Wide Bandgap Power Electronics Technology Assessment

Contents

1. Introduction to the Technology/System

The field of power electronics deals with the use of solid state electrical devices for the conversion, control and processing of electric power. To accomplish these tasks silicon (Si) semiconductors have traditionally been employed in power circuits. However, it now appears that silicon device technology has evolved to such a mature state that it is approaching its material limitations.

Wide bandgap (WBG) semiconductors have the capability to operate at higher voltages, temperatures, and switching frequencies with greater efficiencies compared to existing Si devices. These characteristics not only result in less losses but enables significantly reduced volume, due to decreased cooling requirements and smaller passive components contributing to overall lower system costs.

Reducing energy consumption is critical to U.S economic, health, and security interests. To that end, increasing the efficiency of power electronics is imperative. Today, U.S. industrial plants account for 3.32 quadrillion Btu (quads) of electricity consumption—over a quarter of end-use electrical consumption in the U.S. It is projected that this consumption will grow by 30% to 4.34 quads between 2013 and 2040

(U.S. Energy Information Administration, 2014). Motors and generators are critical in these applications, driving equipment such as fans, pumps, compressors, and conveyer systems. The use of WBG semiconductors in variable frequency drives 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 and the electric motors. For example, one estimate stated that the heat sink size for the variable speed drive of a 10 HP industrial electric motor could be reduced by 66% if WBG-based power electronics were used (Hull, 2013). 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. In total, it is believed that over 25% of the worldwide annual energy consumption can be saved if widespread (>90%) adoption of these highly efficient power electronics technologies can be realized (M. Briere, 2010).

Two major WBG materials with the potential to allow significant advances in power electronics are silicon carbide (SiC) and gallium nitride (GaN). SiC and GaN combined device sales are projected to have significant growth, becoming a ~$8B industry by 2023 as shown in Figure 1. The majority of projected GaN device sales are expected to be for power factor correction (PFC) circuits in power supplies while SiC devices are expected to be sold for a wider range of applications (Eden, 2013; Yole Developpement, 2012).

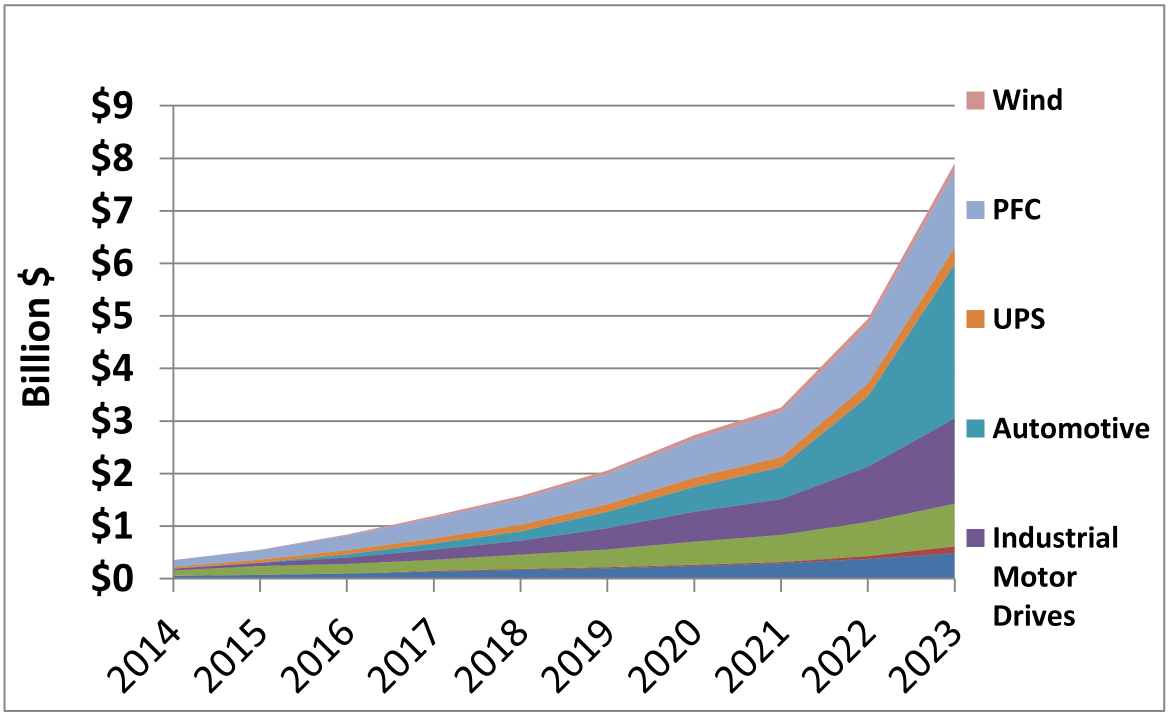

Figure 1. Projected sales for WBG power electronic devices (Eden, 2013)

To date, the predominant use of SiC in electronics is as a substrate for GaN LEDs. While SiC currently has limited use in power electronics, its role is expected to grow as it becomes the prevailing WBG replacement for silicon in applications requiring device ratings in excess of 600 volts (Extance, 2013). A major challenge to widespread adoption of SiC power electronics devices is the high cost of substrate and epitaxial material. 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 silicon transistors in PV inverters and hybrid vehicle chargers. Their greatest revenue generating application is forecast to be in industrial motor drives (Eden, 2013) and hybrid and electric vehicles (Yole Developpement, 2012).

GaN is currently widely used in LEDs and RF amplifiers. It's emergence in power electronics is relatively recent (Eden, 2013). Challenges for GaN on silicon semiconductors, the most cost effective method for fabricating GaN power devices, are mostly related to its lack of maturity. Issues include overcoming material challenges such as the high lattice strain at the GaN and silicon interface due to mismatches in the coefficient of thermal expansion. GaN is expected to be the dominant WBG semiconductor replacement for silicon for applications requiring device ratings less than 600 volts (Extance, 2013), but its impact is expected to be predominantly for RF and power supply applications (Eden, 2013).

Currently, the United States is among the leading countries developing WBG technologies. Retaining and strengthening the WBG industry has been deemed a priority by the U.S. government for energy savings, economic development, and national security reasons. 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 Manufacturing Innovation Institute (PowerAmerica) led by North Carolina State University. The institute was announced in January of 2014 with the stated goal of making WBG power electronics cost-competitive within five years. Sufficient progress has been made over the past 20 years in the material quality of SiC substrates, SiC epitaxy, GaN/SiC and GaN/Si epitaxy with Department of Defense funding. The PowerAmerica Institute is therefore focusing its activities on device manufacturing, WBG specific power module development and electronics to exploit the attributes of WBG devices rather than 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 $500 million partnership of over 100 private companies including 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.

2. Technology Assessment and Potential

2.1 Performance advances in SiC

Silicon carbide power semiconductors are a relatively new entrant in the commercial marketplace, with the first SiC Schottky diode introduced in 2001 (Eden, 2013). This milestone and others in the history of SiC power electronics are noted in the timeline in **Figure 2**. Despite their relatively recent emergence, significant advances have been made in SiC power devices. Six inch SiC wafers are currently in production—they were first announced by Cree in August of 2012 (Cree Inc., 2014)—though they are not yet commonly used to produce power electronics devices. The wafer quality has also improved. The most common defects in SiC wafers have historically been micropipes. The densities for these defects were in the range of 5–10/cm^2 in 2006 (Singh, 2006), improving to 0.75/cm^2 in 2014 (Millan, Godignon, Perpina, Perez-Tomas, & Rebollo, 2014). Japanese manufacturer Showa Denko has claimed even lower defect densities of 0.25/cm^2 in their six inch wafers, announced in September of 2014 (JCN Newswire, 2014).

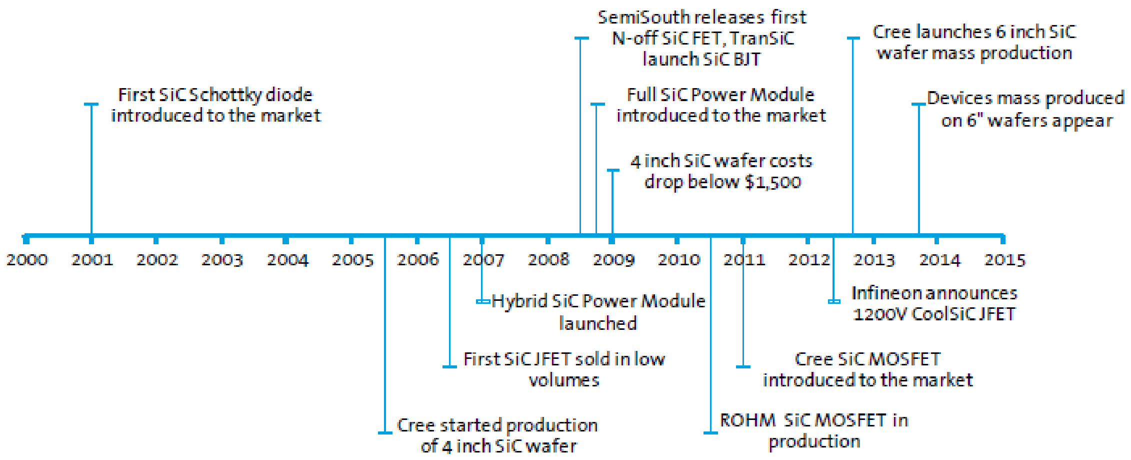

Figure 2. Milestones in SiC power electronics development (Eden, 2013)

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. In fact, four-inch SiC wafers have decreased in price from $1,200–1,400 in 2009 to $600–$750 in 2012 (Hull, 2013). This time span also saw SiC power device sales more than triple (Yole Developpement, 2012). **Figure 3** shows the impact of these changes on the price of Cree devices from their introduction through 2012 (Hull, 2013).

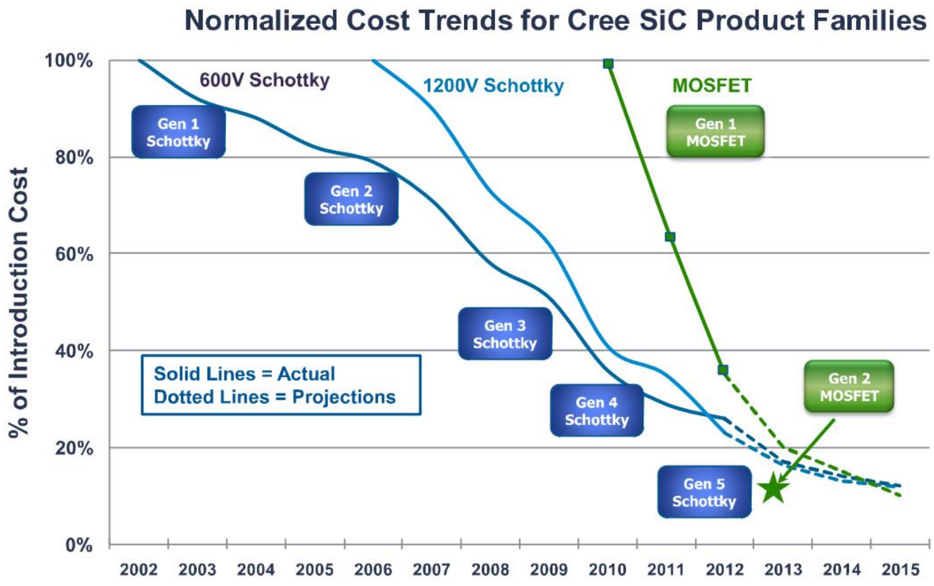

Figure 3. Decline of device cost for Cree SiC products over time (Hull, 2013)

SiC device performance has also improved. The general growth trend in current density for all SiC devices for 2010 through 2012 is shown in **Figure 4** with performance predictions for later years (Yole Developpement, 2012). This shows a steady increase in current density that 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 available today with current ratings up to 50 amps, while 25 amps was the highest available in 2005 (Zolper, 2005). Also, pronounced improvements in performance have occurred between subsequent generations of SiC power 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 timeframe (Hull, 2013). Such performance improvements have been made possible through material developments (Friedrichs, 2013).

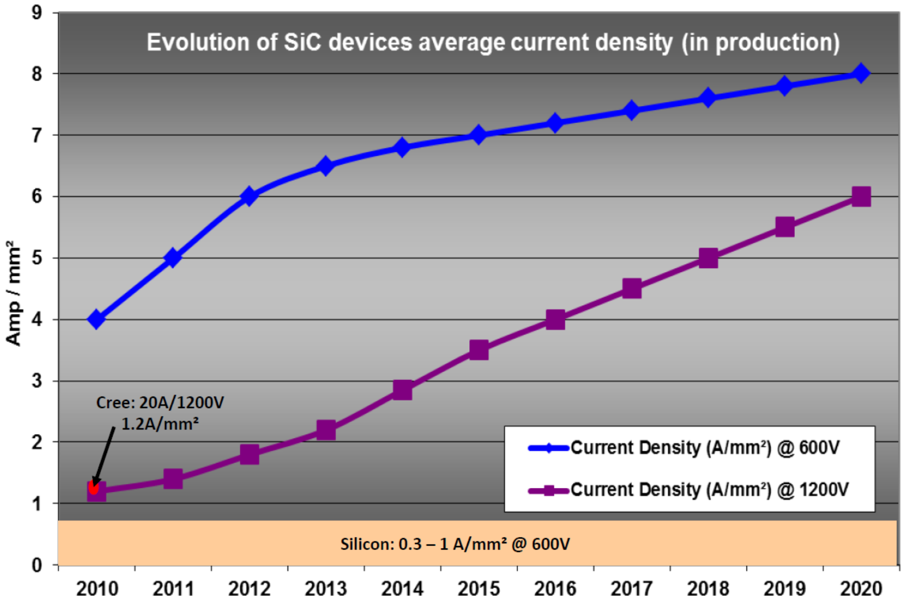

Figure 4. Current Density evolution for SiC (Yole Developpement, 2012)

SiC power electronics are approaching the time when many technological advances will be driven by companies within the value chain, and device manufacturers will be key players. **Table 1** lists the leading silicon carbide power electronics device companies in terms of 2010 revenues (Yole Developpement, 2012). The $0.05 billion silicon carbide power electronics market in 2010 was led by two companies—Germany-headquartered Infineon (51% market share), and U.S. headquartered Cree Technologies (37% share) (Yole Developpement, 2012). Both companies' SiC fabs are in the developed world—Infineon's in Villach, Austria, and Cree Technologies' in Durham, North Carolina. In 2010 silicon carbide power electronics was manufactured primarily in Europe (54%), the United States (41%), and Japan (2%) (Yole Developpement, 2012). The distribution of market share is expected to change radically by year 2020, at which time Japan is expected to have a 35% market share due to heavy industry and government investment (Roussel, 2013). Toyota has recently announced the beginning of on-road testing of silicon carbide (SiC) power semiconductors in a Camry hybrid prototype and a fuel cell bus (Green Car Congress, 2015). These tests will evaluate the performance of SiC technology, which could lead to significant efficiency improvements in hybrids and other electric-drive vehicles.

Table 1. Distribution of 2010 silicon carbide power electronics device revenues by company and fab location (Yole Developpement, 2012).

Company	**2010 SiC Power Electronics Revenue (Million $)**	**Headquarter**	**Fab location**
Infineon	$27.1	Germany	Villach, Austria
Cree Technologies	$19.7	U.S.A	Durham, NC, U.S.A
STMicro	$1.6	Switzerland	Catania, Italy
Rohm	$1.1	Japan	Fukuoka, Japan and Miyazaki, Japan
All others	$3.7		
Total	**$53.2**		

2.2 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 (Würfl & Hilt, 2013). These devices are the result of significant public and private research activities focusing on the development of GaN transistors on silicon substrates. This work culminated in the announcement of the first GaN on silicon HEMT (High Electron Mobility Transistor) by International Rectifier in 2010. International Rectifier's announcement was quickly followed by a public device release from Efficient Power Conversion (EPC). These milestones and others are shown in **Figure 5**. One of the developments that made this shift possible was the improvement in GaN-on-silicon epitaxy techniques (Eden, 2013). This technique allows for the creation of substrates with less impressive properties but at orders of magnitude lower cost than GaN on bulk SiC or GaN substrates. Relatively low prices without any volume requirements discussed in (Würfl & Hilt, 2013) were $100 for a 4" silicon wafer for GaN epitaxy as opposed to $3,130 for a 4" high performance SiC wafer or $7,500 for a GaN wafer for GaN epitaxy.

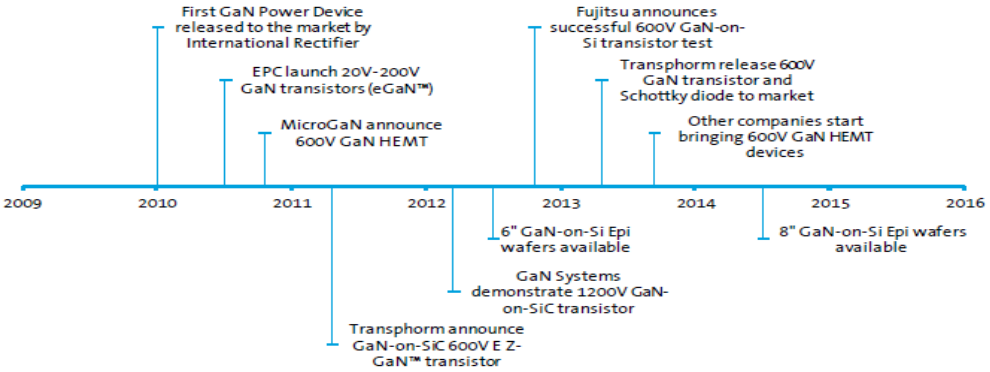

Figure 5. Milestones in GaN power electronics development (Eden, 2013)

The general trend of average current density values for all GaN devices up to 2012 with predictions for future years can be seen in the in **Figure 6** (Yole Developpement, 2012). Other GaN advances involve the move to larger GaN-on-silicon epitaxial wafers—8" wafers have been demonstrated (Ravkowski, Peftitsis, & Nee, 2014), and the development of gate injection transistors (GITs) 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.

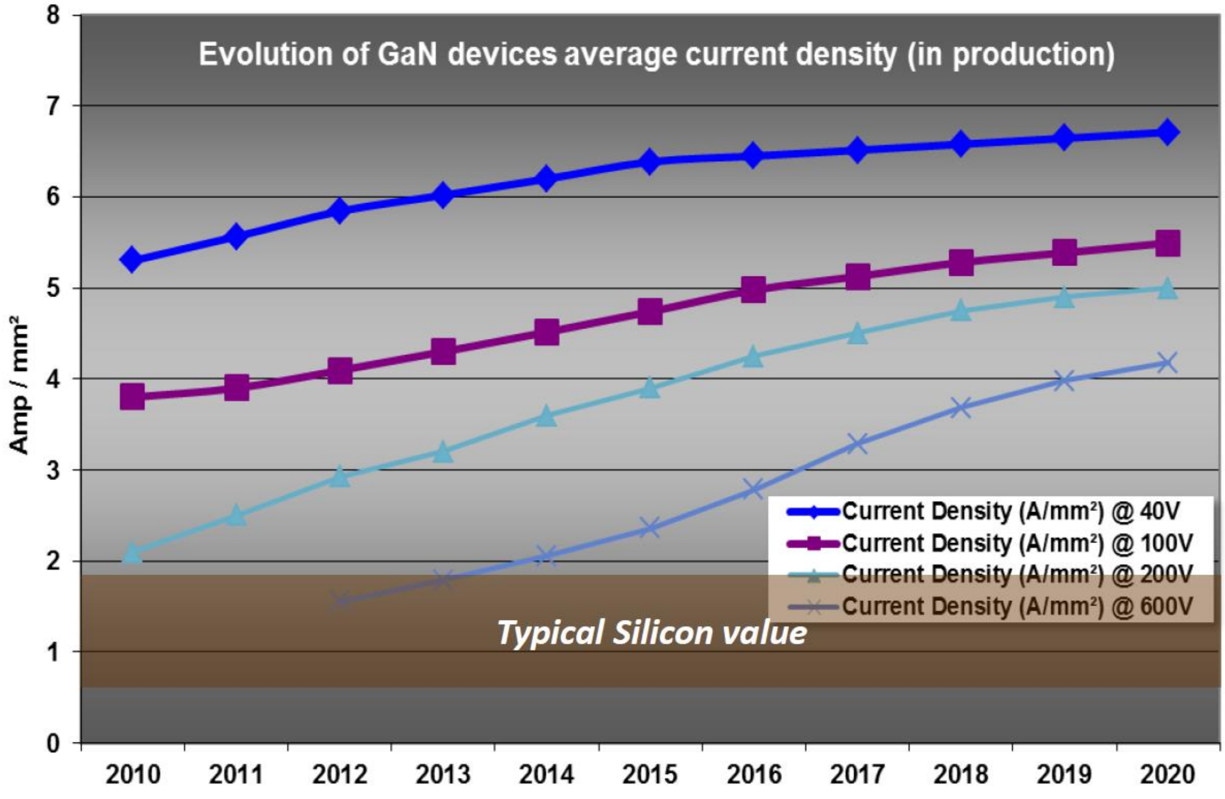

Figure 6. Current Density evolution for GaN (Yole Developpement, 2012)

Significant progress in GaN device technology is attributable to research labs and universities. A major contributor has been the University of California Santa Barbara (UCSB), which was cited in a survey of industry representatives as being the only institution producing PhD graduates with the training to contribute to efforts to produce high quality GaN for power electronics (ORNL, 2013). In the private sector, a majority of the companies that have brought GaN devices to market are based in the United States. **Table 2** shows the development stage and the product focus for companies involved with GaN research (Diel, 2013). Of the five that had products on the market in 2013, four (all except MicroGaN) were based in the U.S. 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 like Texas Instruments and Panasonic.

Table 2. Development stages and product types for companies involved in GaN power electronics (Diel, 2013)

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					●	●		

2.3 Technology Needs

The greatest challenge to the adoption of WBG components in power electronics is their high cost.

Substrate material accounts for 1/3 to 1/2 of the cost of a SiC device, while traditional Si-based power device substrates account for only 5–7% (Eden, 2013). However, it is possible to get 100x more amperes per SiC wafer compared to the same size Si wafer, due to the 100x lower specific on-resistance of the SiC devices. Therefore, although SiC substrates and epi layers are currently more expensive than Si they can still compete with Si devices costs on a cost/area basis.

In the case of SiC, cost reduction can be realized through high volume processing of wafers. The PowerAmerica Institute is working to lower upfront costs of WBG power electronics by investing in a commercial foundry model. This will allow small fabless companies to enter the market, develop improved device processing steps and produce devices at lower costs. Such a foundry could play a foundational role in the rise of WBG semiconductors in the same way that MOSIS did for silicon ICs.

Material quality still remains an area for improvement. SiC MOSFETs are by far the most prominent WBG switching device used today but they are limited by MOS interface quality issues. Problems with the interface can lead to variability in threshold voltages as well as lower device reliability. This has led to the limited adoption of SiC JFETs and BJTs in preference 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-silicon devices, but there are efforts that could be made to decrease costs further. One mechanism would be to reduce the thickness of eight inch silicon wafers to around 675 microns. This would allow GaN-on-silicon wafers to be processed on CMOS IC production lines so the development of new production equipment could be avoided. GaN-on-Si epi layers are currently more expensive and lower quality than GaN-on-SiC epi layers but it is expected this will be addressed over time, as manufacturing volumes increase.

Putting GaN on silicon substrates necessitates having an AlN nucleation layer for GaN crystal growth (Mishra & Kazior, 2008). Cost effective growth of high quality nucleation layers is difficult because a pre-reaction between the gases used for the nucleation layer at high pressure leads to a tradeoff between growth rate and quality (Ubukata et al., 2013). Moreover, interfacial charges between AlN and adjacent materials can prevent normally off device operation (Hung, Krishnamoorthy, Nath, Park, & Rajan, 2013). 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 silicon low voltage MOSFET solves this problem but results in extra switching losses making it difficult to operate at very high switching frequencies; negating 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 are available from select vendors, such as EPC. 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 silicon. 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 (Eden, 2013). If the price of bulk GaN wafers was sufficiently reduced vertical device architectures could be utilized, as opposed to lateral devices with GaN-on-silicon. Vertical devices would allow GaN to be used in higher power applications, above 100kW (Chowdhury & Mishra, 2013). 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.

Advancements toward vertical GaN devices have been recognized as important by the DOE’s Advanced Research Projects Agency-Energy (ARPAe). 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 $27M program announced in October of 2013 funding 14 projects involving universities, national labs, and private companies (ARPA-E, 2013b). Projects focused on vertical GaN technology within this program include partnerships led by UCSB with Arizona State University, Transphorm, and the U.S. Naval Research Laboratory (ARPA-E, 2013a); Avogy in collaboration with ABB, North Carolina State University, Oak Ridge National Laboratory, and Soraa; as well as several others involving Columbia University, HRL Laboratories, and SixPoint Materials (ARPA-E, 2013a). Transphorm and Fujitsu semiconductor have recently announced the start of mass production of Transphorm’s GaN power devices for switching applications (Transphorm, 2015). The start of the mass production in a CMOS IC production line is a significant step forward toward achieving the widespread use of GaN power devices.

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 ten years 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 insure greater reliability for new transistor designs will be useful, but large scale adoption will not occur until lifetimes in excess of ten years can be conclusively proven in demanding applications.

2.4 System Integration Needs

For both SiC and GaN power electronics devices, their benefits are not realized if they are treated as drop-in replacements for silicon 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 withstand the higher temperature capabilities of WBG power devices. Higher power and temperature operation will necessitate robust bonding mechanisms to both the dies and module substrates that can withstand repeated power and temperature cycling. Higher switching frequencies lead to new concerns at both the power module and board level. Parasitic inductances and resistances can result in significant power losses when the circuit is switched at high frequencies (Reusch, 2013). Attention to the minimization of parasitic properties can also significantly decrease voltage and current overshoots reducing EMI filter requirements, circuit volume and cost. Figure 7 shows the effect of parasitic inductance for a 12 V to 1.2 V buck converter circuit with two EPC eGaN FETs operated at 1 MHz by comparing the efficiency of an optimized layout to more traditional vertical or lateral circuit designs.

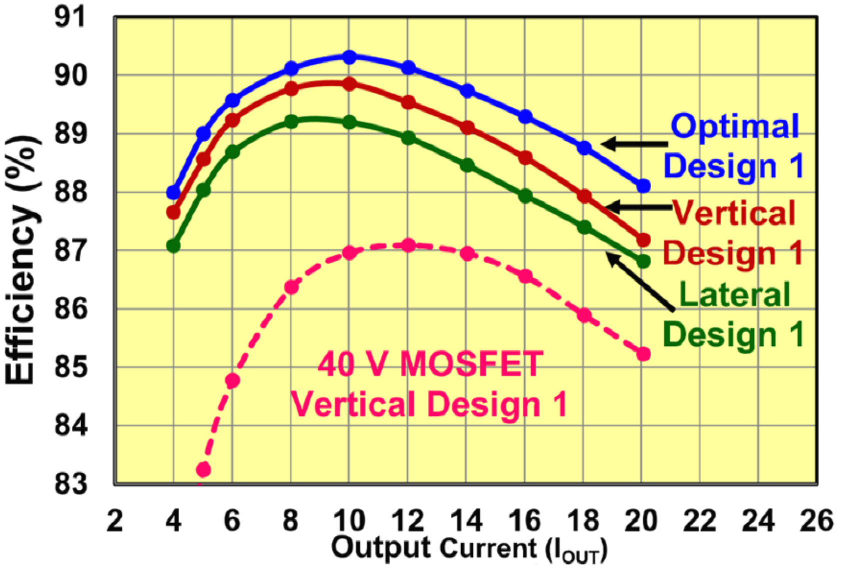

Figure 7. Efficiency impact of board design to avoid parasitic inductance (Reusch, 2013)

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.

2.5 Potential for Improvements

There is certainly opportunity for reduction in the price of WBG power electronic devices. An IHS market report from 2013 forecasts average prices for different WBG devices (Eden, 2013). SiC Schottky diodes are expected to decline moderately (11%) in price from an average (across all devices) of $0.71 in 2014 to $0.63 per device in 2022. SiC MOSFET prices are expected to drop more dramatically (44%) from $6.51 to $3.32 per device, and GaN transistors are expected to see the greatest decrease in price (80%) from $2.68 to $0.54 per device. The fabless foundry model that the PowerAmerica Institute is pursuing will be instrumental in achieving these cost reductions.

A dedicated foundry, today, requires a $100-200M investment and cannot become profitable unless fully loaded with, for example, at least 10,000 wafer starts a month. Since 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 (Agarwal, 2014a) and is the concept currently being implemented in the PowerAmerica Institute. As approximately 90% of the processes involved with the manufacture of WBG devices are similar to Si processes, processing costs can be significantly reduced by utilizing idle time in the Si foundry for WBG fabrication runs. This also takes advantage of the fully depreciated equipment and reduced overhead costs of a commercial foundry. The 10% of the processes which are unique to WBG manufacturing can be implemented at a cost of roughly $10M. Once this is done, the commercial foundry approach has a potential to provide a fabless model to many companies, universities and labs. As a result, innovations in designs and processes can occur quickly which will attract new venture capital. New companies can quickly launch a product with as little as $1-2M as opposed to having to invest $100-200M 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 $0.54/A or five times the cost of silicon devices ($.10/A). Assuming substrate and epi-layer costs will decline in higher volumes costs could drop to as little as 7.4¢/A (Agarwal, 2014b). It is projected that through technological innovations and the move to 8” wafers, the cost of a SiC MOSFET could be competitive to current cost of silicon devices in five years (Agarwal, 2014b).

A promising area for GaN research is based on the fact that present-day GaN power devices are being developed on silicon substrates. This creates the opportunity to develop high frequency GaN power transistors alongside driver ICs on a common silicon 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 (Eden, 2013). 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 (Chowdhury & Mishra, 2013).

2.6 Potential Impacts

The value proposition for WBG devices consists of four major points.

Reduced energy costs – Because WBG semiconductors are inherently more efficient than silicon, less energy is expended as heat, resulting in smaller system sizes and material costs.

Higher power density (smaller volume) – Higher switching frequencies and operational temperatures than silicon result in lower cooling requirements, smaller heat sinks, and reduced magnetics.

Higher switching frequency – The higher switching frequencies for WBG devices allows smaller inductors and capacitors to be used in power circuits. The inductance and capacitance scale down in proportion to the frequency – a 10X increase in frequency produces a 10X decrease in the 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 (Eden, 2013).

Lower system cost – While WBG semiconductors are generally higher cost than silicon, system level cost reductions are sometimes possible through the use of WBG by reducing the size/costs of other components such as passive inductive and capacitive circuit elements, filters, cooling etc.

Hull (2013) illustrates the first three of these points in a discussion of a 30 hp electric motor where silicon power electronic devices in the motor’s variable frequency drive (VFD) are replaced with SiC devices. The higher cost of the WBG-based VFD in this example is recovered in six to twenty four months depending upon the assumed per kilowatt-hour cost of electricity. Such a payback period is acceptable when considering VFDs that are designed to have a life in excess of ten years. Regarding power density, silicon-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 its former size. A leading manufacturer of VFDs confirms that higher power density VFDs is a very important value proposition for its customers (Lenk, 2013). Regarding switching frequency, the silicon carbide solution allows for a motor output of 30 hp for any switching frequency in the range of 8 kilohertz (kHz) up to 16 kHz. By contrast, the silicon solution is limited to only 8 kHz switching if a motor output of 30 hp is to be achieved. At 16 kHz switching, the motor output is limited to only 20 hp with the silicon solution. Hull provides an example of the fourth point, system cost reduction, with a case where the cost of a silicon carbide-based boost converter is reduced by 20% over its silicon counterpart through reduced inductors and heat sink costs.

SiC devices in hybrid vehicle motor inverters have the potential for additional impact because of their improved high temperature properties over silicon 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 (Eden, 2012). In fact, according to McKinsey & Company (McKinsey & Company, 2012), when all the cost savings for the OEM and consumer are considered, the value proposition for SiC devices in HEV inverters is better than the value proposition for IGBTs. **Figure 8** illustrates this conclusion with a waterfall chart where fuel savings over an 8-year vehicle life at $3/gal gasoline are realized by consumers, while savings from weight reduction, reduced passive component requirements, and reduced cooling system requirements are realized by OEMs.

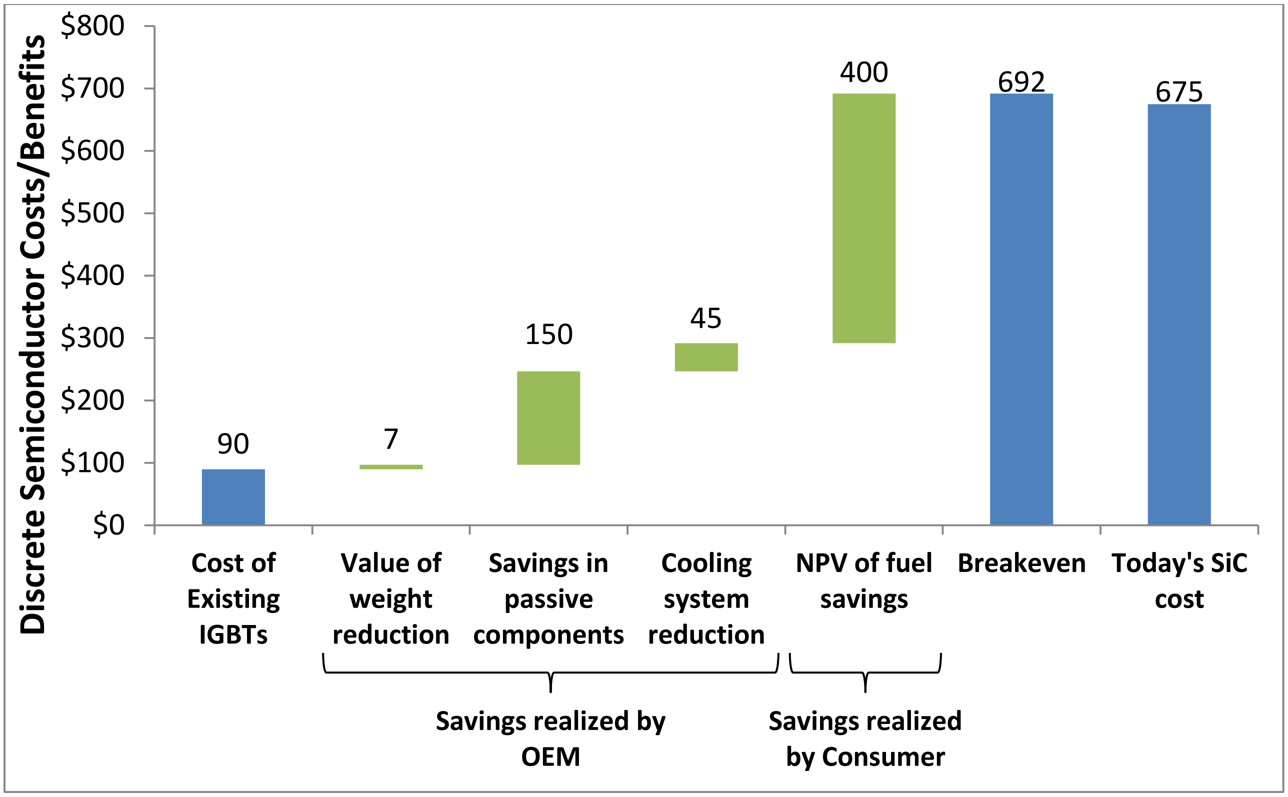

Figure 8. Cost-effectiveness of SiC transistors over IGBTs for HEV inverters based on the entire value chain (McKinsey & Company, 2012).

Information to quantify the benefits of switching from silicon-based SJ-MOSFETs to GaN-based HEMTs on a system level is not widely available. One available comparison is for a 250W internal power supply of an all-in-one iMac desktop computer (Transphorm, 2014). The GaN-based power supply used three Transphorm HEMTs and switched at 200 kHz as opposed to 50-80 kHz for the silicon-based iMac supply. This allowed for a 55% size reduction, as well as efficiency increases from 82% to 85% for a 15W output supply and 92% to 94% for a supply with 180W 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. (2014) have discussed the efficiency gains for a GaN based Buck-PFC circuit as might be used in a 90W laptop adapter. They compared the 115VAC performance of a Buck-PFC evaluation module from Texas Instruments with a GaN HEMT and SiC Schottky diode against the same module with a SJ-MOSFET and a silicon Hyperfast diode. The WBG module allowed for a 1–2 percentage point efficiency improvement with more pronounced gains at lower power levels. A number of sources claim transistor efficiency improvements of 3–7 percentage points (Reusch, 2013; Texas Instruments, 2012) and DC-DC conversion efficiency improvements of 2–4 percentage points (M. A. Briere, 2012; Extance, 2013) with the greatest improvements at the low end of a device’s power range.

3. Program Considerations to Support R&D

Based on a 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 (ORNL, 2013). There was also a perception that materials research was 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 U.S. However, it should be noted that DoD has heavily funded basic materials research in GaN and SiC over the last 20 years. As a result of this sustained funding, wafer diameters have increased from 1” to 6” along with much improved material quality. Therefore, it was deemed important by DOE to focus resources in 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 epi layers to manufacture 600 V to 15 kV devices. Once the wide-spread adoption of WBG devices occurs as a result of reduced chip cost, it will create a market pull for increasing the substrate diameter to 200 and even 250 mm which is expected to happen without external funding.

A lack of scientists and engineers with the training to characterize the physics of atomic film structures and their interfaces between materials was also mentioned. There was also a general perception that the U.S. government was not investing enough money in WBG research to keep up with Japan or possibly to avoid being eclipsed by China. In addition to direct funding of research, tax policies that would encourage internal research and the purchasing of capital equipment for WBG processing were also discussed. Other comments concerned the overseas flow of intellectual property that was directly or indirectly developed through U.S. government funding, and what mechanisms might be used to reduce this (ORNL, 2013).

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 choose a more expensive part that 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 the manufacturer had no incentive to pay the few extra dollars to add them, since manufacturers don’t pay the operating costs.

In addition to the PowerAmerica Institute, other public/private partnerships are being formed to advance WBG power electronics manufacturing in the U.S. New York State will partner with a large number of private companies, led by General Electric (GE) and including Lockheed Martin, to launch the New York Power Electronics Manufacturing Consortium (NY-PEMC). The public-private partnership will invest more than $500M over five years, focused on the development of next-generation wide-bandgap semiconductor materials and processes at the state-owned R&D facility in Albany, NY. GE will be a lead partner in the fab, housed at the newly merged State University of New York (SUNY) College of Nanoscale Science and Engineering (CNSE) Nano Tech complex, which aims to develop and produce low-cost 6” silicon carbide (SiC) wafers (Semiconductor Today, 2014).

NextEnergy and the Power Electronics Industry Collaborative (PEIC) are focusing activities on identifying domestic challenges, opportunities and pathways forward in wide band gap technologies for the power electronics industry (NextEnergy, 2013). In an industry led workshop held in 2013 they recommended actions to address specific gaps including adopting an application-driven approach, a lack of adequate testing procedures to demonstrate reliability, and methods of accelerating and de-risking innovation. Other recommendations included the strengthening of power electronics expertise and means of reducing in the talent deficit in the U.S.

4. Risk and Uncertainty, and other Considerations

Risks of increased research and investment in WBG materials for power electronics include the anxiety, discussed by many participants in the survey mentioned in Section 3, that intellectual property could be lost to countries like China that have large capabilities for the production of silicon semiconductor devices.

Risks that are more intrinsic to the devices themselves include 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 have shown marked improvement in this area that are helping to alleviate these concerns.

Finally there are external factors that could affect the penetration of WBG devices in power electronics. One is that emerging markets could be lax in 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 not see a short enough payback period.

The cost of WBG devices will achieve parity with today's silicon prices (10 cents/A for 1200 V Si IGBT) in 5 years through the use of commercial silicon foundries and may fall to much lower value (1.5 cents/A for 1200 V SiC MOSFET) in the next 8 years through the advent of fine-line lithography (Total on Resistance (Ron) from today's 5 mohm-cm^2 to 1 mohm-cm^2) made possible by flatter wafers. When 8" wafers are introduced in 5-8 years, the price of 1200 V SiC MOSFETs could fall to 1 cent/A (Agarwal, 2014b).

5. Sidebars

5.1 AC Adapter Global Energy Consumption

EPRI estimated that 130TWh of electricity was consumed by U.S. residential electronics in 2008 (EPRI, 2009). A 2009 report for the International Energy Agency assessed the global energy consumption of external power supplies for electronic devices like laptops and mobile phones in 2008 at nearly 50TWh, or about 1% of global electricity consumption (Ellis & Jollands, 2009). Mobile phones, MP3 and AC adapters were estimated to use 45% of this energy or roughly 23TWh 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 external power supplies (EPSs). A report for the Department of Energy (DOE) (Navigant Consulting Inc., D&R International Ltd., & Lawrence Berkeley National Laboratory, 2012) classifies 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. 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 404GWh.

Based on the 2.6 Potential Impacts section, it is reasonable to assume that introduction of GaN HEMTs to laptop adapters could increase laptop efficiency by 3%. This is a conservative assumption as 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 5**. The 2014 sales numbers in this table were based on (Eykyn, 2013; Gartner, 2014). The 3 year projected adapter life used to determine the global stock was based on (Boyd, Horvath, & Dornfeld, 2009). The 1,904GWh saved for laptop adapters would amount to $114 million assuming a cost of $0.06/kWh.

The table 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 (Navigant Consulting Inc. et al., 2012). 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 7,670GWh from the use of WBG transistors in these adapters is on the scale of the annual output of a mid-sized 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. 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 which enables their introduction into flat screen TV power supplies substantial energy savings will be achieved through their higher efficiencies.

Table 3. Potential impact of WBG components on global energy use.

Transistor Material	Application	Average power rating (W) (1)	Average active mode efficiency (1)	Annual loss per unit (kWh)	2014 Global sales (MM) (2)	Assumed product life (yrs) (3)	Global stock (MM units in service)	Annual electricity loss by global stock (GWh)
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	5610	23,562
	Total							**33,237**
WBG	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	5610	18,125
	Total							**25,567**
WBG Savings (GWh/year)								**7,670**
WBG Savings (TBtu/year)								**26.2**

Sources: 1 (Navigant Consulting Inc. et al., 2012), 2 (Eykyn, 2013; Gartner, 2014), 3 (Boyd et al., 2009)

5.2 Data Centers

Data centers in the U.S. consumed approximately 2.2% of total U.S. electricity in 2012, amounting to 288 TBtu (ASE 2012, EIA 2013). Power conversion activities inside an average data center (Power Use Effectiveness (PUE=1.8) account for 10.4% of the energy consumed in the average data center (EPA 2007). Switching from Si based devices to WBG based devices increases conversion efficiency from 90% to 98% (ORNL 2005). This means that data centers will see an 8.3% reduction in energy usage by the power electronics.

Beyond this direct reduction in energy usage, the losses that would have been occurred 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 36.6 TBtu of energy savings from the full implementation of wide bandgap devices in data centers.

5.3 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 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 redirected or counteracted in some way so that not all of it reaches the load. This is an inherent inefficiency that could be addressed with greater adoption of VFDs. An example of a motor driven system without an ASD is a fan system where airflow is controlled by dampers. At all times in such a system, more airflow than is actually needed is generated by the fan, and dampers are used to divert excess airflow after energy has already been expended by the motor. By contrast, incorporation of an ASD in such a system allows for precise control of motor speed such that it is exactly matched with airflow requirements, thereby saving energy.

Estimating the potential energy savings from increased adoption of VFDs in the global stock of electric motors is difficult because 1) the potential benefits vary from one application to the next, and 2) 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% respectively have been estimated through the use of VFDs (Lowe, Golini, & Gereffi, 2010). The current penetration rate of VFDs for electric motors is thought to be quite small at less than 10% in industrial applications (U.S. Department of Energy, 1998). If it is assumed that VFDs can achieve an average energy savings of 15% of in the global stock of industrial electric motors, and that 90% of such motors are not presently equipped with VFDs, then electricity consumption in the industrial sector could potentially be reduced from 4488 TWh/yr to 3882 TWh/yr if 100% penetration is achieved.

Currently, VFDs use conventional silicon-based semiconductors which are less efficient than WBG semiconductors. As an extension of the preceding energy estimate, if it is assumed that silicon VFDs have an average efficiency of 94.5%, with 100% penetration of silicon VFDs, global electricity losses in industrial electric motor drives can be estimated to be 214 TWh/yr (3882 TWh/yr × 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/yr (214 TWh/yr × 45%) of VSD losses. In other words, WBG semiconductors could offer additional electricity savings of 117 TWh/yr (399 TBtu) over traditional silicon-based VFDs, provided 100% penetration of WBG was achieved as shown in **Figure 9**. In summary, if SiC VFDs achieved 100% adoption for relevant motors systems the global energy savings would be 723 TWh/yr. The energy savings potential is significantly lower, i.e., 11 TWh/yr when limited to U.S. market and the energy savings are based on the improvement in VFDs resulting from WBG materials use (Energetics, 2014).

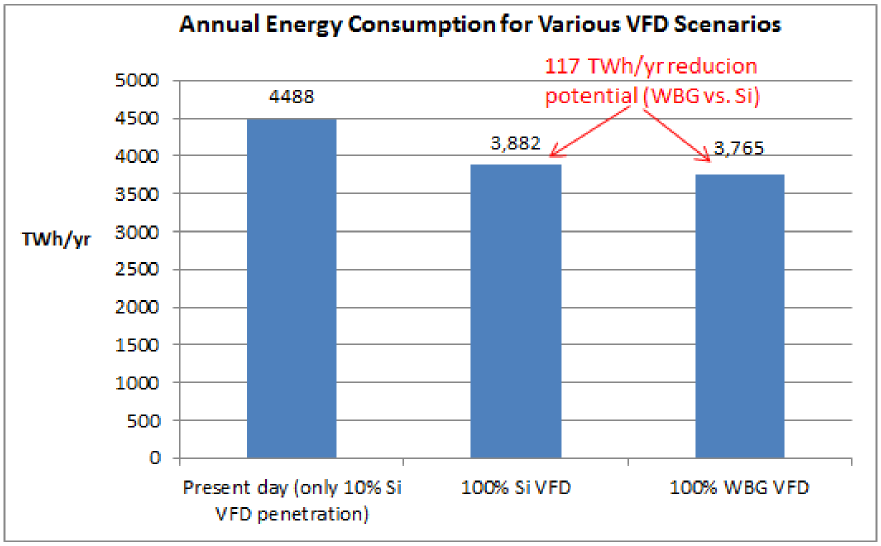

Figure 9. Electricity reduction potential in industrial electric motors from silicon- and WBG-based VFDs

5.4 Renewable Energy Generation

Renewable power sources are distinct from other sources of power generation in that the current must often be converted between DC and AC power to produce power suitable for grid interconnection. The values discussed in this section are based upon 2013 U.S. operation (EIA 2013); given the rapid deployment of renewable energy generation the opportunity is expected to grow in lockstep.

Solar panels (photovoltaics or PV) 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, 22.6 billion kWhr (77.0 TBtu) of power was generated by solar PV in the U.S. The energy savings rate of SiC inverter over a Si inverter was found in literature to be equal to 3% (from 96% to 99%) (Burger 2006, McDonald 2011, and APEI 2014). Assuming full implementation of SiC devices in solar panel inverters, an additional 2.3 (= 77.0 *3.0%) TBtu of renewable energy could be produced.

Modern wind turbines generate variable frequency AC power depending on the wind speed. This AC current of variable frequency is then rectified to DC before being inverted back to AC at the necessary grid frequency. While this set-up has losses associated with the conversion process, it permits wind turbines to operate at peak generating efficiency. Therefore, the deployment of wide-bandgap based semiconductors would increase efficiency. In 2014, 572 TBtu of energy was produced by wind turbines in the U.S. (NREL 2012). It is estimated that there would be a 4.6% absolute improvement in efficiency at 3 kHz switching speed, from 93.5% efficiency of silicon to 97.8% efficiency of WBG system, based on literature (Zhang 2011). The additional annual generation possible from 100% implementation of SiC in wind turbine converters is 572*4.6%=26.3 TBtu.

The displacement of Si by SiC- based devices could allow renewable power sources to generate an additional 28.6 TBtu of renewable power.

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