Opportunities and Challenges of Wide Band Gap Power Devices

Introduction

In their White Paper "Driving Innovation in Power Electronics Across the UK Community", Power Electronics UK [1] identified the top 10 technology challenges in power electronics. These included higher reliability and robustness in semiconductor devices and other low level components, more advanced semiconductors that yield better voltage and current ratings, faster switching speeds, greater efficiency (lower losses), higher operating temperatures, and (at high power) higher switching voltage. A new generation of semiconductor products based on Wide Band Gap materials is now emerging as the answer of the power electronics industry to overcome these technology challenges.

For more than 60 years since their invention, semiconductors based on silicon (Si) have been a cornerstone of the electronics industry. They are used across a wide range of industries and applications to help with the processing of signals or the conversion of energy. Silicon devices have been dominant in power electronics for as many years, but as with every technology, it is now getting close to the physical limits of what can be done with it as a switch. There is a general trend to make electronics smaller. One of the best ways of making power converters smaller is to increase the switching frequency, but all semiconductors waste energy as they switch. If the switches are run faster, then more energy is wasted. If the trend to smaller and more efficient electronics is to be continued, a new class of semiconductor is required. Wide Band Gap (WBG) semiconductors have the potential to continue the technology trends and even open new fields and applications with their superior properties.

A broad range of WBG materials has been studied over the years and some of the best for power electronics are based on compound semiconductors. These are composed of more than one element from the periodic table. These materials include among others, silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaS), indium phosphide (InP). Although not a compound, diamond also qualifies as a wide band gap material. For power electronics (PE) applications, the most promising candidates are SiC and GaN based semiconductors. SiC devices are most suited for high voltage, high power applications. By comparison, GaN promises to be the ideal material for use in lower power, high switching frequency applications.

This paper discusses the relative benefits of WBG, and specifically SiC and GaN, over silicon-based semiconductors. It also analyses the challenges that industry is facing to the widespread adoption of WBG semiconductors. It continues with a review of the applications, existing and new, that will benefit from this new generation of semiconductors. Finally, it assesses what future research is needed to continue the development and corresponding adoption of WBG semiconductors to unleash new application solutions for power electronics.

Perceived advantages of WBG compared to Si

WBG semiconductors represent a paradigm shift for the semiconductor industry thanks to certain power electronic performance advantages that these devices offer over traditional and more established silicon-based solutions. The main advantage is a marked reduction in power losses for a given rating.

Traditionally, power electronics engineers have had to deal with a design trade-off between system efficiency and system compactness. Indeed, they have the choice of switching their semiconductors at a higher frequency in order to reduce the size of their passive components to increase the system power density. The price to pay for this design choice is an increase in power losses leading to an increase in heat dissipation and a corresponding reduction in system efficiency. The opposite available choice is to maximise system efficiency at the expense of lower power density due to the proportionally larger passive components needed at lower frequency. WBG devices offer an exciting alternative path that allows more freedom in these hard trade-offs. Indeed, with the use of WBG semiconductors, it is not only possible to operate at a higher switching frequency, leading to smaller PE systems, but also maintain lower levels of power losses when compared with what is possible with silicon semiconductors.

The increased performance of WBG devices is due in great part to the broader energy bandgap that exists between the electron valence band and conduction band of the semiconductor when compared to Si based products. For instance, while the bandgap for silicon is 1.1eV (see Table 1 for material properties), it is nearly three times larger at 3.2eV for silicon carbide (SiC-4H) and 3.4eV for gallium nitride (GaN).

Material Property	**Si**	**SiC-4H**	**GaN**
Band Gap (eV)	1.1	3.2	3.4
Critical Field (10^6 V/cm)	0.3	3	3.5
Electron Mobility (cm^2/V.s)	1450	900	2000
Electron Saturation Velocity (10^6 cm/sec)	10	22	25
Thermal Conductivity (Watts/cm^2.K)	1.5	5	1.3

Table 1: Material properties (source: Microsemi [2])

This difference in bandgap defines how much energy is needed for electrons to jump from the valence band to the conduction band. One of the ways for electrons to gain the required energy is from heat. Once thermally excited electrons are in the conduction band, the semiconductor will conduct and any electronic switch made of this semiconductor may be unable to turn-off. Having a wide bandgap means that WBG semiconductors can operate at higher temperature than Si. This higher temperature performance gives the designer the option of operating in a high temperature environment, or of making the switch smaller than a similarly rated Si device to increase the power density. Maximum junction temperatures for silicon based Insulated Gate Bipolar Transistors (IGBT) are typically 150°C. By comparison, commercially available SiC MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor) devices of the same power rating can operate with junction temperatures of up to 200°C.

Another way that electrons can jump to the conduction band is by the application of an electric field above a critical level. SiC and GaN have higher critical electric fields (see Table 1) about 10 times that of Si. This allows them to withstand higher voltage levels for a given size. With this material property, it is possible to design power devices that are smaller in all dimensions, which in turn leads to a lower chip price and higher power density for the power converters. For example, the drift region of a power device can be made much thinner and lower resistance giving a big decrease in the conduction losses [3]. Also, owing to the smaller chip dimensions, device capacitances will be reduced compared to Si. As a result of these factors, conduction and switching losses are significantly reduced leading to higher efficiency.

SiC devices also benefit from an improved thermal conductivity compared to Si. Indeed, SiC has more than three times the thermal conductivity of Si. This drastically improves heat dissipation. When combined with the low losses generated by the device, it can be seen why SiC can be the best choice for high power applications.

Perceived challenges of WBG compared to Si based solutions

While WBG devices have been available commercially for more than a decade, their application in the field is still rather limited as of today. Several reasons can be given to explain the present situation.

Low technology maturity

As the device technology is less mature when compared to Si devices, this leads to:

- Lower device reliability
- Lower availability and higher device costs
- Lack of accurate simulation models

Lower device reliability comes from poorly understood material defects that can occur during the manufacturing process. It is also linked to technical difficulty with the repeatability of gate oxide in SiC MOSFETs. Reliability can also be affected by packaging problems that lead to an imperfect heat spreading within the device. Finally, unseen fast voltage spikes can provoke an early device failure due to over-voltage or too much transient power loss. In GaN HEMTs the conduction path is in a very thin 30nm sheet called a 2DEG (2-dimension electron gas). Any imperfection in this sheet will have a severe effect on the operation of the transistor.

Any new technology will take some time to enter volume manufacture and during this time the availability of parts will be lower than for a more mature technology. SiC and GaN are currently experiencing this problem with availability. Widespread adoption of WBGs will need high levels of investment in new manufacturing equipment and this will come in time when the benefits have been proven. For similar reasons today’s lower volume manufacture and immature technology leads to higher cost of manufacture for WBG devices, in particular for chips.

Finally, a lack of accurate simulation models is also a source of unreliability as it makes it difficult to simulate complex operating modes and fault conditions. These operating conditions might be difficult to physically test, so the designer might assume that all is well when it is not.

New measurement equipment needed

It is currently difficult to define the properties of the new WBG devices since the required measurements to fully characterise them are in some cases beyond the specifications of existing laboratory test equipment. Therefore, new equipment together with new techniques are needed to measure with significant accuracy the very fast switching and very low level of power losses from WBGs.

Points to consider when choosing and designing new test equipment are:

- Measuring a signal will affect the circuit
- High speed high voltage probes need a high speed high voltage probe compensation reference pulse circuit
- High current, high bandwidth current sensors are large and will need the creation of special structures to allow them to be used without affecting the circuit too much

Higher switching frequency operation

SiC and GaN transistors can operate at very high switching frequency owing to the dramatic reduction in switching loss compared to Si. To do so comes with a few challenges some of which are outlined below.

The cost of the control circuit will increase as the frequency increases because faster control of the switches is needed.

High dV/dt and di/dt in the circuit will cause EMI problems with long development time needed to find a way to achieve EMC. New layouts, gate drive and construction techniques will be needed. New topologies and control will also be needed if it is necessary to move from hard switching to resonant switching.

Poor body diode

Poor body diode (eg. SiC MOSFET) or no body diode (GaN HEMT) can require

- More complex control needed to give synchronous rectification (eg. Adaptive gate drive)
- Additional anti-parallel SiC Schottky diode may be needed [4]

Packages

Semiconductor packaging has been designed and optimised for use with silicon. As WBG chips have different requirements, existing packages are therefore ill-adapted to deliver the full benefit of WBGs.

For SiC transistors and diodes, the main problem is the smaller chip size for a given power loss. Heat spreading and improved mounting techniques are needed for wider temperature ranges than used for Si otherwise the greater temperature cycling may cause damage to the chip or the interconnections. Similarly, GaN transistors switch so fast that ultra-low inductance packages are needed to prevent the device from being destroyed from high voltage spikes caused by the rapid switching.

A number of manufacturers have created new packages that better suit the new WBG technology, but these are unique to particular manufacturers which makes multi-sourcing difficult.

Competition from Si

On-going improvements in Si MOSFETs and IGBTs mean that Si based solutions will continue to slow the adoption of WBG devices. Si will give the best solution for many applications for some time yet.

Lower system reliability

The fast switching action of WBG devices that is benefiting the system overall through a reduction in size and weight also introduces some challenges that require to be mitigated properly at the design stage to avoid reliability issue over time.

In particular, the high dV/dt that accompanies the fast switching can cause multiple problems including the following:

- Motor and cable insulation damage in hard-switched motor drive applications
- Insulation damage inside the power converter
- Hot spots in PCBs
- Higher than expected losses in capacitors and magnetic components

Lack of skills

The emergence of a new technology creates knowledge gaps in the workforce. This lack of skills in design teams prevents the best use of the new technology. Therefore, an emphasis shall be put on training and upskilling the workforce to maximise the use of these new WBG semiconductors.

Applications

Best applications for Si today

Silicon based semiconductors are still dominating the landscape of applications using power electronics equipment. Figure 1 from Infineon illustrates which device is currently the most suited for each segment of the market. The required power is mapped against the switching frequency chosen for the application. For example, for an ultra-high power application such as an HVDC system, thyristors are used to form a Line Commutated Converters (LCC) capable of transmitting gigawatts of power but with the Si thyristors commutating only at mains frequency. By comparison, a Si MOSFET operating at low power and mid frequency is the device of choice for Switch Mode Power Supplies (SMPS).

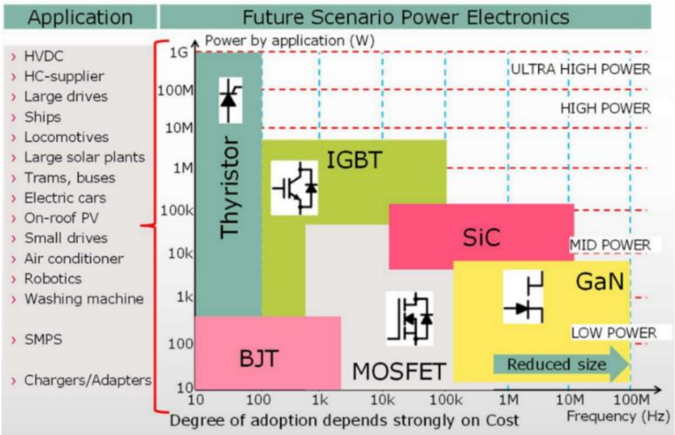

Figure 1: Semiconductor applications relative to level of power and frequency (source: Infineon Technologies AG [5])

As WBGs grab an ever-larger share of the semiconductor market moving forward, there will still be some applications for which silicon devices will remain the most appropriate choice.

These applications include:

- Un-controlled line frequency rectification (diodes)
- Low cost line frequency control (thyristors)
- Where robust short-circuit behaviour is needed (IGBTs)
- Where lowest cost is more important than anything else
- >10MW applications
- DC load switching (battery enabling)
- Where a micro-controller must be integrated with the power switch (WBG micro-controllers are not currently possible)

Best applications for SiC today

There are already today some applications that commercially exploit the benefits of silicon carbide devices. These applications include:

1. SiC Schottky diodes
2. SiC MOSFETs where power is more than 1kW and device voltage is 1200V and
    a. smallest system size and weight is more important than anything else
    b. Fastest response time is more important than anything else.
3. JFETs for applications where robustness (temperature and lack of gate oxide vulnerability due to cosmic rays etc.) is more important than anything else
4. Where high temperature operation is more important than anything else

Best applications for GaN today

GaN devices are currently not as advanced when compared to SiC. Nevertheless, there are already a number of applications that exploit these semiconductors, including:

1 GaN HEMTs on GaN, Si or sapphire where power is less than 5kW and device voltage is 600V and
    a. smallest system size and weight is more important than anything else.
    b. fastest response time is more important than anything else.
2. High temperature magnetic field and current sensing

Further research

To facilitate an accelerated adoption of WBG semiconductors, further research is required in several critical subjects.

Magnetics

New magnetic materials [6] are especially needed to achieve components with low loss at high frequency and high flux density that can be better integrated with WBG at the system level. For illustration, GaN power transistors are being used in laptop chargers. A 45W charger from Mu has GaN devices capable of operating at 10MHz. However, it is only run at about 300kHz because of the limitations of the magnetics and control IC.

Higher voltage GaN

Another area of research is to achieve an increase in voltage rating for GaN devices and in particular:

- 1200V GaN on Sapphire
- Higher voltage GaN ICs with integrated power transistors.

Lower Cost

Lowering the unit cost of WBG will play a key role in democratising the use of these devices. Researches that will help with this important goal are:

- Develop a vertical GaN on Si to enable lower device cost
- Improvements in GaN and SiC yield leading to a reduction in cost and increased availability
- Scale-up of manufacturing plants for GaN and SiC generating economies of scale savings
- Continue to research alternative WBG materials such as GaO

New device designs

The optimal exploitation of WBGs can also be realised through the creation of new power topologies that make the best use of GaN and SiC. The development of bi-directional GaN and SiC transistors with easy gate drive will enable matrix converters, Vienna rectifiers etc.

Whilst Si thyristors dominate power conversion at the largest scale today, SiC is a superior choice in certain applications and new high voltage SiC switches based on bipolar technology like thyristors and IGBTs are already in the design stage.

Packaging

Improvements in cooling technology will be needed to give good reliability under the more severe thermal loading than seen with silicon devices. Furthermore, improved dielectrics are essential for operation at high frequency and high temperature in a small size.

To take full advantage of the faster switching property of WBG and to increase power density will require greater system integration in package. Finally, agreement on high performance standard packages for GaN and SiC is needed.

Conclusion and Recommendations

Thanks to their superior performance allowing for faster, more energy efficient and more compact systems for certain applications, Wide Band Gap semiconductors are already becoming accepted into the mainstream for power electronics applications and will continue to make in-roads into the dominant position of the incumbent silicon-based products.

As with any new technology, challenges and hurdles have to be overcome for these new WBG devices to be more widely adopted. Progress in the basic materials and the devices themselves is required to make WBG more cost effective and reliable. In addition, the desired increase in performance can only be unleashed if these devices are integrated into power systems capable of supporting them. This means the development of a new type of passive components that can cope with the high frequency or operating temperatures. It also means customised gate drivers and sensors that can control and protect these new devices. Finally, it also implies careful thermal and EMI management to achieve the most compact and energy efficient systems possible.

As volume and economy of scale start to gather pace, SiC and GaN at the device level will become cost-competitive against existing Si products. When combined with the system level benefits that come with lower losses and higher power density, Wide Band Gap devices will unleash a new wave of application solutions for power electronics systems that are today not possible with silicon technology.

References

[1] “*Driving Innovation in Power Electronics Across the UK Community*” Power Electronics UK, 2017. https://www.power-electronics.org.uk/

[2] Gallium Nitride (GaN) versus Silicon Carbide (SiC) In The High Frequency (RF) and Power Switching Applications, Microsemi

[3] “*SiC features 10x the breakdown electric field strength of silicon, making it possible to configure higher voltage (600V to thousands of V) power devices through a thinner drift layer and higher impurity concentration. Since most of the resistance component of high-voltage devices is located in the drift layer resistance, SiC makes it possible to achieve greater withstand voltages with extremely low ON-resistance per unit area. Theoretically, the drift layer resistance per area can be reduced by 300x compared with silicon at the same withstand voltage.”* From Rohm website.

[4] “*Is an antiparallel SiC-Schottky diode necessary? Calorimetric analysis of SiC-MOSFETs switching behavior*” Kreutzer, Billmann, Marz. PCIM 2018

[5] *“The Future of Power Semiconductors, Rugged and High Performing Silicon Carbide Transistors”,* Dr. Peter Friedrichs and Marc Buschkühle, Infineon Technologies AG

[6] “*Empowering the Electronics Industry A Power Technology Roadmap*” PSMA – APEC 2017

Acronyms

EMC	Electro Magnetic Compatibility
EMI	Electro Magnetic Interference
HEMT	High electron mobility transistor. A type of structure usually used to make GaN power transistors
IGBT	Insulated gate bi-polar transistor
MOSFET	Metal oxide semiconductor field effect transistor
WBG	Wide Band Gap