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Review of Wide Bandgap Materials and their Impact in New Power Devices

David Garrido-Diez[1] and Igor Baraia[2]
Electronics and Computing Department
Mondragon Unibertsitatea
Mondragon, Spain
E-mail: [1]dgarrido@mondragon.edu, [2]ibaraia@mondragon.edu

***Abstract*—Power electronic converters use semiconductors to satisfy the needs of different applications. Nowadays, these semiconductors are mainly based on Silicon (Si), which can be processed virtually without defects. However, the limits of Si are being reached and in consequence, Si based semiconductors have limited voltage blocking capability, limited heat transfer capability, limited efficiency and maximum junction temperature. In recent years, power semiconductor devices have been built with wide-bandgap materials such as Silicon Carbide (SiC) and Gallium Nitride (GaN). The use of these materials promises to surpass the limits imposed by Si. More compact and efficient devices can be fabricated with these materials. However, in order to exploit the benefits of these devices, is necessary to know all the implications that the adoption of these new components has in the converter. This paper provides a review of current SiC and GaN materials and devices comparing their benefits and drawbacks for real power applications.**

***Index Terms*—Wide Bandgap Semiconductor; SiC; GaN; Power Devices;**

I. INTRODUCTION

The growing electrical energy consumption is strongly related to the continuous economic and social development [1]. From an environmental point of view, the reduction in fossil resources consumption and the promotion of renewable energy sources is desired [2]. Efficiency is a key parameter to achieve a sustainable increase of the energy consumption. From the energy generation to the energy consumption there are several energy conversion stages. During the last years, the use of power electronic converters in these power conversion stages has increased as the result of the development and improvement of power semiconductors in terms of current and voltage handling capabilities [3]. Generally speaking, up to now, the vast majority of those power converters are based on Si devices (MOSFETs, IGBTs, diodes…). In consequence, the efficiency, cooling requirements and power rating of the electronic converters depend on the efficiency, thermal conductivity and voltage and current limits imposed by Si. During the last years, new power semiconductors based on wide band gap materials (SiC and GaN) have penetrate into the market [4]. Although these new wide bandgap devices are in an early stage of development, they have promising characteristics to overcome the limits imposed by Si. However, the use of these devices implies new challenges in driver circuits, layouts, EMI considerations,…

We expose first Wide Bandgap (WBG) materials and their characteristics, focusing on those that are being applied in industry, mainly SiC and GaN. Secondly, a state of the art on WBG power devices is presented, focusing in technology maturity, applicability, benefits and drawbacks.

II. WIDE-BANDGAP MATERIALS

The energy required by an electron to jump from the highest part of the valence band to the lowest part of the conduction band is the energy bandgap of a semiconductor, W_g. While the Silicon has an energy bandgap of 1.1 electron volt (eV), materials with more than 2 eV of energy are known as Wide Band-Gap (WBG) materials.

In order to evaluate the influence of different materials on power semiconductors, Table I shows properties of different WBG materials and Silicon.

E_{crit} is the maximum electric field that the material can support before the avalanche breakdown. Higher value of E_{crit} leads to a greater voltage blocking capability, shorter drift width and makes possible the increase of the doping concentration. Thus, even on the case of high voltage devices, low drift resistance and low conduction losses can be achieved. The electron mobility μ_n is the speed achieved by the electron under a given electric field. Great mobility implies less electrical resistance and in consequence, lower conduction losses. The relative electric field permittivity ε_r has an important influence on the value of interelectrode capacitances. Low capacitance implies higher switching speeds and low switching losses. Finally, a low free carrier concentration n_i in an intrinsic material (without any dopant @ 300 K) makes possible strong doping concentrations to reduce the electrical resistivity of the material [7].

From the WBG semiconductor materials presented in Table I, SiC and GaN are nowadays the most used ones in power semiconductor devices, discarding for now others such as the Diamond due to its prohibitive manufacture cost [8].

A. SiC Material

Silicon Carbide (SiC) is a binary composite material made up of silicon and carbon. Each silicon atom shares its electrons

TABLE I
SI & WBG MATERIALS ELECTRICAL PROPERTIES [5] [6]

Semiconductor Material	W_g (eV)	E_{crit} (MV/cm)	μ_n (cm^2/Vs)	ε_r	n_i (cm^{-3})	λ (W/cmK)
Si	1.12	0.29	1350	11.9	$1e^{10}$	1.5
3C-SiC	2.35	1.5	900	9.7	$1.5e^{-1}$	3.2
4H-SiC	3.28	2.2	800	9.6	$8e^{-9}$	3.8
6H-SiC	2.96	3.2	370	9.6	$5e^{-9}$	4.9
GaN	3.4	2	1700	9	$2e^{-10}$	1.3/3
Diamond	5.5	20	2200	5.7	$1e^{-20}$	20

with four carbon atoms forming a tetrahedral crystalline structure. From this basic structure, different SiC polytypes can be formed. These polytypes are variations of the same composite material which, although identical in two dimensions, differ in the third, giving rise to different crystalline structures with different properties (Fig. 1). There are more than 250 SiC polytypes [9]. A slight temperature variation during the manufacture of the material, gives rise to differences in the way in which its crystalline structure grows. Between all, due to their promising characteristics, the $3C$-SiC, $4H$-SiC and $6H$-SiC polytypes have received the most attention from the power electronics industry.

The $4H$-SiC and $6H$-SiC polytypes are the only substrates available for power electronic devices whereas the $3C$-SiC wafers and devices, which may carry a manufacture cost reduction, are not yet available although presumably they will be in the near future [11]. The manufacture of SiC devices ($4H$-SiC and $6H$-SiC) is performed by the deposition of homoepitaxial layers on SiC substrate. Epitaxial deposition is a method for depositing different layers of monocrystalline material on a monocrystalline substrate. This substrate acts as seed crystal and the deposited layer grows with the same crystalline structure as that of the substrate. In this way, devices with different doped layers can be fabricated while maintaining the original structure of the substrate [12]. When creating electronic devices, it is necessary that the crystalline structures of the materials contain few or no defects, both in the substrate and in the epitaxial layers, since this implies uniformity of the device working area, thus having the same electrical and thermal properties. Most current SiC devices are based on the $4H$-SiC polytype due to its higher carrier mobility μ_n and due to the low anisotropy of its electrical properties [13] [14].

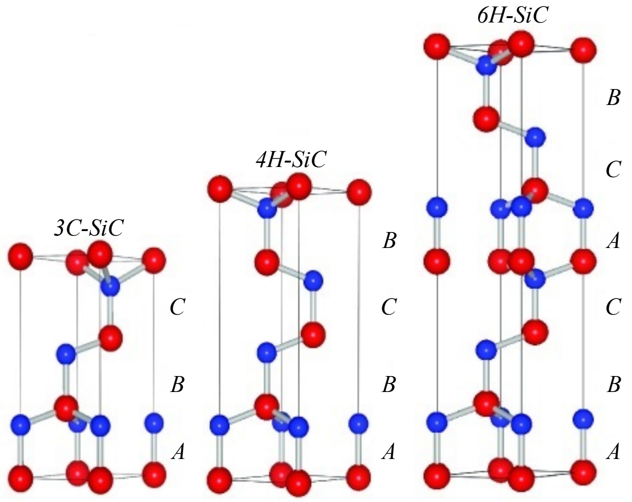

Fig. 1. Atomic structure of $3C$-SiC, $4H$-SiC and $6H$-SiC polytipes [10].

Production cost and quality of SiC material have limited its market penetration. In recent years great improvements in manufacturing have been achieved, definitively solving micropipe defects in the material [15]. Degradation of the direct voltage drop characteristic in bipolar devices based on SiC material has also been drastically reduced [16]. This degradation is due to the generation of ‘stacking faults’ in the crystalline structure, but since it has not been completely solved, the industry opts mainly for the manufacture of unipolar devices.

The capacity of the SiC material to withstand an electric field is 10 times higher than the capacity of the Si. In consequence, it could be said that SiC devices have the ability to withstand the same blocking voltage with a material 10 times thinner. This reduction on the thickness of the drift region, reduces the electrical resistance of the material during the conduction of electrical current [17] and in consequence, higher current densities can be achieved with SiC devices. In addition, due to higher saturation velocity v_{sat} and lower dielectric constant ε_r make possible the operation at higher switching dynamics in SiC devices [18].

In WBG materials, the thermal energy needed by an electron to move from the valence band to the conduction band (creating an electron-hole pair) is high. Thus, even at high junction temperatures the electric properties of the WBG device are kept under certain limits. This makes possible the operation of SiC semiconductor devices at high temperatures. In inversely polarized semiconductor junctions, electron-hole pairs are created due to thermal energy. These charge carriers circulating through the device are known as leakage current. The large leakage current of Si-Schottky diodes is the limiting factor for their use in Medium/High voltage/power applications. The use of WBG materials like SiC, makes possible the reduction of the leakage current of Schottky diodes and their use in Medium/High voltage/power applications. Finally, the higher thermal conductivity of the SiC material allows a more efficient evacuation, which theoretically reduces the cooling requirements of the converter.

B. GaN Material

The atomic junction of GaN is strong since it is composed of nitrogen, a light element. Their net parameter, meaning the distance of the atomic unit cells with respect to their crystalline structure within the same material, is smaller than those of other semiconductors of the conventional periodic table III-V groups [19]. As a result, the gallium nitride material offers better electrical characteristics than Si (Table I). Despite this, GaN devices currently do not achieve Si or SiC power performance mainly due to problems related to the substrate. Unlike the SiC, in the case of GaN, it is very difficult to manufacture devices by deposition of homoepitaxial layers on high quality GaN substrate. Currently, GaN wafer diameters of 2" have been achieved at a price 10 times higher than SiC and up to 100 times higher than silicon [5]. This is why the industry has opted for the deposition of heteroepitaxial GaN layers using another material (Si or SiC) as substrate. This leads to defects due to the difference between the crystalline structures of both materials. For this reason, devices with internal vertical structures, typical structures in power IGBTs and MOSFETs, have not yet been commercialized [20]–[22].

However, one of the most interesting properties of GaN, compared to other semiconductor materials, is the possibility of making AlGaN/GaN heterostructures on Si or SiC substrate. In these heterostructures a two-dimensional electron gas channel (2DEG) is formed, Fig. 2.

In this channel, the electrons move freely in two dimensions but are confined in the third. The 2DEG is formed between the layers of materials GaN and AlGaN due to the great difference between their conduction bands and the presence of fields of piezoelectric and spontaneous polarization [23]. In this channel, the mobility of the electrons can reach values in the range of 1200-2000cm^2/Vs.

Self-heating negatively affects the devices manufactured with this material and structure as the channel can reach several hundred degrees above ambient temperature. This affects not only its performance but it accelerates its degradation. In addition, in order to evacuate the heat generated in the 2DEG channel through the substrate, the thermal conductivity of the substrates becomes relevant [24].

In general, SiC and GaN materials offer similar improvements compared to Si. However, in contrast to SiC, GaN has been widely used on optoelectronics and radiofrequency applications due to its wide energy band and its promising characteristics for high frequency [25]. It has not been until the last decade when some power GaN devices have been commercialized.

III. WIDE BANDGAP POWER DEVICES

Commonly, different semiconductor materials are compared in terms of their impact on power electronic devices and applications. While the future of these materials is promising, they are still far from the voltage and current range of silicon devices. Fig. 3 shows a state of the art of commercially available Si, SiC and GaN power devices. Si power devices are placed for comparison purposes.

A. SiC-Diodes

Power converters require diodes with low conduction and switching losses. Schottky Body Diodes (SBD) and the PiN diodes are the most popular fast power diode structures.

SiC-Schottky Body Diode (SiC-SBD) was the first SiC power device to be marketed. The first generation of this device had a forward voltage V_F, determined by the Schottky junction, two time higher than their Silicon Fast Recovery Diode counterparts (Si-FRDs) [26]. Improvements in its manufacture process have led to voltage drops (V_F) lower than

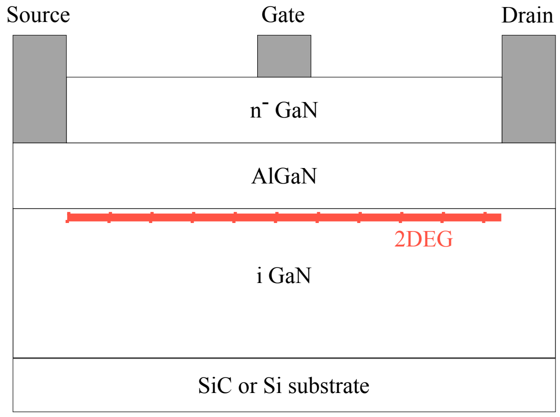

Fig. 2. 2DEG formation in a basic GaN HEMT configuration.

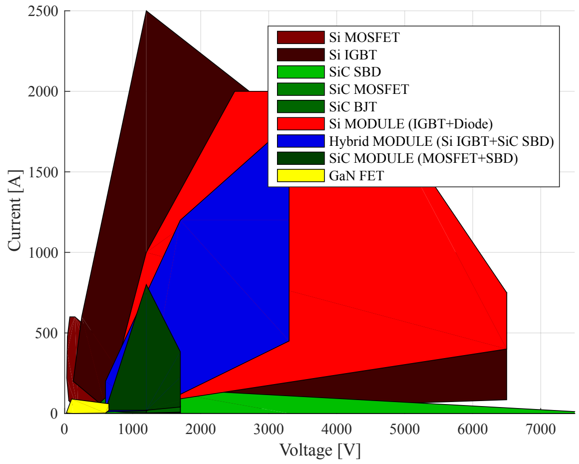

Fig. 3. I-V range of power electronic devices available in the market.

1 V [27]. Due to its positive temperature coefficient, the SiC-SBD can be parallelized to obtain greater current capacity. In addition, in contrast to silicon *pn* or *PiN* diodes, SiC-SBDs are unipolar devices, thus no storage of minority carriers is present in the junction. The reverse recovery current is therefore subject to the discharge current of the metal-semiconductor junction capacitance. The small value of this capacitance reduces the switching losses of the diode.

Commercially available 1200 V SiC-Schottky diodes are being rapidly adopted as substitutes of Si-FRD diodes. The use of Silicon transistors (usually Si-IGBTs) with SiC-Schottky diodes in the same module is known as hybrid module [28].

To reduce the leakage current an additional SiC N^- layer between the *pn* junction is inserted. By this technique, SiC-PiN diodes with blocking voltages up to 26.9 kV have been constructed [29]. However, the use of this additional N^- layer increases the switch off losses due to the presence of minority carriers in the device and becomes the temperature coefficient of the output characteristic negative.

According to [30], SiC-PiN diodes offer the best in class balance between the forward voltage drop, switching losses and maximum operation temperature for diodes with breakdown voltages from 10 kV to 20 kV. Several manufacturers, such as Wolfspeed, are combining PiN and Schottky structures to create diodes with low forward voltage drop and low switching losses (Schottky) with high voltage blocking capabilities (PiN). These diodes are known as MPS diodes (Merged PiN Schottky). The forward voltage drop of the SiC-MPS is determined by the resitance of the drift region, the metal-SiC junction (Schottky junction) and the implanted regions of doped material P^+. When the diode is forward biased, the presence of the implanted P^+ regions reduces the electric field at the metal-SiC junction due to the two-dimensional charge distribution. Under reverse bias, the depletion regions between the N^- region and the implanted P^+ regions grow, suppressing the leakage current arising from the Schottky structure [31].

B. SiC-FETs

SiC-JFETs have been postulated as an alternative to conventional power devices. The structure of JFET is simple and its gate terminal is not isolated from the device body. Thus, it has not got the stability problems related to the isolator material used in the gate terminal of the SiC-MOSFET [32]. Once the conduction channel of the JFET has been created, the current can circulate in both directions. The majority of actual SiC-JFET devices have vertical structures, thus, in order to increase the blocking voltage capability of the device the width of the drift region must be increased.

The basic JFET structure has a normally-on behavior. Thus, if a zero gate-source voltage (V_{GS}) is applied, the channel is completely opened. Negative gate-source voltages increase the depletion layer between the gate terminal and the body and thus, reducing the conductivity of the device or even driving the device into the blocking state. This behavior can be a problem during the turn on process of the converter since the on state of these devices can create short circuits in the converter.

The cascode configuration (Si-MOSFET + SiC-JFET) makes possible the construction of normally-off JFET devices. A conventional gate driver actively controls the low voltage MOSFET whereas the drain-source voltage of the MOSFET indirectly controls the SiC-JFET.

SiC JFETs can operate at very high current and voltage dynamics, which can derive in EMI problems. New gate drivers for JFETs are being studied to control the switching process without sacrificing the low switching losses [33].

In normally-off JFETs, the additional power losses in the low voltage Si-MOSFET $R_{DS\ ON}$ can be around 0.01% of the total power losses. However, normally-on JFETs are more efficient in hard switching applications due to the absence of this additional $R_{DS\ ON}$ [34].

C. SiC-MOSFET

One of the most important challenge in the fabrication of SiC-MOSFETs was the lack of a reliable insulator for the gate terminal. A proper insulator is needed to achieve stable forward I-V characteristic and a stable gate threshold voltage. For this reason, the SiC-MOSFET was commercialized later than the SiC-JFET. SiC-MOSFETs have low $R_{DS\ ON}$ even in high voltage devices and as unipolar devices, they do not have tail current during the switch off process. These characteristics have allowed the SiC-MOSFET to compete with Si-IGBTs in real power applications. In contrast to Si-MOSFETs, in a SIC-MOSFET there is not a clear limit between the ohmic and the saturation region in the output characteristic.

As a unipolar device, the switching process of the SiC-MOSFET is fast and efficient. This makes possible the operation at high frequencies and then, the SiC-MOSFET contributes to the size reduction of passive components. However, required large dV/dt-s can cause unintentional turn-on of the SiC-MOSFET. Large dV/dt-s injects current through C_{GD} to the gate terminal, Fig. 4. If the voltage in this terminal exceeds the threshold voltage, the MOSFET is turned on. In addition, a large dV/dt injects current through the C_{DB} capacitance to the base resistance of the internal parasitic BJT. In contrast to Si-MOSFETs, SiC-MOSFETs are especially vulnerable to

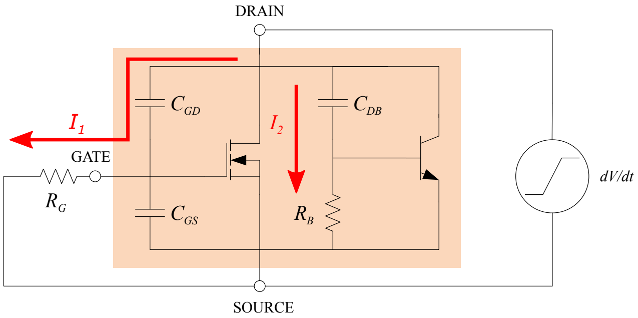

Fig. 4. SiC-MOSFET equivalent circuit showing dV/dt induced turn-on mechanisims.

both turn on mechanisms due to the larger value of the C_{DB} capacitance and a smaller gate threshold voltage.

Most MOSFETs contain a PiN diode inherent to their structure. This diode has a forward bias voltage around $2.5\ V$. During the conduction of the body diode, if the MOSFET is turned on, the forward characteristic of the body diode can be virtually improved and thus, the conduction losses reduced. To guarantee a stable characteristic of the gate threshold voltage, the minimum gate voltage during the blocking state should not be below $-5\ V$ [27].

D. SiC-BJT

Despite its good conduction characteristics, Silicon Bipolar Junction Transistor (Si-BJT) was set aside from power applications mainly due to the large amount of required driver energy. SiC-BJTs overcomes this drawback and $10.5\ kV$ devices with current gains of 75 and a conduction resistance of $110\ m\Omega$-cm^2, near the limit of the unipolar SiC devices ($94\ m\Omega$-cm^2) have been constructed [35]. The output characteristic of the SiC-BJT has almost no threshold voltage. Its positive temperature coefficient makes possible the easy parallelization of devices. Since it has not got any charge carrier storage in the collector region, there is not tail current during the switch off process [36].

Being a current-controlled device, it is immune to both electrostatic charges and unintended ignition due to large dV/dt-s. It does not have the manufacturing and instability problems present in the SiC- MOSFET as it doesn't have the gate oxide layer [37].

The main challenge for the massive commercialization of SiC-BJT devices is the degradation due to crystal structure defects [38].

E. SiC-IGBT

In the near future, it is expected that SiC-IGBT will play an important role in high voltage applications ($> 10\ kV$) due to their low conduction losses and high temperature operation. Thus, in contrast to Si-IGBTs, SiC-IGBTs will permit operation frequencies up to $10\ kHz$. In addition, the forward voltage drop at high temperatures will remain low (specially compared with SiC-MOSFETs) [39] since at high temperatures, the reduction of electron mobility is compensated by an increase of the carrier lifetime. dV/dt-s up to $100\ kV/\mu$s are expected for SiC-IGBTs and therefore, problems related to insulation of loads (electrical windings, transformers,...) and disruption in control and measurements signals are expected [40]. The required gate driver is similar to that required by SiC-MOSFETs ($20\ V$ to $-5\ V$).

No commercial devices or data are available yet, although Infineon-CREE is carrying research on these devices reporting $15\ kV$-$10\ A$ devices in testing stage [41].

F. GaN-HEMT

GaN high electron mobility transistors (HEMT) are especially attractive for high frequency applications due to their high switching speed and low conduction losses. In the 2DEG region, there is a high electron mobility due to the absence of impurities (dopants) enabling very low resistance and fast switching behavior.

The intrinsic capacitances (C_{GS} and C_{DS}) in FET architectures are smaller than the ones obtained with other materials. Similar to a MOSFET, this device can conduct in reverse mode, having the same voltage drop in both directions. Most of the GaN-HEMT transistors have lateral structures. This implies that their voltage blocking capability is lower than devices with a vertical structure. In consequence, one challenge of this technology is the increase of the blocking voltage capability of the device. In [42], a $3\ kV$ device with an on-resistance about $10\ m\Omega$-cm^2 has been reported.

However, commercially available GaN-HEMTs are normally-on devices. That means that special care must be taken during the turn on process of the converter. As in the case of SiC-JFETs, a cascade configuration turns the device into a normally-off device at the cost of a larger $R_{DS\ ON}$. In addition, due to the current collapse phenomena, the $R_{DS\ ON}$ and conduction power are increased. Finally, dV/dt immunity problems and large dI/dt problems related to overvoltages in the gate path are also drawbacks related to these power devices.

IV. CONCLUSIONS

In this paper, a review of SiC and GaN based power devices has been shown. It can be concluded that standard converter design guidelines can be applied but the faster switching behavior of these devices requires a more comprehensive understanding of the effects of parasitic elements.

These devices are prone to EMI problems, voltage ringing and overshoots since their fast switching dynamics excite resonant circuits comprising leakage inductances and parasitic capacitances. To reduce these problems, decoupling capacitors with low Equivalent Series Inductance (ESL) and layouts with minimum leakage inductances are mandatory.

Finally, in order to exploit the high junction temperature operation capability of WBG devices, it is mandatory the operation capability of packages, other surrounding auxiliary components and power devices at high temperatures.

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