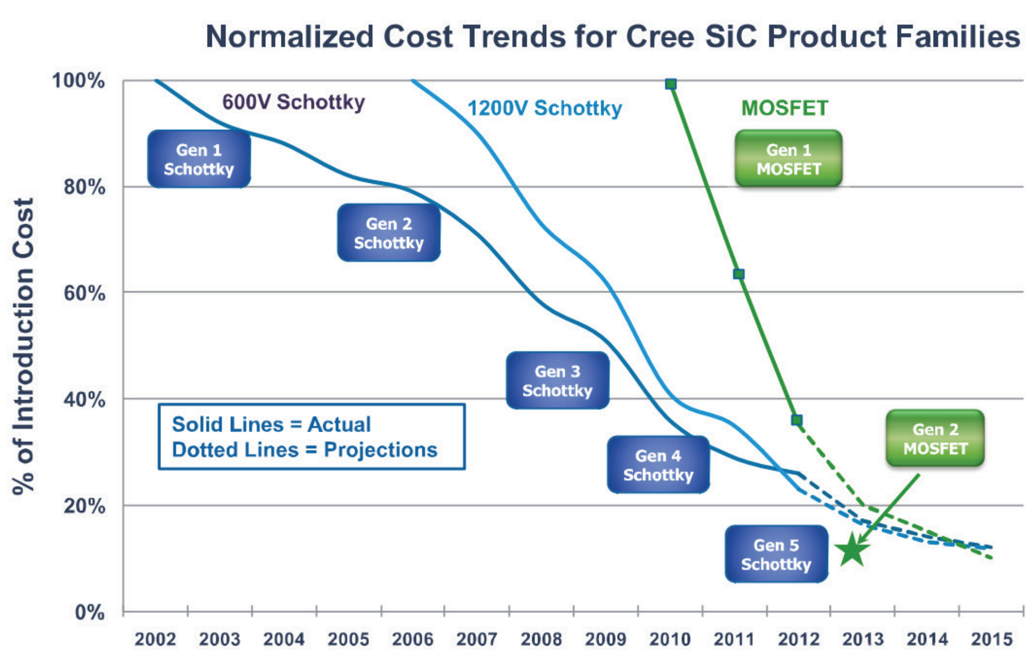
Credit: IHS Technology (http://technology.ihs.com): *The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors* - 2013 Edition



In part because of improvements in wafer fabrication and production volume increases, device costs have declined dramatically since the first SiC Schottky diode was produced from a $5,000, two-inch wafer. Four-inch SiC wafers have decreased in price from $1,200–$1,400 in 2009 to $600–$750 in 2012.[4] This time span also saw SiC power device sales more than triple.[8] Figure 6.N.2 shows the impact of these changes on the price of Cree, Inc., devices, from their introduction through 2012.[4]

Figure 6.N.2 Decline of Device Cost for Cree, Inc., SiC Products Over Time[4]

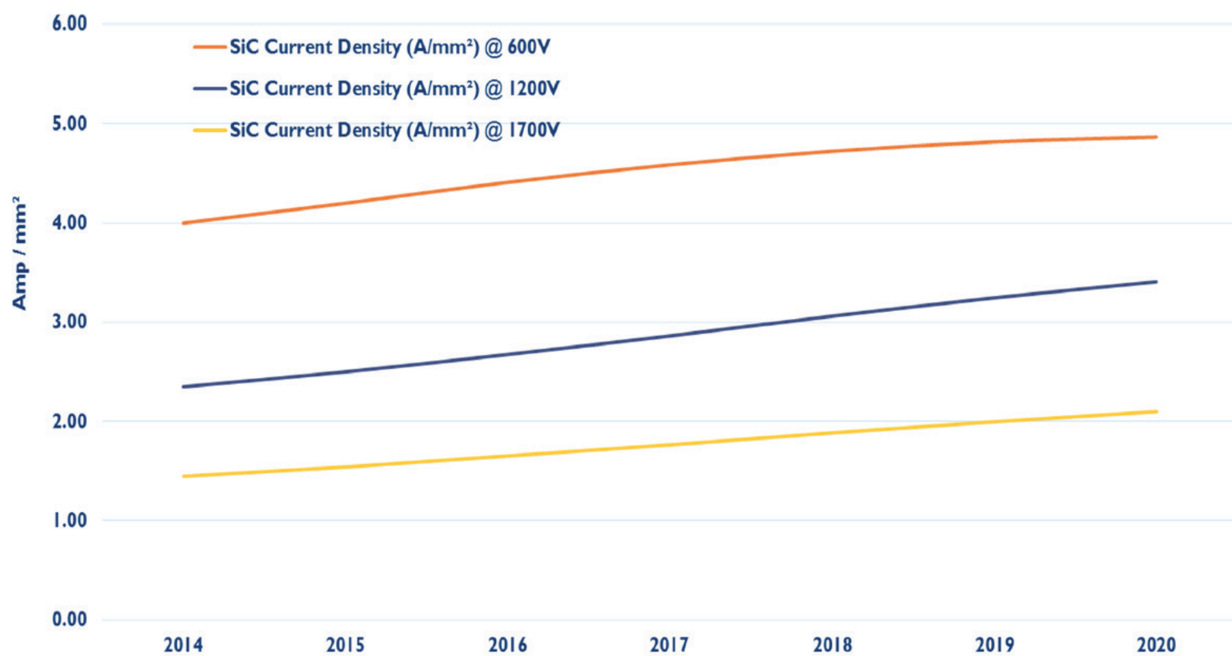
Credit: Cree, Inc.



SiC device performance has also improved: in 2010, a 1200-Volt SiC device from Cree had an average current density of 1.2 A/mm^2; [22] in 2014 this had risen to 2.3 A/mm^2. [23] Growth projections for SiC devices are shown in Figure 6.N.3. A steady increase in current density is expected to continue through 2020 for high voltage devices, while current density growth in low voltage devices is projected to slow in the latter part of the decade. Schottky diodes are currently available with current ratings up to 50 amps, while 25 amps was the highest available in 2005.[24] Also, pronounced improvements in performance have occurred between subsequent generations of SiC power metal-oxide-semiconductor field-effect transistors (MOSFETs). For example, energy switching losses for 1,200V MOSFETs decreased by 28% from 0.78 mJ to 0.56 mJ during the 2011–2013 time frame.[4] Such performance improvements have been made possible through material developments.[25]

Figure 6.N.3 Forecast of SiC Device Average Current Density Through 2020[26]

Credit: Yole Developpement



As SiC power electronics mature, technological advances will increasingly be driven by companies within the value chain, and device manufacturers will be key players. Table 6.N.1 lists the leading SiC power electronics device companies in terms of 2010 revenues.[8] The $53 million SiC power electronics market in 2010 was led by two companies—Germany-headquartered Infineon (51% market share) and U.S. headquartered Cree, Inc. (37% share).[8] Both companies' SiC fabrication facilities are located in the developed world—Infineon in Villach, Austria; and Cree, Inc., in Durham, North Carolina. In 2010, SiC power electronics were manufactured primarily in Europe (54%), the United States (41%), and Japan (2%). The distribution of market share is expected to change radically by 2020, at which time Japan is expected to have a 35% market share as a result of heavy industry and government investment.[27] Toyota has recently announced the beginning of on-road testing of SiC-power semiconductors in a Camry hybrid prototype and a fuel cell bus.[28] These tests will evaluate the performance of SiC technology, which could lead to significant efficiency improvements in hybrids and other electric-drive vehicles.

Table 6.N.1 Distribution of 2010 SiC Power Electronics Device Revenues by Company and Fabrication Location[8]

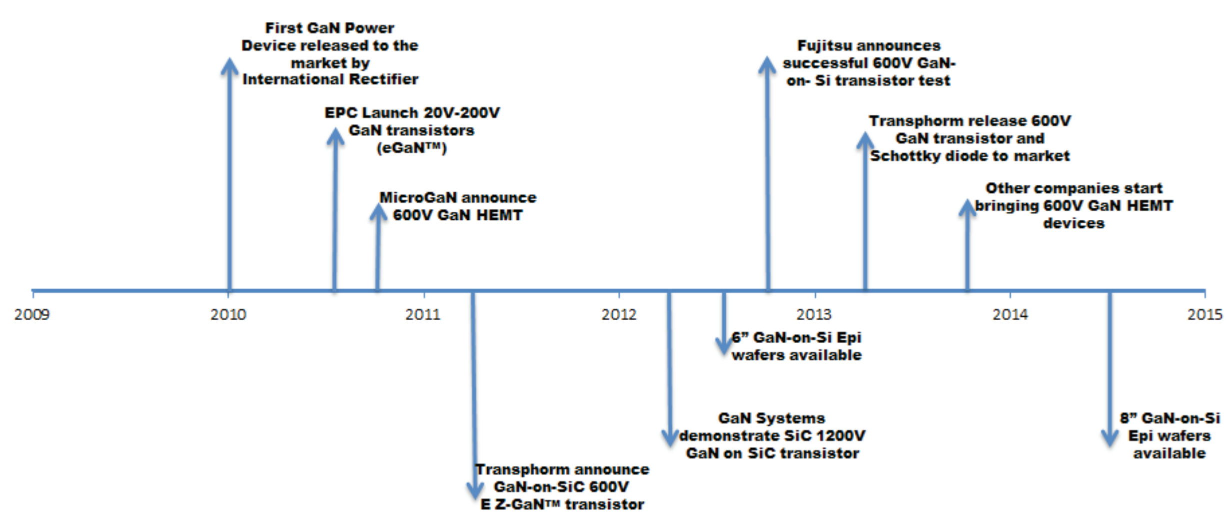
Company	2010 SiC Power Electronics Revenue ($, millions)	Headquarters	Fabrication Location
Infineon	$27.1	Germany	Villach, Austria
Cree, Inc.	$19.7	U.S.	Durham, NC, U.S.A
STMicroelectronics	$1.6	Switzerland	Catania, Italy
ROHM	$1.1	Japan	Fukuoka, Japan and Miyazaki, Japan
All others	$3.7		
Total	**$53.2**		

Performance Advances in GaN

GaN power electronic devices are an even more recent innovation than SiC devices. The advancement in GaN for power electronics in the last decade has been characterized not by iteration on existing products but by a move from microwave applications with low-voltage requirements to low-cost lateral power devices with higher breakdown voltages.[29] These devices are the result of significant public and private research activities focusing on the development of GaN transistors on Si substrates. This work culminated in the announcement of the first GaN-on-Si HEMT by International Rectifier in 2010. International Rectifier's announcement was quickly followed by a public device release from Efficient Power Conversion Corporation (EPC). These milestones and others are shown in Figure 6.N.4. One of the developments that made this shift possible was the improvement in GaN-on-Si epitaxy techniques.[7] The new technique allows for the creation of epitaxial material with slightly inferior properties, but at orders of magnitude lower cost than GaN on bulk SiC or GaN epitaxies: reported costs were $100 for a four-inch Si wafer for GaN epitaxy, as opposed to $3,130 for a four-inch high performance SiC wafer or $7,500 for a GaN wafer for GaN epitaxy.[29]

Figure 6.N.4 Milestones in GaN Power Electronics Development[7]

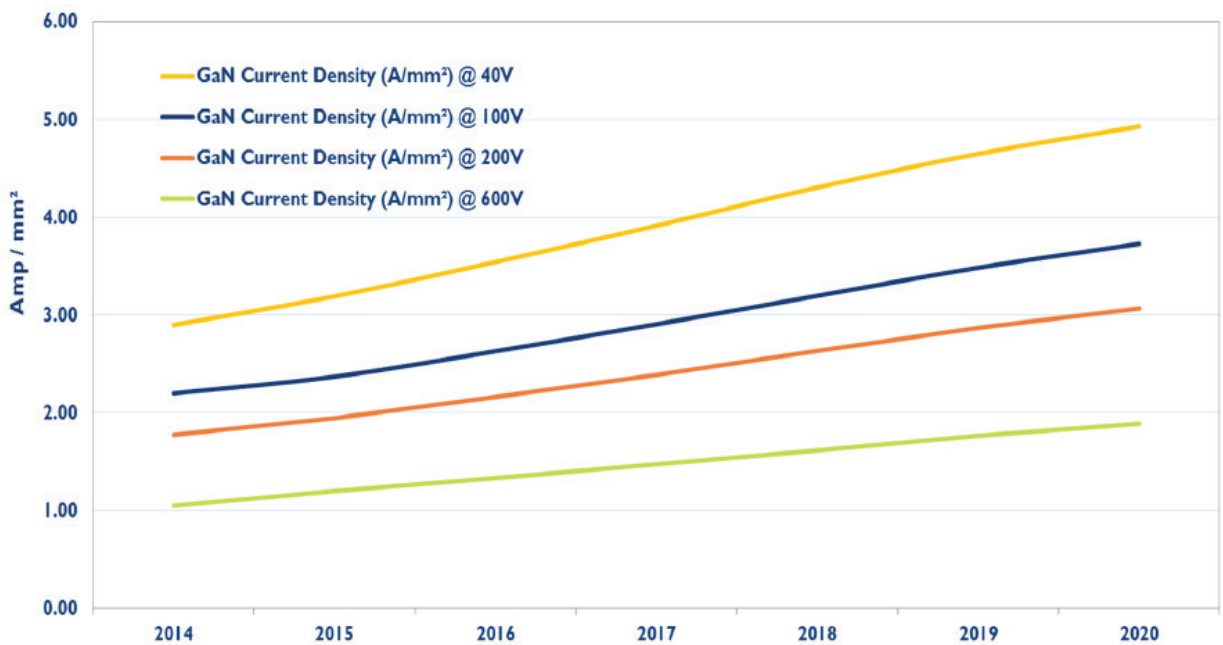
Credit: IHS Technology (http://technology.ihs.com): *The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors* - 2013 Edition



Average current density for GaN devices is expected to increase over the next several years, as shown in Figure 6.N.5.[23] Recent GaN advances include the move to larger GaN-on-Si epitaxial wafers. Eight-inch wafers have been demonstrated,[30] and gate injection transistors (GITs) have been developed to complement traditional HEMT devices in the GaN power electronics space. GITs are well suited to the higher end of the GaN transistor voltage range, with some of the first devices rated for 600 V.

Figure 6.N.5 Forecast of GaN-on-Si HEMT Device Average Current Density Through 2020[26]

Credit: Yole Developpement



In the private sector, a majority of the companies that have brought GaN devices to market are based in the United States. Table 6.N.2 shows the development stage and product focus for companies involved with GaN research.[31] Of the five companies that had products on the market in 2013, four (all except MicroGaN) were based in the United States. Three of the companies—EPC, Transphorm, and MicroGaN—are primarily focused on GaN for power electronics. Many major companies have GaN devices in development, including traditional Si-focused device companies such as Texas Instruments and Panasonic.

Table 6.N.2 Development Stages and Product Types for Companies Involved in GaN Power Electronics[31]*

Vendor	Products		Technology	Development		Product Types		
	Open market	Closed market	Foundry services	Collaborative	In-house	Discrete	IC	Module
IRF		●				●		●
EPC	●					●		
Transphorm		●				●		●
Fujitsu					●			
Sanken					●	●	●	
MicroGaN		●	●			●		
Infineon					●	●		
HRL					●	●		
Panasonic					●	●	●	
STM					●	●	○	
RFMD		●	●			●		
Toshiba					●	●		
GaN Systems					●	●		
NXP				●		○		
TI					●	●	●	
Freescale					●	●	○	
Powdec					●	●		
Renesas					●	●		
Furukawa					●	●		
POWI					●		●	
ON Semi				●		●	○	
Intersil				●	●		●	
Alpha & Omega					●	●		

*Note: Filled circles indicate actual production of products and product types (as of Dec. 2012); open circles indicate future potential.

Technology Needs

The greatest challenge to the adoption of WBG components in power electronics is their high cost. Substrate materials account for 30%–50% of the cost of an SiC device, while traditional Si-based power device substrates account for only 5%–7%.[7] However, it is possible to achieve higher currents in a SiC wafer compared to the same size Si wafer because of the lower specific on-resistance of the SiC devices. Therefore, although SiC substrates and epitaxial layers are currently more expensive than Si, they can still compete with Si devices costs on a cost/area basis. Issues such as localized heating and parasitic current leaking in the vicinity of impurities and crystal defects (exacerbated at high currents) must be addressed to take full advantage of SiC's low specific on-resistance.[32]

In the case of SiC, cost reduction can be realized through high-volume processing of wafers. PowerAmerica is working to lower upfront costs of WBG power electronics by investing in a commercial foundry model.[33] This will allow small "fabless" companies to enter the market, develop improved device processing steps, and produce devices at lower costs. Such a model could play a foundational role in the rise of WBG semiconductors in the same way that the Metal Oxide Semiconductor Implementation System (MOSIS) did for Si integrated circuits (ICs).[34] These small fabless companies would then rely on pure-play semiconductor foundries that do not offer IC products of their own design, but instead operate semiconductor fabrication plants focused on producing ICs for other companies.[35]

Material quality still remains an area for improvement. SiC MOSFETs are by far the most prominent WBG switching devices used today, but they are limited by metal-oxide-semiconductor interface quality issues. Problems with the interface can lead to variability in threshold voltages as well as low device reliability. This has led to the limited adoption of SiC junction gate field-effect transistors and bipolar junction transistors compared to SiC MOSFETs, which otherwise would have been the preferable solution.

Because of the relatively low cost of power electronics-grade Si substrates, substrate cost is not a great concern for GaN-on-Si devices, but there are efforts underway to decrease costs further. One mechanism would be to reduce the thickness of eight-inch Si wafers to around 0.027 inches (675 microns). This would allow GaN-on-Si wafers to be processed on existing complementary metal-oxide semiconductor (CMOS) IC production lines, avoiding the need for new production equipment. GaN-on-Si epitaxial layers are currently more expensive and may be lower quality than GaN-on-SiC epitaxial layers, but it is expected that this will be addressed over time as manufacturing volumes increase.

The application of GaN on Si substrates necessitates a nucleation layer for GaN crystal growth—typically aluminum nitride (AlN).[36] Cost-effective growth of high-quality nucleation layers is difficult because a pre-reaction between the gases used to deposit the nucleation layer at high pressure leads to a trade-off between growth rate and quality.[37] Moreover, interfacial charges between AlN and adjacent materials can prevent normally off device operation.[38] The primary issue with the acceptance of GaN lateral devices is the fact that they are generally normally on, which means the devices are conducting when the gate is grounded. This is not acceptable to the power electronics industry at large. A cascode circuit configuration with a Si low-voltage MOSFET solves this problem but results in extra switching losses, making it difficult to operate at very high switching frequencies; this can negate the primary advantage of GaN devices. A true GaN enhancement mode transistor is needed, with a threshold voltage of 3–4V and >10V gate voltage operation. A limited offering of enhancement mode devices is available from select vendors. These devices generally have approximately 30% higher specific on resistance compared to normally on devices. This reduces their net efficiency advantage over normally on devices. The use of a gate dielectric necessary to achieve enhancement mode operation also leads to instabilities that are currently being addressed by researchers.

GaN power device research needs include techniques to address the high strain in the GaN layers due to GaN's crystal lattice mismatch with Si. GaN's low thermal conductivity in comparison with SiC also needs to be addressed in order to better characterize the temperature limits of high performance GaN devices.[7] If the price of bulk GaN wafers were sufficiently reduced, vertical device architectures could be utilized as opposed to lateral devices with GaN-on-Si. Vertical devices would allow GaN to be used in higher power applications above 100 kW.[39] It is anticipated that over the next few years the rapidly increasing demand for LED lighting solutions will help drive down the cost of GaN wafers.

According to Shenai,[40] though horizontal GaN devices have excellent theoretical performance characteristics, power devices with this architecture are vulnerable to surface breakdown and are difficult to scale to high voltages or currents. Vertical GaN devices are therefore necessary for applications with voltages above roughly 600 V. Research and characterization efforts needed to enable new techniques for producing GaN substrates include studies of the relationship between dislocation density and leakage current with GaN substrates produced through the sodium flux method.[41] Progress in vertical GaN power devices could be aided by progress in vertical GaN LED research and development (R&D), as vertical architectures have been embraced for LEDs due to better current spreading and heat dissipation behavior.[42] Vertical GaN R&D has also produced significant accomplishments in high voltage power electronic devices, including vertical GaN transistors with blocking voltages of 1.6 kV and vertical Schottky diodes with blocking voltages of 2 kV.[43]

Advancements toward vertical GaN devices have been recognized as important by the Department of Energy (DOE) Advanced Research Projects Agency-Energy (ARPA-E). Research into the materials and manufacturing processes necessary for these devices figures prominently in the agency's "Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems" (SWITCHES) program. SWITCHES is a $27 million program announced in October 2013 and is funding 14 projects, involving universities, national laboratories, and private companies.[44] Projects focused on vertical GaN technology within this program include partnerships led by the University of California, Santa Barbara, with Arizona State University, Transphorm, and the U.S. Naval Research Laboratory;[45] Avogy in collaboration with ABB, North Carolina State University, Oak Ridge National Laboratory (ORNL), and Soraa; and several others involving Columbia University, HRL Laboratories, and SixPoint Materials.[45] Transphorm and Fujitsu Semiconductor have recently announced the start of mass production of Transphorm's GaN power devices for switching applications.[46] The start of mass production in a CMOS IC production line is a significant step forward toward achieving the widespread use of GaN power devices.

The rest of the circuit is also critical to the large-scale implementation of more efficient WBG power systems as a result of their ability to operate at high frequency, specifically the magnetic systems. While WBG semiconductors can easily switch high voltages and currents at MHz frequencies, the transformers and inductors have much higher losses at those frequencies. New circuit designs, better soft magnet alloys, and alternate transformer designs are all potential areas for development.

Long-term reliability data is also needed to gain marketplace acceptance for both SiC and GaN power electronics devices. Fundamental reliability research at the device level needs to be performed as well as new packaging methods developed that will allow WBG devices to operate at their full potential. The only commercial WBG power devices with more than 10 years of market performance are SiC Schottky diodes. As such, they are the only devices with proof of their reliability on the scale required for high-end applications. Standardization of tests to ensure greater reliability for new transistor designs will be useful, but large-scale adoption will not occur until lifetimes in excess of 10 years can be conclusively proven in demanding applications.

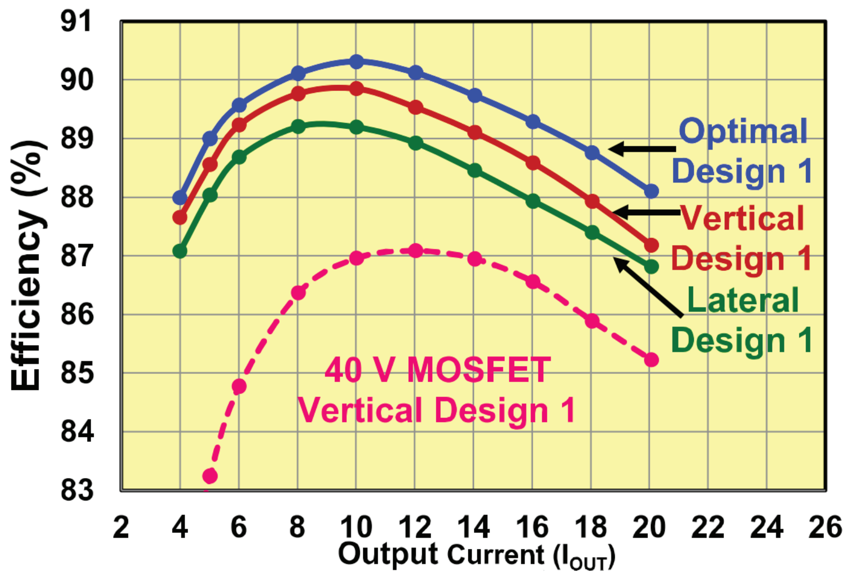
System Integration Needs

For both SiC and GaN power electronics devices, their benefits will not be fully realized if they are treated as drop-in replacements for Si devices. Instead, packaging techniques and circuit designs are needed that optimize their properties, resulting in minimization of size and costs of cooling and auxiliary circuit components.

At the power module level, there is a need for new materials and packaging methods to enable and capture the benefits of the higher temperature capabilities of WBG power devices. Higher power and temperature operation will necessitate robust bonding mechanisms for both the dies and module substrates that can withstand repeated power and temperature cycling. Higher switching frequencies introduce new concerns at both the power module and board levels. Parasitic inductances and resistances can result in significant power losses when the circuit is switched at high frequencies.[47] Attention to the minimization of parasitic properties can also significantly decrease voltage and current overshoots, reducing electromagnetic interference (EMI) filter requirements, circuit volume, and cost. Figure 6.N.6 shows the effect of parasitic inductance for a 12 V to 1.2 V buck converter circuit with two EPC enhancement-mode GaN field-effect transistors (EGaN FETs) operated at 1 MHz by comparing the efficiency of an optimized layout to more traditional vertical or lateral circuit designs.

Figure 6.N.6 Efficiency Impact of Board Design to Avoid Parasitic Inductance[47]

Credit: Efficient Power Conversion Corporation



At the system level, the use of WBG devices can significantly reduce cooling requirements. Reducing the size of heat sinks, radiators, pumps, and piping can result in cost savings from both a materials and manufacturing perspective as well as ancillary power savings, translating to higher system-level efficiency.

The key motivation for leveraging the frequency increase facilitated by WBG semiconductors use is miniaturization, integration, and improved performance (bandwidth). Passive energy storage components (especially magnetics) are the dominant constraints. Magnetic core materials largely impact frequency scaling; however, integration/batch fabrication of passive components imposes further challenges.

Though high-frequency operation can improve system performance in a number of ways (reduced equipment size, reduced losses in magnetic components, etc.), it is challenging to achieve high power conversion efficiencies at frequencies higher than 500 kHz in conventional discrete systems because of large losses in the long interconnects and parasitic inductance from their long bond wires. It is also challenging in conventional discrete systems to use high external current gate drivers due to high gate drive losses. Although this suggests that progressively moving into integrated inductors could be advantageous, there are currently several challenges in inductor integration, such as the fact that integrated air core inductors typically do not have sufficient inductance to meet circuit requirements in the limited volume available from the device geometry.

The production of integrated inductors with magnetic cores may require high-temperature processing such as the co-fired ceramic process, but the high temperatures in these processes could damage the fabricated device with the integrated power electronics.

Potential for Improvements

There is opportunity for reduction in the price of WBG power electronic devices. An IHS market report from 2013 forecasted average prices for different WBG devices.[7] SiC Schottky diodes rated at 20A, used for industrial motor drives, are expected to decline in price from about $0.22/A in 2014 to $0.10/A in 2022. SiC MOSFET prices for similar applications are expected to decline in price from about $0.96/A to $0.55/A, and GaN transistors are expected to decline in price from about $0.35/A to $0.12/A. The fabless foundry model that PowerAmerica is pursuing could play a key role in achieving these cost reductions.

Currently, a dedicated foundry requires a $100–$200 million investment and cannot become profitable unless fully loaded with, for example, at least 10,000 wafer starts a month. Because the present demand for WBG devices is low (approximately 100–200 wafer starts per month), the investment in a dedicated foundry cannot be justified.

The idea of using an established Si commercial foundry for the manufacture of WBG devices was proposed by DOE[48] and is the concept currently being implemented by PowerAmerica. Because approximately 90% of the processes involved with the manufacture of WBG devices are similar to Si processes, processing costs can be significantly reduced by using idle time in the Si foundry for WBG fabrication runs. This also takes advantage of existing equipment and reduced overhead costs of a commercial foundry. The remaining 10% of processes that are unique to WBG manufacturing can be implemented at a cost of roughly $10 million.[49] The commercial foundry approach will then have the potential to provide a fabless model to many companies, universities, and laboratories. MICREL and X-Tab are the two major domestic foundries working on six-inch Si wafers today. The commercial foundry approach will facilitate innovations in designs and processes, thereby attracting new venture capital. As little as $1–$2 million investment will be required by new companies as opposed to having to invest $100–$200 million in a dedicated foundry. As more clients take advantage of the opportunities afforded by their involvement in a commercial foundry, device cost per amp will be significantly reduced due to increased aggregated volume production. Current dedicated foundries produce SiC devices (1200 V, 20 A SiC MOSFET) at roughly $0.54/A or five times the cost of Si devices ($0.10/A). Assuming substrate and epitaxial layer costs will decline at higher volumes, costs could drop to as little as $0.074/A.[50] It is projected that through technological innovations and the move to eight-inch wafers,[51] the cost of an SiC MOSFET could become competitive with the current cost of Si devices within five years.[50] Even with six-inch wafers, modest technology advancements, the commercial foundry approach, and an increase in volume can make SiC competitive with Si.

GaN could be a drop-in replacement for existing Si FETs, but the incremental benefit of that approach does not take advantage of the full value that GaN can offer. Instead, GaN can be used in advanced topologies, enabling higher performance, efficiency, and power density than current Si FETs. A promising area for GaN research is based on the fact that present-day GaN power devices are being developed on Si substrates. This creates the opportunity to develop high frequency GaN power transistors alongside driver ICs on a common Si substrate. In addition to lowering costs, this would address one of the major hurdles for integrating GaN into power electronic devices, which is that GaN transistors are perceived as being difficult to drive.[7] However, Si ICs for these duplexed devices would still be limited in the switching speeds they could achieve. Better GaN processing techniques would allow for the creation of GaN ICs that could reach higher switching speeds. These improved techniques could be applied to more cost-effective growth of bulk GaN wafers in order to produce vertical GaN-on-GaN devices that could be used in higher power (100 kW or greater) applications.[52]

Potential Impacts

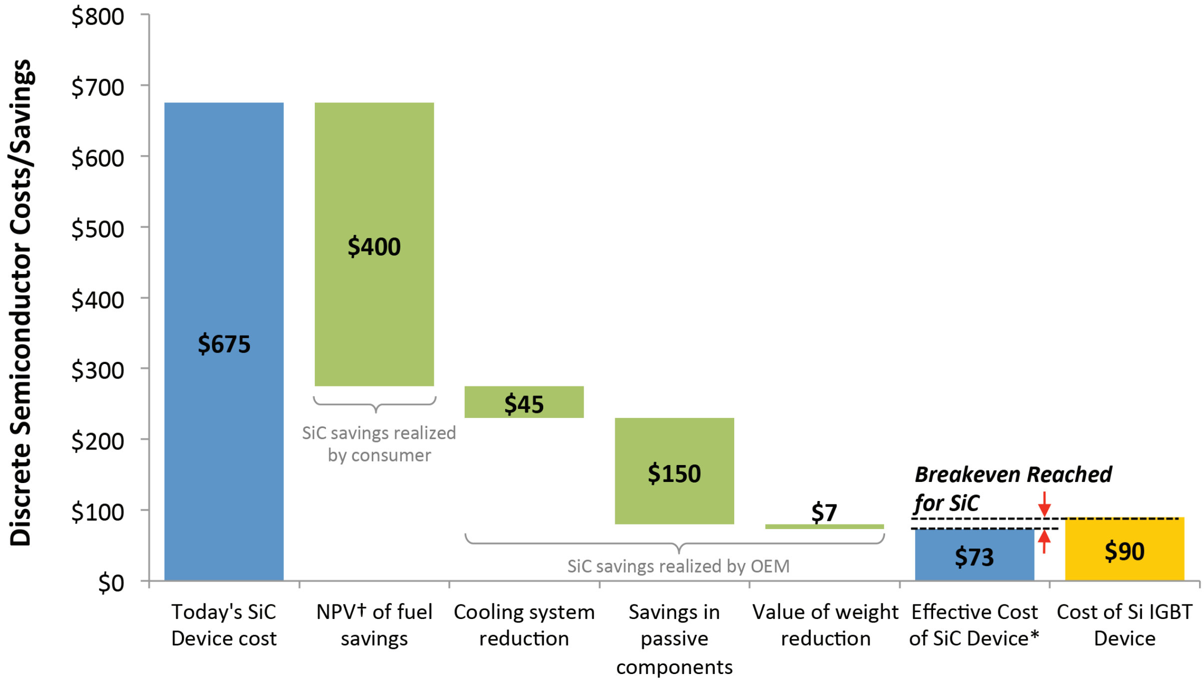
The value proposition for WBG devices consists of the following four major points:

- *Reduced energy and material costs.* Because WBG semiconductors are inherently more efficient than Si devices, less energy is expended as heat, resulting in smaller system sizes and lower material costs.
- *Higher power density (smaller volume).* Higher switching frequencies and operational temperatures than Si result in lower cooling requirements, smaller heat sinks, and reduced magnetics.
- *Higher switching frequency.* The higher switching frequencies for WBG devices allow smaller inductors and capacitors to be used in power circuits. Inductance and capacitance scale with the frequency—a 10x increase in frequency produces a 10x decrease in the required capacitance and inductance. This can result in an enormous decrease in weight and volume as well as cost. In addition, higher frequency can result in less acoustic noise in motor drive applications.[7]
- *Lower system cost.* While WBG semiconductors are generally higher cost than Si, system level cost reductions are sometimes possible through the use of WBG by reducing the size/costs of other components, such as inductive and capacitive circuit elements, filters, and cooling.

Hull[4] illustrates the first three of these points in a discussion of a 30 hp electric inverter motor where Si power electronic devices in the motor's VFD are replaced with SiC devices. The 3-phase drive uses a 1,200 V, 50 A, six transistor module. The higher cost of the WBG-based VFD in this example is recovered in 6 to 24 months, depending on the assumed per-kilowatt-hour cost of electricity. Such a payback period is acceptable when VFDs that are designed to have a life in excess of 10 years are considered. Regarding power density, Si-based VFDs for large motors occupy significant plant floor space, which could be substantially reduced with the use of WBG devices. In the motor example, the SiC solution allows for the heat sink to be reduced to one-third of its former size. A leading manufacturer of VFDs confirms that higher power density VFDs are an important value proposition for its customers.[53] Regarding switching frequency, the SiC solution allows for a motor output of 30 hp motor output power over a broad range of switching frequencies. The SiC switches could drive the motor at 30 hp for any switching frequency in the range of 8 kilohertz (kHz) up to 16 kHz. Losses prevented the Si-based VFD from driving the motor at 30 hp with frequencies of 12.5 kHz or higher. At 16 kHz switching, the motor output is limited to only 20 hp with the Si solution. Hull[4] provides an example of the fourth point, system cost reduction, with a case where the cost of a SiC-based boost converter is reduced by 20% over its Si counterpart through reduced inductor and heat sink sizes and costs.

SiC devices in hybrid vehicle motor inverters have the potential for additional impact because of their improved high-temperature properties over Si devices. In most hybrid vehicles, the inverter is near the internal combustion engine and requires a separate cooling system. If SiC devices are used in the inverter, this could allow for the inverter to be kept at a temperature nearer to the engine temperature, which would allow for the use of a single cooling system.[54] According to McKinsey & Company,[55] when all the cost savings for the original equipment manufacturer (OEM) and consumer are considered, the value proposition for SiC devices in hybrid electric vehicle (HEV) inverters is already better than the value proposition for Si insulated-gate bipolar transistors (IGBTs), despite the higher device cost for SiC, as shown in Figure 6.N.7. Fuel savings (assumed over an eight-year vehicle life at $3/gallon gasoline) are realized by consumers, while savings from weight reduction, reduced passive component requirements, and reduced cooling system requirements are realized by OEMs.

Figure 6.N.7 Value Advantage Gained from Use of SiC Transistors Compared to IGBTs for Hybrid-Electric Vehicle (HEV) Inverters, Based on the Entire Value Chain[55]



* when considering value chain savings
† NPV = Net Present Value

Information to quantify the benefits of switching from Si-based superjunction (SJ) MOSFETs to GaN-based HEMTs on a system level is not widely available. One available comparison is for a 250 W internal power supply of an all-in-one iMac desktop computer.[56] The GaN-based power supply used three Transphorm HEMTs and switched at 200 kHz as opposed to 50–80 kHz for the Si-based iMac supply. This allowed for a 55% size reduction as well as efficiency increases from 82% to 85% for a 15 W output supply and from 92% to 94% for a supply with 180 W output.

More empirical results of efficiency benefits of GaN HEMTs exist for individual power supply circuits, such as power factor correction (PFC) and DC–DC conversion stages. Zhang et al. have discussed the efficiency gains for a GaN based Buck-PFC circuit as might be used in a 90 W laptop adapter.[57] They compared the 115 Volt AC performance of a Buck-PFC evaluation module from Texas Instruments with a GaN HEMT and SiC Schottky diode against the same module with an SJ-MOSFET and a Si Hyperfast diode. The WBG module allowed for a 1%–2% efficiency improvement, with more pronounced gains at lower power levels. A number of sources claim transistor efficiency improvements of 3%–7%[47, 58] and DC-DC conversion efficiency improvements of 2%–4%,[5, 6] with the greatest improvements at the low end of a device's power range.

Enabling R&D

Based on an ORNL survey of WBG industry contacts, there appears to be a common perception that there are not enough engineers or physicists with adequate training to address WBG material production issues on the scale necessary for greater commercialization.[59] There was also a perception that materials research in this area is not encouraged and that an innovation center specifically focused on next-generation materials would help in the development of WBG power electronics technology in the United States. However, it should be noted that the Department of Defense has heavily funded basic materials research in GaN and SiC over the last 20 years.[16, 60] During this period, wafer diameters have increased from one inch to six inches, along with greatly improved material quality. Therefore, it was deemed important to focus on reducing the cost of device fabrication, packaging, and power electronics rather than the further development of materials. The material quality is considered sufficient for 150 mm substrates and epitaxial layers to manufacture 600 V to 15 kV devices. A widespread adoption of WBG devices is expected to occur as a result of reduced chip cost; this will create a market pull for increasing the substrate diameter to 200 mm (7.9 inches) and even 250 mm (9.8 inches), which is expected to happen without external funding.

The United States has substantial presence in developing WBG devices, but most WBG device end users are outside. Currently, the major pure-play semiconductor foundries are located either in China or Taiwan, in close proximity to most of the manufacturers using these devices. This presents a huge challenge for U.S.-based manufacturers, as these foundries will facilitate the early manufacturing of WBG semiconductors. The ORNL survey found a general perception that the U.S. was not keeping up in WBG research, manufacturing, and use, underscoring the risk of the U.S. being eclipsed in the critical area of power electronics by China and other countries. These and other concerns motivated the creation of PowerAmerica, which has a goal of providing an ecosystem for power electronics manufacturing and R&D in the United States. The survey of U.S. WBG suppliers identified the following key needs to improve the environment for WBG innovation:[59]

- sufficient funding of research;
- tax policies that would encourage internal research and the purchasing of capital equipment for WBG processing; and
- mechanisms to stem the flow of intellectual property overseas that was directly or indirectly developed through U.S. government funding.

Regulations and standards are an important means to encourage efficiency improvements in power electronics for consumer goods. It can be difficult for a manufacturer to make the case for choosing a more expensive part, even when it would lead to greater product efficiency. One participant in the aforementioned survey stated that the use of SiC components in a refrigerator compressor drive could cut energy losses by 25%, but that manufacturers had no incentive to pay the few extra dollars to add them because manufacturers do not pay the operating costs.

In addition to PowerAmerica, other public/private partnerships are being formed to advance WBG power electronics manufacturing in the United States. As mentioned earlier, New York State is partnering with a large number of private companies, led by GE and including Lockheed Martin, to launch the NY-PEMC. The public–private partnership will invest more than $500 million over five years, focused on the development of next-generation WBG semiconductor materials and processes at the state-owned R&D facility in Albany, New York. GE will be a lead partner in the fabrication plant, housed at the newly merged State University of New York Colleges of Nanoscale Science and Engineering NanoTech Complex, which aims to develop and produce low-cost six-inch SiC wafers.[61]

NextEnergy and the Power Electronics Industry Collaborative are focusing activities on identifying domestic challenges, opportunities, and pathways forward in WBG technologies for the power electronics industry.[62] In an industry-led workshop held in 2013, they recommended actions to address specific gaps, including adopting an application-driven approach, addressing the lack of adequate testing procedures to demonstrate reliability, and other methods for accelerating innovation and reducing innovation risk. Other recommendations included the strengthening of power electronics expertise and means of reducing the talent deficit in the United States.

Risk and Uncertainty, and Other Considerations

The previous section on "Enabling R&D" highlighted issues and associated approaches that can help mitigate risks regarding public, private, and public/private partnership investments in manufacturing WBG technologies in the U.S. More fundamentally, there are also risks that could impede the uptake of WBG technologies, including the possibility that device costs might never be low enough, or reliability high enough, for widespread penetration into targeted applications. To help address cost, PowerAmerica was established with the stated goal of making WBG power electronics cost-competitive within five years. For reliability, recent SiC device reliability data from industrial leaders, including GE and Cree, Inc., has shown marked improvement in this area and is helping to alleviate these concerns.

There are also external factors that could affect the penetration of WBG devices in power electronics applications. One is that emerging markets could impose less rigorous efficiency standards, which would limit the motivation for manufacturers to use high-efficiency power electronics. Another is that electricity prices could fall low enough that businesses that might otherwise have chosen high-efficiency power electronics will be dissuaded from doing so due to long payback periods.

Case Studies

AC Adapter Global Energy Consumption

The Electric Power Research Institute (EPRI) estimated that 130 TWh of electricity was consumed by U.S. residential electronics in 2008.[63] A 2009 report for the International Energy Agency assessed the global energy consumption of external power supplies (EPSs) for electronic devices such as laptops and mobile phones in 2008 at nearly 50 TWh, or about 1% of global electricity consumption.[64] Mobile phones, MP3s, and AC adapters were estimated to use 45% of this energy, or roughly 23 TWh, which also accounted for the losses between the AC power source and the electronic device.

Many assumptions must be made in order to estimate the energy use of AC adapters or EPSs. A report for DOE classified four broad EPS modes—active, no-load, off, and unplugged—depending on the state of the EPS connection to the mains, its connection to the application, and the state of the EPS on/off switch.[65] The active mode classification can be broken down further. Six states were discussed within the active mode for laptop computers, ranging from using 66% of the EPS nameplate output power when the computer is on and the battery is being charged to 0.6% nameplate power when the computer is off with a fully charged battery. These usage profiles result in an average power much lower than the rated power of the adapter. In fact, the capacity factors (the ratios of the average annual power output to the rated power output) for the EPSs discussed were around 13%. The report also discussed annual sales for active mode EPSs with various efficiency levels from 85% to 92%. For the annual U.S. shipped stock of 36.7 million laptops and netbooks in this study, the average active mode efficiency was 87% and the annual power consumption of all units was 404 million kWh.

Based on the earlier discussion under *Potential Impacts*, it is reasonable to assume that the introduction of GaN HEMTs to laptop adapters could increase laptop efficiency by 3%. This is a conservative assumption because laptop adapters typically provide a small percentage of their rated power, and the benefits of GaN HEMTs are more pronounced at low power levels. The effects of a 3% efficiency increase on the global stock of laptop adapters can be seen in Table 6.N.3. The 2014 sales numbers in this table were based on Eykyn[66] and Gartner.[67] The three-year projected adapter life used to determine the global stock was based on Boyd.[68] The 1,904 million kWh saved for laptop adapters would amount to $114 million, assuming a cost of $0.06/kWh.

Table 6.N.3 also shows the same calculation for tablet and cell phone adapters. These adapters have significant standby power losses in addition to their active mode losses.[65] The implementation of GaN HEMTs in these adapters can reduce annual per-unit losses by 23%, corresponding to a laptop adapter efficiency increase from 87% to 90%. The total annual savings of 7,670 million kWh from the use of WBG transistors in these adapters is on the scale of the annual output of a midsized coal power plant.

In addition to power savings, an important benefit of using high frequency GaN electronics is that the adapter size can be reduced by 10x. Many consumers will be willing to pay the incremental higher cost for a much smaller adapter, helping to drive up volume sales, achieving corresponding cost reductions. When the cost of GaN devices eventually reaches the cost-sensitive price point that enables their introduction into flat-screen TV power supplies, substantial energy savings will be achieved through their higher efficiencies.

Table 6.N.3 Potential Impact of GaN WBG Components on Global Energy Use[65, 66, 67, 68]

Transistor Material	Application	Average power rating (W)[65]	Average active mode efficiency[65]	Annual loss per unit (kWh)	2014 global sales (millions)[66, 67]	Assumed product life (yrs)[68]	Global stock (million units in service)	Annual electricity loss by global stock (million kWh)
Si	Laptop	60	87%	11.0	$250	3	750	8,250
	Tablet	12	80%	1.9	$250	3	750	1,425
	Cell phone	5	63%	4.2	$1,870	3	5,610	23,562
	Total							**33,237**
GaN	Laptop	60	90%	8.5	$250	3	750	6,346
	Tablet	12	85%	1.5	$250	3	750	1,096
	Cell phone	5	72%	3.2	$1,870	3	5,610	18,125
	Total							**25,567**
Savings Enabled by GaN WBG Semiconductor (million kWh/year)								**7,670**
Savings Enabled by GaN WBG Semiconductor (TBtu/year, end use energy)								**26.2**

Data Centers

Data centers in the United States consumed approximately 2.2% of the total U.S. electricity in 2012, amounting to 84 billion kWh (288 TBtu).[69, 70] Power conversion activities inside an average data center (power use effectiveness = 1.8) account for 10.4% of the energy consumed in the average data center.[71] Switching from Si-based devices to WBG-based devices could increase conversion efficiency from 90% to 98%.[72] This would amount to an 8.3% reduction in energy usage by data center power electronics.

Beyond this direct reduction in energy usage, the losses avoided would have increased the cooling load of the data center itself. Assuming that cooling itself generates no heat, the heating load of the data center is reduced by 12.7%. This represents an overall 4.4% energy savings of a data center.

Adding these two energy saving opportunities means that 12.7% (8.3% + 4.4%) of energy could be saved. This equates to 10.7 billion kWh (36.6 TBtu of end use energy or roughly 111 TBtu of primary energy) of energy savings from the full implementation of WBG devices in data centers.

Increased Penetration of Variable Frequency Drives

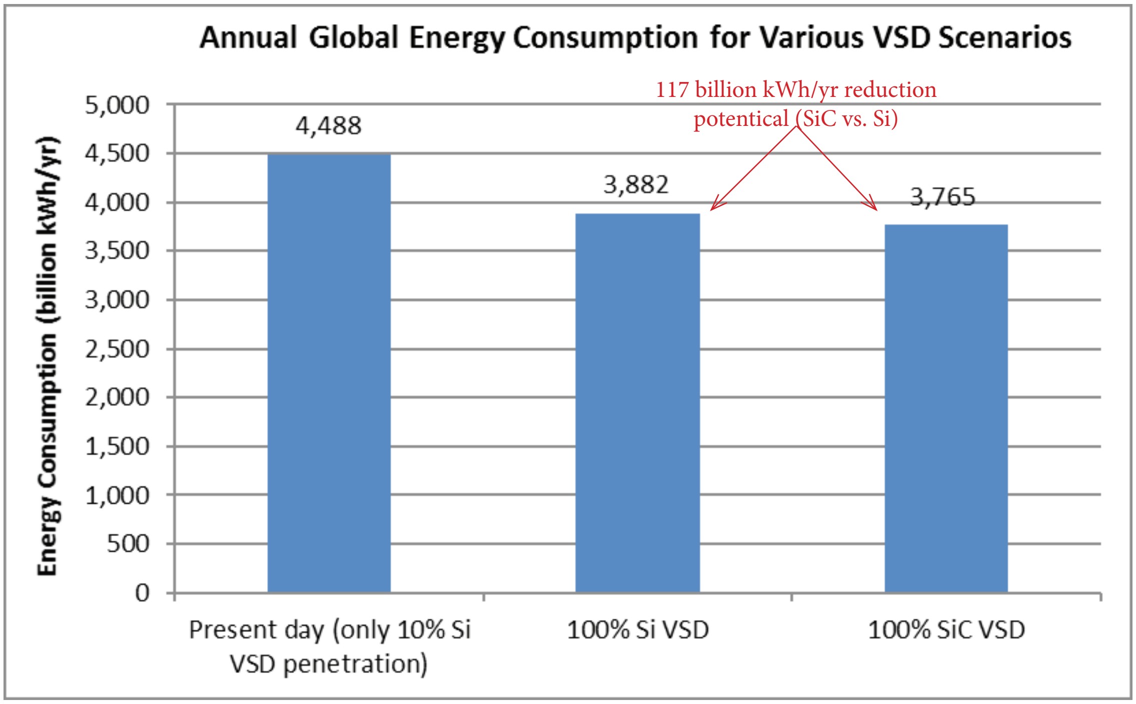
As stated in the introduction, motor drives are expected to be an important application for SiC power electronic devices. If SiC power electronics can improve the system level cost and/or power density of VFDs sufficiently to significantly increase the adoption of VFDs for industrial motor drives, this could have profound effects on the world's electrical energy use. When motors with a variable load do not have some sort of adjustable speed drive (ASD)—typically a VFD for industrial AC motors—to match the motor output to the load, the output of the motor must be throttled. This is an inherent inefficiency that could be addressed with greater adoption of VFDs. An example of an AC motor-driven system without a VFD is a fan system where airflow is controlled by dampers. In such a system, more airflow than is actually needed is generated by the fan and dampers are used to control excess airflow after energy has already been expended by the motor. In addition, this process usually moves the fan off its design point, thereby further reducing overall efficiency. By contrast, incorporation of a VFD in such a system allows for precise control of motor speed such that it is exactly matched with airflow requirements, thereby saving energy. An important takeaway from this example is that most energy savings come from the design and control decisions made possible by a switch to VFDs, not from the VFDs themselves.

Estimating the potential energy savings from increased adoption of VFDs in the global stock of electric motors is difficult because the potential benefits vary from one application to the next and the present penetration rate of VFDs is uncertain. For the global stock of refrigeration, air compressor, and pump/fan applications, average energy savings of 10%, 15%, and 20% have been estimated through the use of VFDs, respectively.[73] The current penetration rate of VFDs for electric motors is thought to be quite small at less than 10% in industrial applications.[74] If it is assumed that VFDs can achieve an average energy savings of 15% in the global stock of industrial electric motors and that 90% of such motors are not presently equipped with VFDs, then electricity consumption by motor-driven equipment in the industrial sector could potentially be reduced from approximately 4,490 billion kWh/yr to 3,880 billion kWh/year if 100% penetration were achieved. Note that this is an optimistic projection because motors that run at a consistent speed and do not use throttling valves, vanes, or other such controls, are not likely to benefit from VFDs.

Currently, VFDs use conventional Si-based semiconductors, which are less efficient than WBG semiconductors. As an extension of the preceding energy estimate, if it is assumed that Si VFDs have an average efficiency of 94.5% with 100% penetration of Si VFDs, global electricity losses in industrial electric motor drives can be estimated to be 214 TWh/year (3,882 TWh/year × 5.5%). If WBG semiconductors were to replace their Si counterparts, they could reduce VSD losses by 55%; 100% penetration of WBG-based VSDs would lead to 96 TWh/year (214 TWh/year × 45%) of VFD losses. In other words, WBG semiconductors could offer additional electricity savings of 117 TWh/year (399 TBtu) over traditional Si-based VFDs, assuming 100% penetration of WBG VFDs as shown in Figure 6.N.8.

In summary, if SiC VFDs achieved 100% adoption for relevant motors systems, the global energy savings could be 723 billion kWh/year. Again, caution is required with this estimate because there are motor systems that would not benefit from VFD installation.

Figure 6.N.8 Global Electricity Reduction Potential in Industrial Electric Motors from Si- and WBG-based VFDs



Renewable Energy Generation

Photovoltaic (PV) panels use the sun's radiation to directly generate DC current. This DC current is then inverted to AC to generate power suitable for the grid. In 2014, 15 billion kWh of power was generated by solar PV in the United States.[76] The energy savings rate of an SiC inverter over an Si inverter was found to be 3% (from 96% to 99% efficiency).[77, 78, 79] Rapid growth of PV installations thus offers significant energy gains and a market for SiC devices.

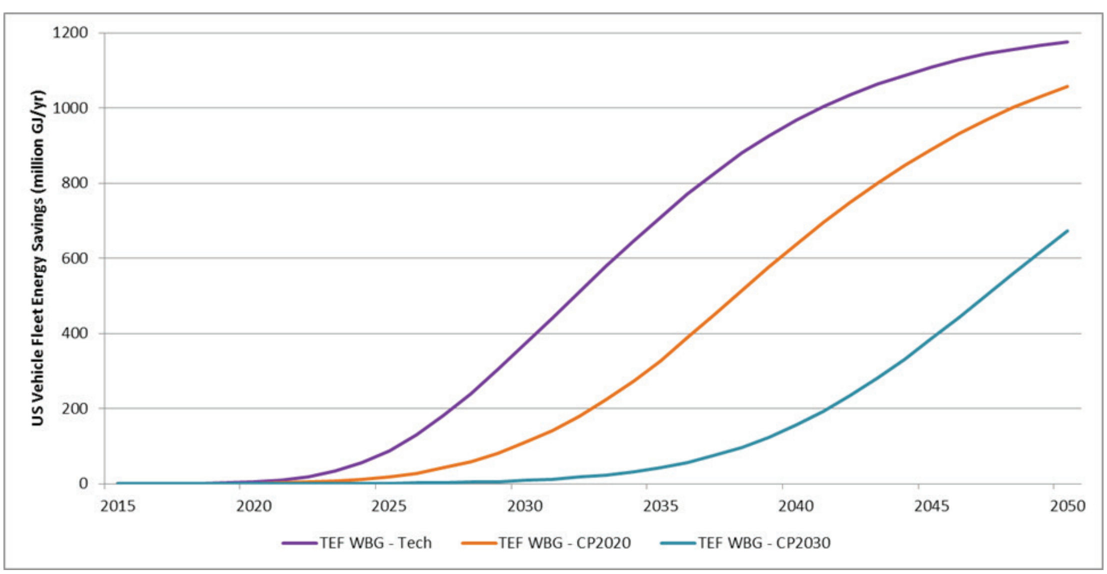
Modern wind turbines generate variable frequency AC power, depending on the wind speed. This current must be rectified to DC before being inverted back to AC at the necessary grid frequency. While this setup has losses associated with the conversion process, it permits wind turbines to operate at peak generating efficiency. Therefore, the deployment of WBG-based semiconductors would increase efficiency. In 2014, 182 billion kWh of energy was produced by wind turbines in the United States.[76] It is estimated that there would be a 4.6% absolute improvement in efficiency at 3 kHz switching speed, from 93.2% efficiency of Si to 97.8% efficiency of WBG system.[80] The additional annual generation possible from 100% implementation of SiC in wind turbine converters is 9 billion kWh. This potential would increase if the amount of electricity provided by renewable resources increases.

Electric Vehicles

In electric vehicles, switching losses in power electronics degrade overall efficiency and range as useful energy is wasted as heat. With WBG semiconductors, switching losses are reduced compared with conventional Si switches on Si substrates so that overall fuel economy is improved. A recent study has explored the vehicle-level benefits of an all-SiC motor inverter in a 2004 Toyota Prius by simulation with Argonne National Laboratory's Powertrain System Analysis Toolkit, accounting for not only inverter level benefits but also the effects of higher efficiency, lighter weight, smaller volume, and other factors on overall fuel economy, which is improved from 3.94 L/100 km for the conventional Si/Si vehicle to 3.36 L/100 km for the SiC/SiC vehicle, a 14.7% improvement.[81] A life-cycle energy savings of SiC/SiC versus the conventional Si/Si power electronics in electric vehicles (i.e., HEV, plug-in hybrid electric vehicles, and battery-electric vehicles) has been considered, assuming an aggressive penetration of alternative vehicles as considered in the DOE Transportation Energy Futures (TEF) study.[82] In addition, the dependency of adoption of WBG semiconductors on their relative cost and performance benefits compared to their Si counterparts has been considered by assuming when the cost parity with Si will be achieved.

Figure 6.N.9 illustrates the potential impact on fleet-wide energy savings from WBG associated with different timelines for achieving cost parity. For the cost parity (CP) in 2020 scenario (TEF WBG—CP2020), an estimated 10% reduction in annual energy savings relative to the baseline technical potential scenario (TEF WBG—Tech) is predicted to be achieved by the end of the period (2050). The 2050 annual energy savings are predicted to be 43% less than technical potential if cost parity is delayed until 2030 (i.e., TEF WBG—CP2030). By 2050, domestic fleet energy savings are estimated to be in the range of 640–1,120 TBtu/year. Although SiC/SiC is more than 2.5x as energy intensive in the materials and manufacturing on a per cm^2 basis, vehicle use energy savings exceed the marginal increase in WBG semiconductor manufacturing energy consumption versus Si/Si by two orders of magnitude.

Figure 6.N.9 U.S. Vehicle Fleet Energy Savings Potential in Electric Vehicles from SiC-based WBG Power Electronics



Endnotes

1 U.S. Energy Information Administration. (2015). *Monthly Energy Review October 2015*. Table 7.6. Available at: http://www.eia.gov/totalenergy/data/monthly/pdf/sec7_19.pdf.

2 The 955 billion kWh figure was for end use electricity consumption. The total primary energy consumption of the industrial sector in 2014 was 9.17 trillion kWh, but this includes on-site primary energy consumption. The electrical system energy loss for the industrial sector was 1.95 trillion kWh meaning that the primary energy consumption for industrial electricity was 2.90 trillion kWh. U.S. Energy Information Administration. (2015). *Monthly Energy Review October 2015*. Available at: http://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf.

3 U.S. Energy Information Administration. (2014). *Annual Energy Outlook 2014 with Projections to 2040*. Washington, DC. Available at: http://www.eia.gov/forecasts/archive/aeo14/.

4 Hull, B. (2013). "SiC Power Devices—Fundamentals, MOSFETs and High Voltage Devices." In *The 1st IEEE Workshop on Wide Bandgap Power Devices and Applications*. Columbus, OH: IEEE.

5 Briere, M. A. (2012). "So What's All This GaN Stuff Anyways?" In *PSMA Webinar*. International Rectifier.

6 Extance, A. (2013). "SiC and GaN Power Devices Jostle to Grow Their Role." *Power Dev*, pp. 1–4. Available at: http://www.yole.fr/iso_upload/mag/powerdev_april2013_ir.pdf.

7 Eden, R. (2013). *The World Market for Silicon Carbide & Gallium Nitride Power Semiconductors—2013 Edition* (Vol. 9790). IHS. Wellingborough.

8 Yole Developpement. (2012). *Status of the Power Electronics Industry: A Comprehensive Overview of the Power Electronics Semiconductors Business*.

9 Ren, F. (2013). "Wide Bandgap Semiconductors for Sensing Applications." *The Electrochemical Society*. Available at: http://www.electrochem.org/meetings/biannual/223/gordon_e_moore/.

10 Ostrovsky, G. (2008). "Smaller, Cooler Gallium Nitride (GaN) LEDs for Medical Devices." *MedGadget*. Available at: http://www.medgadget.com/2008/02/smaller_cooler_leds_for_medical_devices.html

11 Massarweh, N.N.; Cosgriff, N.; Slakey, D. P. "Electrosurgery: History, Principles, and Current and Future Uses." *J. Am. Coll. Surg.*, 202(3):520, 2006.

12 Tucker, R.D.; Schmitt, O. H.; Sievert, C.E.; Silvis, S.E. "Demodulated Low Frequency Currents from Electrosurgical Procedures." *Surg Gynecol Obstet*, 159(1):39, 1984.

13 Davis, S. (2014). "Energy Harvesting Poised to Eliminate Pacemaker Battery." *Power Electronics*. Available at: http://powerelectronics.com/energy-harvesting/energy-harvesting-poised-eliminate-pacemaker-battery?page=3.

14 The White House (2014). "Wide Bandgap Semiconductors: Essential to Our Technology Future." Available at: https://www.whitehouse.gov/blog/2014/01/15/wide-bandgap-semiconductors-essential-our-technology-future

15 Henshall, D. (2015), "A Pathway to Commercialization of Wide Bandgap Semiconductors in Power Electronics," ARPA-e presentation at the 2015 *Applied Power Electronics Conference*. Available at: http://www.apec-conf.org/wp-content/uploads/IS-14.1.pdf

16 Power Electronics (2005). "Navy Contract Supports SiC Development for Shipboard Power Management." Available at: http://powerelectronics.com/news/navy-contract-supports-sic-development-shipboard-power-management.

17 Rosker, M. J.; Albrecht, J. D.; Cohen, E.; Hodak, J.; Chang, Tsu-His (2010). "DARPA's GaN Technology Thrust." *Microwave Symposium Digest* (MTT), 2010, IEEE MTT-S International, pp. 1214-1217.

18 Cree, Inc. (2014). "Milestones." *About Cree*. Available at: http://www.cree.com/About-Cree/History-and-Milestones/Milestones.

19 Singh, R. "Reliability and Performance Limitations in Sic Power Devices." *Microelectronics Reliability*, 46, 2006; pp. 713–730. doi:10.1016/j.microre1.2005.10.013

20 Millan, J.; Godignon, P.; Perpina, X.; Perez-Tomas, A.; Rebollo, J. "A Survey of Wide Bandgap Power Semiconductor Devices." *IEEE Transactions on Power Electronics*, 29(5), 2014; pp. 2155–2163.

21 JCN Newswire. (2014). "SDK Increases Capacity to Produce 6" SiC Epi-Wafers for Power Devices." *Sys-con Media*. Available at: http://www.sys-con.com/node/3192617.

22 Yole Developpement. (2012). *Status of the Power Electronics Industry: A Comprehensive Overview of the Power Electronics Semiconductors Business*.

23 Yole Developpement. (2015). *GaN and SiC Devices for Power Electronics Applications*.

24 Zolper, J. C. (2005). "Emerging Silicon Carbide Power Electronics Components." In *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition*, 2005 (Vol. 1, pp. 11–17). IEEE. DOI:10.1109/APEC.2005.1452877.

25 Friedrichs, P. (2013). Further Prospects with SiC power semiconductors - Schottky diodes, JFET transistors and package considerations. In *The 1st IEEE Workshop on Wide Bandgap Power Devices and Applications*. Columbus, OH: IEEE.

26 Yole Developpement. (2015). *SiC, GaN, and other Wide Band Gap (WBG) Materials for Power Electronics Applications*. Note: Data were updated by Yole Développement in January 2016 for use in this Technology Assessment.

[27] Roussel, P. (2013). "All Change For Silicon Carbide." *Compound Semiconductor*. Available at: http://www.compoundsemiconductor.net/article/90863-all-change-for-silicon-carbide.html.

[28] Green Car Congress (2015). "Toyota Beginning On-Road Testing of New SiC Power Semiconductor Technology; Hybrid Camry and Fuel Cell Bus." Jan. 29. Available at: http://www.greencarcongress.com/2015/01/20150129-toyotasic.html.

[29] Würfl, J.; Hilt, O. (2013). "Power Electronic Devices Based on GaN: Advantages and Perspectives." In *Int. Conf. and Exhibition on Automotive Power Electronics. Paris*.

[30] Ravkowski, J.; Peftitsis, D.; Nee, H.-P. (2014). "Recent Advances in Power Semiconductor Technology." In H. Abu-Rub, H.; Malinowski, M.; Al-Haddad, K. (eds.), *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications*. Chichester, UK: John Wiley & Sons, Ltd. doi:1002/9781118755525.ch4.

[31] Diel, Z. (2013). "Commercial Status of the GaN-on-Silicon Power Industry. *Compound Semiconductor*, 2013; pp. 11–15. Available at: http://venture-q.com/pdf/Venture-Q Article-Web.03.05.13.pdf.

[32] Neudeck, P.G. (2006), "Silicon Carbide Technology," in: Chen, W.-K. (ed.), *The VLSI Handbook*, 2nd Edition, Chapter 5. CRC Press, 2006.

[33] U.S. DOE Office of Energy Efficiency & Renewable Energy. (2015). "Accelerating Innovation: PowerAmerica is Up and Running." Available at: http://energy.gov/eere/amo/accelerating-innovation-poweramerica-and-running

[34] Banerjee, S., Matocha, K., and Chatty, K. (2014). "Redefining Power Conversion with Cost-Effective Silicon Carbide Technology: SiC Manufacturing – The Fabless Approach." Presented at the NIST/DOE Workshop on High Megawatt Direct-Drive Motors and Front-End Power Electronics, September 4, 2014. Available at: http://www.nist.gov/pml/high_megawatt/upload/Banerjee-APPROVED.pdf

[35] Chen, R. (2008). "The future of Semiconductor Industry from 'Fabless' Perspective." UC Berkeley Solid-State Seminar. February 1, 2008. Available at: http://microlab.berkeley.edu/text/seminars/slides/RChen.pdf

[36] Mishra, U. K.; Kazior, T. E. "GaN-Based RF Power Devices and Amplifiers." *Proceedings of the IEEE*, 96(2), 2008; pp. 287–305. doi:10.1109/JPROC.2007.911060

[37] Ubukata, A.; Yano, Y.; Shimamura, H.; Yamaguchi, A.; Tabuchi, T.; Matsumoto, K. (2013). "High-Growth-Rate AlGaN Buffer Layers and Atmospheric-Pressure Growth of Low-Carbon GaN for AlGaN/GaN HEMT on the 6-in.-Diameter Si Substrate Metal-Organic Vapor Phase Epitaxy System." *Journal of Crystal Growth*, 370, 2013; pp. 269–272. doi:10.1016/j.jcrysgro.2012.10.023

[38] Hung, T.-H.; Krishnamoorthy, S.; Nath, D. N.; Park, P. S.; Rajan, S. (2013). "Interface Charge Engineering in GaN-based MIS-HEMTs." In *The 1st IEEE Workshop on Wide Bandgap Power Devices and Applications*, 2013; pp. 147–150. IEEE. doi:10.1109/WiPDA.2013.6695583

[39] Chowdhury, S.; Mishra, U. K. "Lateral and Vertical Transistors Using the AlGaN/GaN Heterostructure." *IEEE Transactions on Electron Devices*, 60(10), 2013; pp. 3060–3066.

[40] Shenai, K. (2013). "Switching MegaWatts with Power Transistors." *Electrochemical Society Interface*, 22(1), 2013; pp. 47–53. Available at: http://electrochem.org/dl/interface/spr/spr13/spr13_p047_053.pdf.

[41] Kachi, T.; Uesugi, T. "Evaluation of GaN Substrate for Vertical GaN Power Device Applications." *Sensors and Materials*, 25(3), 2013; pp. 219–227. Available at: http://myukk.org/sm_pdf/SM0915.pdf.

[42] Li, C.; Wu, Y. "Study on the Current Spreading Effect and Light Extraction Enhancement of Vertical GaN/InGaN LEDs. *IEEE Transactions on Electron Devices*, 59(2), 2012; pp. 400–407. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6096403.

[43] Cooke, M. (2014). "Vertical GaN Transistor with 1.6kV Blocking Voltage." *Semiconductor Today*. Available at: http://www.semiconductor-today.com/news_items/2014/FEB/TOYODAGOSEI_200214.shtml.

[44] ARPA-E. (2013). U.S. Energy Department's ARPA-E Announces $27 Million for Transformational Grid Technologies. *Latest ARPA-E News*. Available at: http://www.arpa-e.energy.gov/?q=arpa-e-news-item/us-energy-department%E2%80%99s-arpa-e-announces-27-million-transformational-grid

[45] ARPA-E. (2013). SWITCHES. *ARPA-E Programs*. Available at: http://arpa-e.energy.gov/?q=programs/switches.

[46] Transphorm (2015). "Transphorm and Fujitsu Semiconductor Announce the Start of Mass Production of Transphorm's GaN Power Devices." Jan. 26. Available at: http://www.transphormusa.com/2015-01-26-USA.

[47] Reusch, D. (2013). "Enhancement Mode GaN on Silicon Enables Increased Performance and New Applications." In *The 1st IEEE Workshop on Wide Bandgap Power Devices and Applications*. Columbus, OH: IEEE.

[48] Agarwal, A. "WBG Revolution in Power Electronics." In *IEEE Workshop on Wide Bandgap Power Devices and Applications*. Knoxville, TN, 2014.

[49] Shovlin, J.; Woodin, R.; Witt, T. (2007). "Introducing Wide-Band-Gap Silicon Carbide Production into a Silicon Fab." *Micro Magazine*. Available at: http://micromagazine.fabtech.org/archive/04/07/shovlin.html.

[50] Agarwal, A. "Manufacturing Perspective on Wide Bandgap Devices: Can WBG Prices Compete with Today's Si Prices?" MRS 2014 presentation, Boston, MA, December 3, 2014.

[51] Larger semiconductor wafers allow for cost reductions by increasing the number of devices that can be produced in parallel. Semiconductor wafers have nominal diameters in inches corresponding to actual diameters in mm. The current standard size for Si wafers is 300 mm or nominally 12 inches. This size was achieved around 2001. The next generation of Si wafers would be 450 mm or roughly 18 inches in diameter. This transition is projected to occur around 2017. This contrasts with SiC processing where wafers of 200 mm (8 inch) are not yet standard. Si wafers reached that size in 1991. For more information, see: Anysilicon. (2012) "Does size matter? Understanding Wafer Size." Available at: http://anysilicon.com/does-size-matter-understanding-wafer-size/

[52] Chowdhury, S.; Mishra, U. K. "Lateral and Vertical Transistors Using the AlGaN/GaN Heterostructure." *IEEE Transactions on Electron Devices*, 60(10), 2013; pp. 3060–3066.

[53] Lenk, T. Director of Development, Rockwell Automation. Personal communication with Joshua Warren and Laura Marlino, Oak Ridge National Laboratory. Nov. 27, 2013.

[54] Eden, R. (2012). "SiC and GaN Electronics: Where, When, and How Big?" *Compound Semiconductor*. Available at: http://www.compoundsemiconductor.net/article/89752-sic-and-gan-electronics-where,-when-and-how-big.html.

[55] McKinsey & Company. (2012). "Unleashing Growth in Wide Bandgap: The Upcoming Disruptions in Power Electronics." In *GSA Semiconductor Leaders Forum Taiwan*. Available at: http://www.gsaglobal.org/events/2012/1107/docs/slft2012_wiseman.pdf

[56] Transphorm. (2014). "EZ-GaN Evaluation Board, All-in-One Power Supply." *Transphorm Demo Boards*. Available at: http://www.transphormusa.com/sites/default/files/public/All-in-One_TDPS250E2D2_0.pdf.

[57] Zhang, X.; Yao, C.; Lu, X.; Davidson, E.; Sievers, M.; Scott, M. J.; Wang, J. (2014). "A GaN Transistor Based 90W AC/DC Adapter with a Buck-PFC Stage and an Isolated Quasi-Switched-Capacitor DC/DC Stage." *2014 IEEE Applied Power Electronics Conference and Exposition—APEC 2014*, pp. 109–116. doi:10.1109/APEC.2014.6803296

[58] Texas Instruments. (2012). *Gate Drivers for Enhancement Mode GaN Power FETs*. Available at: http://www.ti.com/lit/ml/slyb189/slyb189.pdf

[59] ORNL (2013). "Oak Ridge National Lab Wide Band Gap Device Suppliers Survey."

[60] Rosker, M. J.; Albrecht, J. D.; Cohen, E.; Hodak, J.; Chang, Tsu-His (2010). "DARPA's GaN Technology Thrust." *Microwave Symposium Digest (MTT)*, 2010, IEEE MTT-S International, pp. 1214-1217.

[61] Semiconductor Today. (2014). "GE to Lead $500m Five-year State-funded New York Power Electronics Manufacturing Consortium." Available at: http://www.semiconductor-today.com/news_items/2014/JUL/GE_160714.shtml.

[62] NextEnergy. (2013). *Report on Wide Bandgap Workshop*. Available at: http://www.nextenergy.org/wp-content/uploads/2013/07/Wide-Bandgap-Power-Electronics-US-Competitiveness-Workshop-Summary-3-28-2013-NextEnergy-PEIC.pdf.

[63] EPRI. (2009). *Assessment of Achievable Potential from Energy Efficiency and Demand Response Programs in the U.S. (2010–2030)*. Palo Alto, CA. Available at: http://www.epri.com/abstracts/pages/productabstract.aspx?ProductID=000000000001016987

[64] Ellis, M.; Jollands, N. (2009). *Gadgets and Gigawatts: Policies for Energy Efficient Electronics*. Paris: International Energy Agency. Available at: http://www.iea.org/publications/freepublications/publication/gadgets-and-gigawatts-policies-for-energy-efficient-electronics.html.

[65] Navigant Consulting, Inc.; D&R International, Ltd.; Lawrence Berkeley National Laboratory. (2012). *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Battery Chargers and External Power Supplies*.

[66] Eykyn, J. (2013). *The World Market for AC-DC & DC-DC Merchant Power Supplies—2013 Edition* (Vol. 9790). IHS. Wellingborough.

[67] Gartner. (2014). "Gartner Says Worldwide Traditional PC, Tablet, Ultramobile." *Gartner Press Release*. Retrieved October 15, 2014, from: http://www.gartner.com/newsroom/id/2791017.

[68] Boyd, S. B.; Horvath, A.; Dornfeld, D. "Life-Cycle Energy Demand and Global Warming Potential of Computational Logic." *Environmental Science & Technology*, 43(19), 2009; pp. 7303–7309. doi:10.1021/es901514n

[69] ASE (2012). "Data Centers and Energy Efficiency." Available at: http://www.ase.org/resources/data-centers-and-energy-efficiency.

[70] U.S. Energy Information Administration. (2014). *Annual Energy Outlook 2014 with Projections to 2040*. Washington, DC. Available at: http://www.eia.gov/forecasts/archive/aeo14/.

[71] U.S. Environmental Agency (2007). *Report to Congress on Server and Data Center Energy Efficiency Public Law. pp. 109-431*. Available at: http://www.energystar.gov/ia/partners/prod_development/downloads/EPA_Datacenter_Report_Congress_Final1.pdf.

[72] Tolbert, L.M., et al. (2005). "Power Electronics for Distributed Energy Systems and Transmission and Distribution Applications." Oak Ridge National Laboratory Document Number ORNL/TM-2005/230. Available at: http://web.ornl.gov/sci/decc/Reports/PE%20For%20DE%20and%20T&D%20Applications%20(ORNL-TM-2005-230).pdf

[73] Lowe, M.; Golini, R.; Gereffi, G. (2010). *U.S. Adoption of High-Efficiency Motors and Drives: Lessons Learned*. Durham, NC. Available at: http://www.cggc.duke.edu/pdfs/CGGC-Motor_and_Drives_Report_Feb_25_2010.pdf.

[74] U.S. Department of Energy. (2002). *United States Industrial Electric Motor Systems Market Opportunities Assessment*. Available at: http://www.energy.gov/sites/prod/files/2014/04/f15/mtrmkt.pdf

[75] Waide, P. and Brunner, C.U. (2011). "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems." International Energy Agency: Energy Efficiency Series. Available at: https://www.iea.org/publications/freepublications/publication/EE_for_ElectricSystems.pdf

[76] U.S. Energy Information Administration (2015), "Table 1.1.A: Net Generation from Renewable Sources," in *Electric Power Monthly*, released December 24, 2015. Available at: http://www.eia.gov/electricity/monthly/pdf/epm.pdf

[77] Burger, B.; Rüther, R. (2006). "Inverter Sizing of Grid-Connected Photovoltaic Systems in the Light of Local Solar Resource Ditribution Characteristics and Temperature." *Solar Energy*, (80), 2006; pp. 32-45. Available at: http://www.lepten.ufsc.br/publicacoes/solar/periodicos/2006/SOLAR%20ENERGY/burger_ruther.pdf

[78] McDonald, T. (2011). *Impact of Commercialization of GaN based Power Devices on PV Solar Power Generation*. International Rectifier. Available at: http://www.arpa-e.energy.gov/sites/default/files/documents/files/SolarADEPT_Workshop_NxtGenPwr_McDonald.pdf.

[79] APEI (2014). *Wide Bandgap Inverters*. Available at: http://www.apei.net/Applications/Product-Development/Wide-Bandgap-Inverters.aspx.

[80] Zhang, H.; Tolbert, L. "Efficiency Impact of Silicon Carbide Power Electronics for Modern Wind Turbine Full Scale Frequency Converter." *IEEE Transaction on Industrial Electronics* (58:1), 2011; pp. 21-28). doi: 10.1109/TIE.2010.2048292

[81] Zhang, H.; Tolbert, L.M.; Ozpineci, B (2011). "Impact of SiC Devices on Hybrid Electric and Plug-in Hybrid Electric Vehicles. *IEEE T. Ind. Appl.*, 47(2), 2011; pp. 912-921.

[82] Warren, J. A.; Riddle, M. E.; Graziano, D. J.; Upadhyayula, K. K.; Das, S.; Masanet, E. "Life Cycle Energy Impacts of Wide Band Gap Semiconductors in Electric Vehicles." *Environmental Science and Technology* (49:17), 2015; pp. 10294-10302.

Acronyms

AC	Alternating current
ARPA-E	Advanced Research Projects Agency-Energy
ASD	Adjustable speed drive
CMOS	Complementary metal-oxide semiconductor
CP	Cost parity
DC	Direct current
DOE	(U.S.) Department of Energy
EMI	Electromagnetic interference
EPC	Efficient Power Conversion Corporation
EPS	External power supply
EPRI	Electric Power Research Institute
FET	Field-effect transistor
HEMT	High-electron-mobility transistor
HP	Horsepower
IC	Integrated circuit
LED	Light Emitting Diode
MOSIS	Metal Oxide Semiconductor Implementation System
MOSFET	Metal-oxide-semiconductor field-effect transistor
MRI	Magnetic resonance imaging
NY-PEMC	New York Power Electronics Manufacturing Consortium
OEM	Original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PFC	Power factor correction
PV	Photovoltaic
RF	Radio frequency
SWITCHES	Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (ARPA-E program)

TEF	Transportation Energy Futures (U.S. DOE project)
VFD	Variable frequency drive
WBG	Wide bandgap

Glossary

Adjustable speed drive (ASD)	A motor drive system that allows for the adjustment of output speed or frequency to meet the load demands of a machine such as a pump or fan. Variable frequency drives (VFDs) are a subset of ASDs for AC motors that change output speed via changes in AC frequency. Other types of ASDs can change output mechanically or hydraulically.
Bandgap	The span of energy between the valence band and the conduction band in a solid material. Electrons must gain this amount of energy to enter the conduction band from the valence band and allow current to flow. Conductors have negligible bandgaps, insulators have very wide bandgaps, and semiconductors have small but non-negligible bandgaps.
Boost converter	A circuit element that produces a higher output DC voltage than its DC input voltage.
Buck converter	A circuit element that produces a lower output DC voltage than its DC input voltage.
Fabless foundry model	A market model in which companies that own semiconductor device foundries contract to produce devices for fabless companies that design devices and market or integrate them, but don't have production capabilities.
Gallium nitride (GaN)	A wide bandgap (WBG) semiconductor material at a less advanced development stage than Silicon Carbide (SiC). GaN is used in high-electron-mobility transistors (HEMTs).
High-electron-mobility transistor (HEMT)	A high frequency transistor using a combination of semiconductors with different bandgaps. HEMTS are a target application for gallium nitride (GaN).
Light emitting diode (LED)	A semiconductor junction that allows current flow in one direction and produces monochromatic light in response to that current flow. LEDs produce light very efficiently compared to incandescent and (most) fluorescent light bulbs.
Metal-oxide-semiconductor field-effect transistor (MOSFET)	An electronic switch or amplifier driven by electric fields induced by a control voltage. MOSFETs require less control current and can deliver more load current than regular transistors.
Micropipe	A common defect in silicon carbide (SiC) substrate production resulting from the propagation of a screw dislocation.

PowerAmerica	A National Network for Manufacturing Innovation institute established in 2014 as a public-private partnership between the U.S. DOE, industry and academia. PowerAmerica is led by North Carolina State University, and is pursuing the key goal of making WBG power electronics cost-competitive within five years.
Power factor correction (PFC)	The action of bringing the power factor (the ratio of the real power seen by the load to the apparent power in a circuit) closer to one by supplying reactive power. This is a common function of elements of external power supplies (EPSs).
Schottky diode	A semiconductor diode with a low reverse bias voltage and fast switching capabilities. Schottky diodes represent an early application for Silicon Carbide (SiC).
Silicon carbide (SiC)	A wide bandgap (WBG) semiconductor material at a more advanced development stage than Gallium Nitride (GaN). SiC was first used in Schottky diodes and later used in MOSFETs.
Variable frequency drive (VFD)	An electric motor drive that alters the output speed of an AC motor by altering the frequency of the AC power input. VFDs are a subset of adjustable speed drives (ASDs). VFDs benefit from wide bandgap switches that can switch at higher frequency with fewer losses.
Wide bandgap (WBG) semiconductor	A semiconductor material with a significantly wider bandgap than conventional semiconductors such as silicon. Generally, a semiconductor is considered WBG if its bandgap is larger than 3 eV; examples include silicon carbide (3.3 eV) and gallium nitride (3.4 eV). WBG materials can enable device operation at higher frequencies, temperatures, and voltages compared to conventional semiconductors.