# A REVIEW OF WBG POWER SEMICONDUCTOR DEVICES

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***Abstract***–*It is worldwide accepted that a real breakthrough in the Power Electronics field mainly comes from the development and use of Wide Band Gap (WBG) semiconductor devices. WBG semiconductors such as SiC, GaN, and diamond show superior material properties, which allow operation at high switching speed, high voltage and high temperature. These unique performances provide a qualitative change in their applications for energy processing. From energy generation to the end-user, the electric energy undergoes a number of conversions, which are currently highly inefficient to the point that it is estimated that only 20% of the whole energy involved in energy generation reaches the end-user. WGB semiconductors increase the conversion efficiency thanks to their outstanding material properties. The recent progress in the development of high voltage WBG power semiconductor devices, especially SiC and GaN, is reviewed. Future trends in device development and industrialization are also addressed.*

***Keywords:*** *SiC, GaN, power devices, rectifiers, MOSFETs, HEMTs.*

## 1. INTRODUCTION

Power Electronics play a key role in the generation-storage-distribution cycle of the electric energy. This is because the main portion of the generated electric energy is consumed after undergoing several transformations, many of them carried out by power electronic converters. They include many types of different systems (power supplies for computers, industrial and telecom systems, domestic appliances, motor drives, industrial converters, etc.). The largest portion of the power losses in these power electronic converters are dissipated in their power semiconductor devices. Currently, these devices are based on the mature and very well established Silicon technology. However, Si exhibits some important limitations regarding its voltage blocking capability, operation temperature and switching frequency. Therefore, a new generation of power devices is required for power converters in applications where electronic systems based on traditional Si power devices cannot operate. Therefore, the new WBG power devices can play a main role in energy efficient systems. Among the possible candidates to be the base materials for these new power devices, SiC and GaN present the better trade-off between theoretical characteristics (high voltage blocking capability, high temperature operation and high switching frequencies), and real commercial availability of the starting material (wafers) and maturity of their technological processes. Table 1 summarizes the main material parameters of WBG semiconductors candidates to replace Si.

**Table. 1.** Physical properties of various semiconductors for power devices.

| Material | $E_g$ (eV) @300K | $\mu_n$ ($cm^2/V.s$) | $\mu_p$ ($cm^2/V.s$) | $v_{sat}$ (cm/s) | $E_c$ (V/cm) | $\lambda$ (W/cm.K) | $\varepsilon_r$ |
|---|---|---|---|---|---|---|---|
| **Si** | 1.12 | 1 450 | 450 | $10^7$ | $3\times10^5$ | 1.3 | 11.7 |
| **GaAs** | 1.4 | 8 500 | 400 | $2\times10^7$ | $4\times10^5$ | 0.54 | 12.9 |
| **3C – SiC** | 2.3 | 1000 | 45 | $2.5\times10^7$ | $2\times10^6$ | 5 | 9.6 |
| **6H – SiC** | 2.9 | 415 | 90 | $2\times10^7$ | $2.5\times10^6$ | 5 | 9.7 |
| **4H - SiC** | 3.2 | 950 | 115 | $2\times10^7$ | $3\times10^6$ | 5 | 10 |
| **GaN** | 3.39 | 1000 | 35 | $2\times10^7$ | $5\times10^6$ | 1.3 | 8.9 |
| **GaP** | 2.26 | 250 | 150 |  | $10^7$ | 1.1 | 11.1 |
| **Diamond** | 5.6 | 2200 | 1800 | $3\times10^7$ | $5.6\times10^7$ | 20 | 5.7 |

GaN and especially SiC process technologies are by far more mature and, therefore, more attractive from the device manufacturer's perspective, especially for high power and high temperature electronics (HTE). GaN can offer better high frequency and high voltage performances, but the lack of good quality bulk substrates is a disadvantage for vertical devices. Nevertheless, GaN presents a lower thermal conductivity than SiC. At present time, SiC is considered to have the best trade-off between properties and commercial maturity with considerable potential for both HTE and high power devices. However, the industrial interest for GaN power devices is a fact. For this reason, SiC and GaN are the more attractive candidates to GaN and especially SiC process technologies are by far more mature and, therefore, more attractive from the device manufacturer's perspective, especially for high power and high temperature electronics (HTE). GaN can offer better high frequency and high voltage performances, but the lack of good quality bulk

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substrates is a disadvantage for vertical devices. Nevertheless, GaN presents a lower thermal conductivity than SiC. At present time, SiC is considered to have the best trade-off between properties and commercial maturity with considerable potential for both HTE and high power devices. However, the industrial interest for GaN power devices is a fact. For this reason, SiC and GaN are the more attractive candidates to replace Si in these applications. In fact, some SiC devices, such as Schottky diodes, are already competing with Si power diodes. On the other hand, GaN allows forming hetero-junctions (InAlGaN alloys) that can be growth either on SiC or Si substrates. Currently, there is a sort of competition between SiC and GaN in a battle of performance versus cost. Nevertheless, scientific and industrial actors agree in considering that both will find their respective application fields with a tremendous potential market.

However, many of the material advantages still remain not fully exploited due to specific material quality, technology limitations, non-optimized device designs and reliability issues. Traps, dislocations, interface states, micro-pipes, micro-cracks, etc. still should be minimized. The role and control of residual strains need new research efforts; the contact resistivity of the metal/WBG-semiconductor has to be significantly reduced; device reliability is in its infancy, etc. Recently SiC power devices reported in literature include high voltage and high temperature diodes, junction controlled devices (like JFETs and MESFETs), MOSFETs, Thyristors and IGBTs. Those based on GaN include diodes, HEMTs and MOSFETs; and advanced research on novel devices concerning low-losses digital switches based on SiC and GaN is also of main concern. These novel devices represent a real breakthrough in power devices.

Furthermore, the development of modelling and electro-thermal characterization tools for these power devices, and the design of their packaging, drivers and controllers need a great research effort and they represent a world-class innovation.

## 2. SiC POWER DEVICES

Although Si has long been the dominant semiconductor material for high-voltage applications, the situation has changed because of the significant achievements in SiC bulk material growth and in SiC process technology. The progress in SiC wafers quality is reflected in the achievement of very low micropipe density (0.75 cm$^{-2}$ for a 75 mm wafer), which provides the basis for a high fabricating process yield of large area SiC power devices. 100 mm SiC wafers are already in the market and it is expected that 150 mm SiC wafers will be available in a near future [1]. One of the major concerns has been reducing the micropipe density in SiC substrates, which has been driven by the phenomenological understanding of the mechanisms responsible for pipe formation during SiC crystal growth. However, other defects, such as basal plane dislocations, are still under investigation causing poor reliability in bipolar devices. Besides, minority carrier lifetime in thick epilayers appears to be long enough for conductivity modulation, as inferred from high voltage (20 kV) reported diodes [2, 3]. High voltage experimental SiC-based two-terminal rectifiers and three-terminal switches have been demonstrated. 4H-SiC unipolar devices could eventually replace Si bipolar rectifiers in the 600-6500 V range, and power switches higher than 1.2 kV in the future [4]. There are three types of power rectifiers: 1) Schottky Barrier Diodes (SBD) with extremely high switching speed and low on-state losses, but lower blocking voltage and high leakage current; 2) PiN diodes with high voltage operation and low leakage current, but showing reverse recovery charging during switching; and 3) Junction Barrier Schottky (JBS) diodes with Schottky-like on-state and switching characteristics, and PiN-like off-state performance. Figure 1 shows the cross-sections of the three SiC rectifiers.

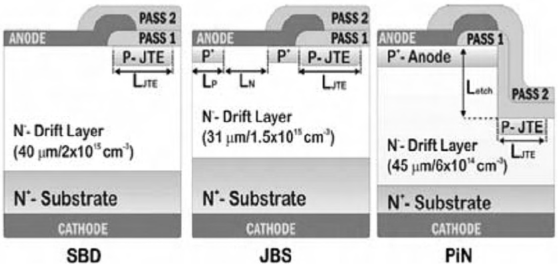


**Fig. 1.** Cross-section of 4H-SiC 3.3 kV Schottky, JBS and PiN diodes [5].

Hybrid rectifiers such as JBS rectifiers, which combine the features of each type, are particularly attractive. SiC SBDs are commercially available since 2001. The most remarkable advantage of SiC SBDs is the continuing increase in the blocking voltage and conduction current ratings. They range from the initial 300 V, 10 A and 600 V, 6 A to the actual 600 V, 20 A and 1.2/1.7 kV. With the latest ratings, it is foreseen that these diodes may replace Si bipolar diodes in medium power motor drive modules. Power Factor Correction and High-Voltage Secondary Side Rectification are applications of 600 V SiC SBDs [6]. Besides, it is expected that SBDs can be advantageously applied for blocking voltages up to 3.5 kV. Large area 3.3 kV SBDs have been fabricated with high temperature operation [5] that are able to supply forward currents in the range of 10-20 A. In comparison with Si counterpart, a ×10 increase in voltage blocking is possible with the same SiC drift layer thickness The main difference to ultra-fast Si PiN diodes lies on the low reverse recovery charge in SiC SBDs. Therefore, SiC SBDs are well suited for high switching speed applications. 1.2 kV SiC SBDs match perfectly as freewheeling diodes with Si IGBTs. Figure 2 displays the reverse recovery of the three SiC rectifiers at 25ºC and 300ºC.

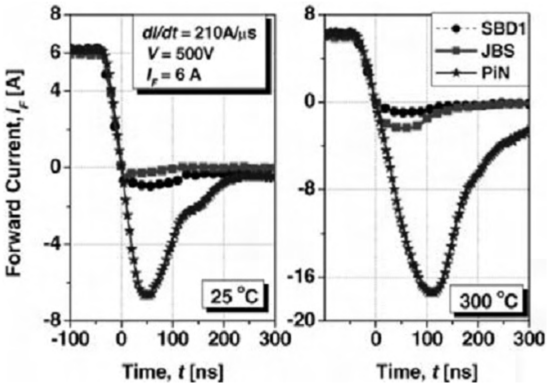


**Fig. 2.** Turn-off current waveforms for the 3.3 kV SiC diodes at 25ºC and 300ºC with inductive load [5].

The high thermal conductivity of SiC is also a great advantage in comparison with Si and GaAs diodes since it allows to operate at higher current density ratings as well as to minimize the size of the cooling systems. Commercial SiC SBDs are expected to continue increasing in voltage and current ratings that currently is 1.2 (1.7) kV [7, 8]. Infineon has presented what they call "The latest SiC Generation: thinQ!™ 3G" [8] aimed at improving the surge current capability and the avalanche ruggedness with a positive temperature coefficient. It is a 600 V SiC merged pn/Schottky structure, i.e., a SiC JBS diode. Due to their aforementioned reliability problems, there is no bipolar diode available in the market. Nevertheless, SiC state-of-the-art PiN diodes include that reported by Cree [9] with a forward voltage of 3.2 V at 180 A (100 A/cm$^2$), capable of blocking 4.5 kV with a reverse leakage current of 1 µA.

SiC power switches in the 600V range have two strong Si competitors: the power MOSFET (including CoolMOS and other advanced trench devices) and the IGBT. Nevertheless, SiC is better suited for switches operating at high voltage and especially at high temperature. A low on-resistance SiC switch able to operate at high junction temperatures has clear advantages in comparison to its Si counterparts. Concerning the blocking voltage range from 1.2 kV to 1.7 kV, the Si MOSFET is not a realistic option and the Si IGBT shows high dynamic losses when requiring fast switching. SiC JFET could be an excellent alternative since this switch shows an ultra-low specific on-resistance and is also able to operate at high temperatures and high frequencies. Infineon has developed a 1.5 kV, 0.5 Ω on-resistance hybrid switch made up of a 1.5 kV vertical SiC normally-on JFET and a 60 V Si MOSFET in cascode configuration [10]. This switch is aimed at resonant converters and power supplies. A 3mm×4.1mm 1.8 kV SiC JFET die has been proposed [11] with a current capability of 15 A at an on-state voltage drop of just 2 V. The technology is said to be viable at voltages of up to 4.5 kV. Nevertheless, this hybrid switch cannot operate at high temperature, and new SiC normally-off JFETs have been developed to overcome this problem [12].The normally-off operation of these devices is due to the high built-in voltage of SiC pn junctions. Nevertheless, SiC normally-off JFETs show high resistive channels and low threshold voltages. Figure 3 shows the cross-sections of normally-on (a) and normally-off (b) JFETs from Infineon and SemiSouth, respectively.

The very low inversion channel mobilities achieved on 4H-SiC have prevented for many years the fabrication of low-resistance MOSFETs that would have proven the SiC potential for power devices. Indeed, the MOS interface and MOSFETs attracts a great deal of attention. Two techniques have emerged as being effective in improving the quality of the MOS interface: the use of nitrogen during post-oxidation annealing and the formation of the MOS channel on alternative crystal faces. Recent advances in SiC MOS device technology have been reached by addressing two critical issues: reducing the density of interface traps ($D_{it}$) and improving surface morphology [13].

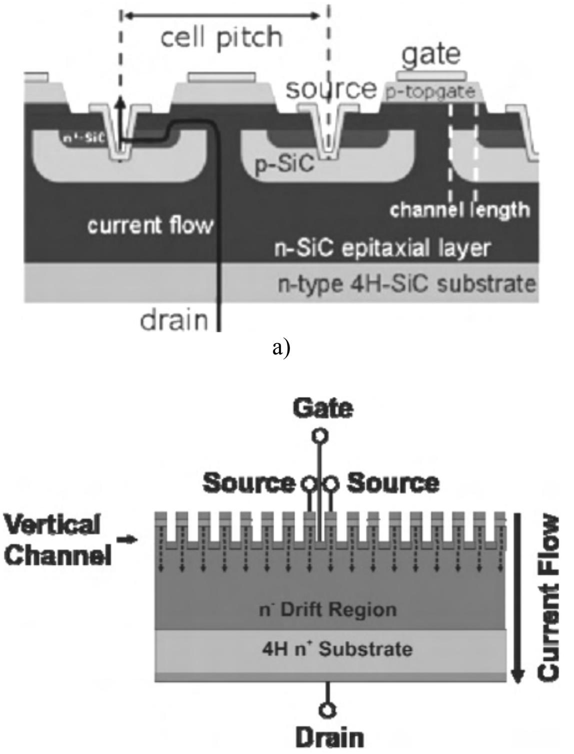


**Fig. 3.** Cross-sections of normally-on (a) and normally-off (b) JFETs from Infineon and SemiSouth, respectively.

Nitridation via NO and $N_2O$ annealing of the SiC MOS interface has been effective in decreasing $D_{it}$ close to the conduction band edge ($D_{it}$ = 2×1011 eV-1·$cm^{-2}$ at 0.2 eV below the conduction band edge) leading to channel carrier mobilities on fabricated lateral MOSFETs of 50 $cm^2/V{\cdot}s$ and 73 $cm^2/V{\cdot}s$ for thermally grown and LPCVD gate oxides, respectively [13]. Other gate dielectrics such as $Al_2O_3$ and high-k dielectrics have been considered as gate dielectrics in 4H-SiC devices, resulting in channel mobilities over 200 $cm^2/Vs$ [14]. Great improvements in MOS channel mobility by using the <1120> crystal face [15] rather than the more commonly used <0001> face have been demonstrated, with channel carrier mobilities >200 $cm^2/Vs$. A 10 kV, 5 A 4H-SiC power DMOSFET has been reported [16], which utilizes a 100 µm thick n-type epitaxial layer with a doping concentration of $6\times10^{14}$ $cm^{-3}$ for drift layer and a thermally grown gate oxide layer NO annealed. The peak effective channel mobility is 13 $cm^2/Vs$. The 4H-SiC DMOSFET with an active area of 0.15 $cm^2$ showed a specific on-resistance of 111 $m\Omega{\cdot}cm^2$ at room temperature and at a gate bias of 15 V. It is worth to point out that two types of n-channel MOS SiC power switches–the MOSFET and the IGBT- have been reported [16]. Both are capable of blocking 10 KV. Recently, ultra high voltage 4H-SiC IGBTs have been reported [18]. A 4H-SiC P-IGBT, with a chip size of 6.7 mm × 6.7 mm and an active area of 0.16 $cm^2$ exhibited a record high blocking voltage of 15 kV, while showing a room temperature differential specific on-resistance of 24 $m\Omega{\cdot}cm^2$ with a gate bias of -20 V. A 4H-SiC N-IGBT with the same area showed a blocking voltage of 12.5 kV, and demonstrated a room temperature differential specific on-resistance of 5.3 $m\Omega{\cdot}cm^2$ with a gate bias of 20 V. Furthermore, the channel mobility of POCl3-annealed MOSFETs has been proved to be ×3 that of NO-annealed MOSFETs [19]. In this sense, 1200 V, 67A and 3000 V, 30 A 4H-SiC DMOSFET (Fig. 4) has been reported [20, 21] and since 2011 a 1.2kV, 33A SiC MOSFET is commercially available (www.cree.com). Cree has recently incorporated to its catalogue the 1200V, 80mΩ Z-FET™ CMF20120D – Industry's First SiC MOSFET to attain record efficiencies with significant reliability improvement over competing Si devices with a nominal current of 33/17 A at 25/100ºC [22]. Besides, Rohm has announced a trench MOSFET configuration for high current density per unit area, which will make it possible to drive 300A from a single chip [23]. Their target is $1m\Omega.cm^2$, 1200V. Currently this company offers 10 A/600 V and 26 A/1200 V encapsulated MOSFETs. SiC BJTs have been developed over the last decade into a sufficiently mature technology. It has culminated into the most recent performance of the 4 kV, 10 A BJT [24] with a current gain of 34 in the active region. The chip area is 4.24 mm×4.24 mm. It is capable of blocking 4.7 kV with a leakage current of 50 µA. The turn-on time is 168 ns and the turn-off time is 106 ns at room temperature. As reported this BJT shows current gain instability, with the gain decreasing by 50% with time under forward stress due to the presence of stacking faults in the base-emitter region. In recent years, some SiC-GTOs have been also developed because they can exploit conductivity modulation and negative temperature dependence of VF (forward voltage) particular to bipolar devices. The state-of-the-art SICGT (SiC Commutated Gate turn-off Thyristor) has been reported in ISPSD 2012 [25]. The reliability of SiC bipolar device modules consisting of and SiC pin diodes fabricated on a $4^0$ off-cut SiC substrate is investigated. According to three-phase inverter operation using a Back to Back system at DC bus voltage of 2 kV and effective output power of approximately 120 kW, the SiC module could achieve the world's first successful inverter operation lasting more than 1000 hours, thereby verifying its reliability in long time inverter operation. Other topics linked to the back-end process, such as passivation schemes, are of crucial importance since they can affect the efficiency of the edge termination. Moreover, the high operating temperature of SiC power devices will certainly contribute to the market growth and industrial utilization. It will be necessary, however, to develop packages able to withstand high operating temperatures.

## 3. GaN POWER DEVICES

GaN is of interest for high voltage and high temperature devices due to its remarkable material properties like wide bandgap, large critical electric field, high electron mobility and reasonably good thermal conductivity. In addition, a large conduction band discontinuity between GaN and AlGaN and the presence of polarization fields allows a large two-dimensional (2D) electron gas concentration to be confined.

Until recently, because of the lack of electrically conducting GaN substrates, most of the GaN Schottky power diodes reported are either lateral or quasi-vertical [26]. Breakdown voltages of lateral GaN rectifiers on Sapphire substrates could be as high as 9.7 kV [27], but the forward voltage drop, VF, is still high. The interest of these diodes lies on their lower cost when implemented on Si or Sapphire substrates. In fact, with the availability of high temperature HVPE (Hydride Vapour Phase Epitaxy) GaN substrates, 600 V vertical GaN Schottky diodes are due to be launched in the market to compete with SiC Schottky rectifiers [28]. GaN JBS diodes could further increase the performance of GaN-based power rectifiers in the 600-3.3 kV range. In this sense, we are working on the optimization of contact resistance to implanted p-type GaN [29]. We have found that protection during post-implantation annealing is very important to obtain a good uniformity on the contact properties. However, the fact of having much more dispersion, as well as lower contact resistance for some of the samples (in the range of $4\times10-5\ \Omega\cdot\mathrm{cm}^2$) for the unprotected samples, makes us to suggest that the contact resistance mechanism is related with the formation of N vacancies on the GaN surface during both the post-implantation and contact annealing (Fig. 4).

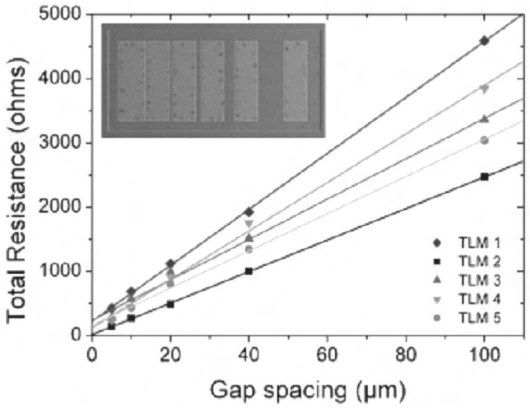


**Fig. 4a).** Total resistance as function of the gap spacing for different TLM structures. Inset: SEM TLM structure image used to evaluate the ρc [29].

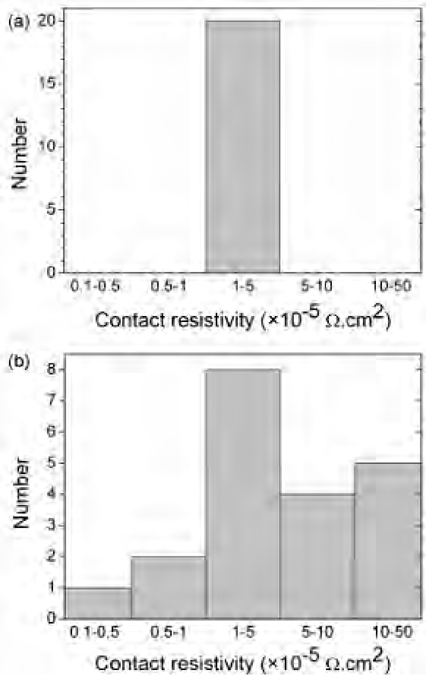


**Fig. 4b).** Statistical repartition of the ρc for the Si-implanted GaN annealed (a) with cap layer and (b) without cap layer [29].

In recent years, GaN High Electron Mobility Transistors (HEMTs) have attracted most attention with remarkable trade-off between specific on-resistance and breakdown voltage. The GaN HEMTs are expected as microwave power devices used for base station of cellular phone and as switching power devices in DC/DC converters. Since the demonstration of the first GaN based HEMT switch [30], rapid progress has been made in the development of GaN-based HEMT devices. Output power densities at microwave frequencies of GaN based HEMTs on both sapphire and SiC substrates have improved from initial 1.1 W/mm in 1996. Recently, it has been demonstrated impressive AlGaN/GaN microwave power HEMTs with high output power capability, as high as 40 W/mm [31]. A major obstacle has been controlling the trap densities in the bulk and surface of the material affecting the performance of these devices by trapping effects though drain-current collapse [32]. To efficiently operate the transistor at high frequency and high voltage, the drain current collapse must be suppressed and the gate-drain breakdown voltage must be improved. Several solutions for the device structure have been proposed including the surface-charge-controlled n-GaN-cap structure, the recessed gate and field-modulating plate structure or the passivation of surface states via silicon nitride or other dielectric [33]. High voltage AlGaN/GaN HEMTs over 1 kV were reported in 2006 [34]. In this sense, a high-voltage/low $R_{on}$ AlGaN/GaN HEMT on semi-insulating SiC [35] has been also reported, which exhibits a record of a high power figure of merit (~$2.3\times10^9$ $V^2$ /$\tilde{\Omega}cm^2$) and exceeds the 6H-SiC theoretical limit. A step further for the most cost-effective and industrially relevant GaN-on-silicon is the removal of the silicon, which limits the amount of power of the GaN-on-Si power HEMTs. Srivastava et al. [36] reported in 2011 a record breakdown voltage for HEMT fabricated on Si <111> by a new local Si substrate removal technology with $V_{BR}$ = 2.2 kV for devices with gate-to-drain distances of 20 µm. This is a remarkable enhancement compared to the reference (on bulk Silicon), which has a saturated $V_{BR}$ = 0.7 kV. Furthermore, an extremely high blocking voltage of 8.3 kV has been achieved while maintaining relative low specific on-state resistance of 186 m$\tilde{\Omega}cm^2$, via-holes through sapphire at the drain electrodes enable very efficient layout of the lateral HEMT array as well as better heat dissipation [37].It has been also demonstrated a GaN power switch [38] for kW power conversion. The switch shows a speed higher than 2 MHz with rise- and fall-time of less than 25 ns, and turn-on/turn-off switching losses of 11 µJ with a resistive load. Switching at 100 V/11 A and 40 V/23 A was achieved with resistive and inductive loads, respectively.

For high voltage power switching applications, the Lateral Double Diffused structure (LDD-MOSFET) has the advantage of naturally normally-off operation and large conduction band offset, which makes it less susceptible to hot electron injection and other reliability problems, in particular those related with surface states and current collapse [39]. With a high quality $SiO_2$/GaN interface, GaN MOSFETs are viable. Lateral GaN MOSFETs with high channel mobility (170 cm2/V·s), which is correlated with the low interface state density and high blocking voltage (2.5 kV) have been demonstrated [39]. Lateral MOSFETs have been fabricated on p-GaN epilayer on sapphire substrates. Source and drain regions were selectively implanted with Si using a PECVD oxide as mask.

The gate dielectric was a deposited (PECVD) 100 nm-thick $SiO_2$. These GaN MOSFETs could be an alternative to SiC MOSFETs and GaN HEMTs. The GaN HEMT is an intrinsically normally-on device due to the existence of the 2DEG (2-Dimensional Electron Gas) (Fig. 5).

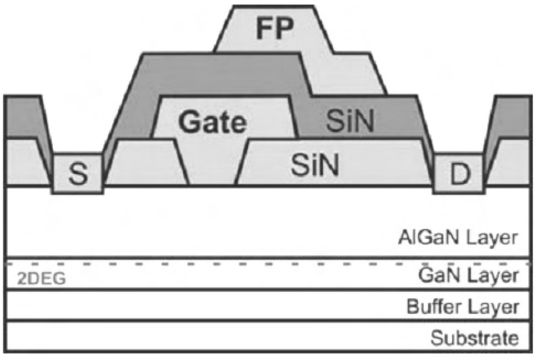


**Fig. 5.** Schematic cross- section of a normally-on GaN HEMT.

Therefore, a negative gate bias is required to switch the device off. Nevertheless, normally-off devices are preferred in power electronic applications. Several approaches have been developed for converting the GaN HEMTs from the conventional normally-on mode to the desired normally-off mode: 1) One approach is to employ a recessed-gate structure (Fig. 6) so that the AlGaN layer under the gate is too thin for inducing a 2DEG, resulting in a low and positive Vth (threshold voltage). The enhancement mode AlGaN HEMT was first reported by M. A. Khan et al. in 1996. [40].

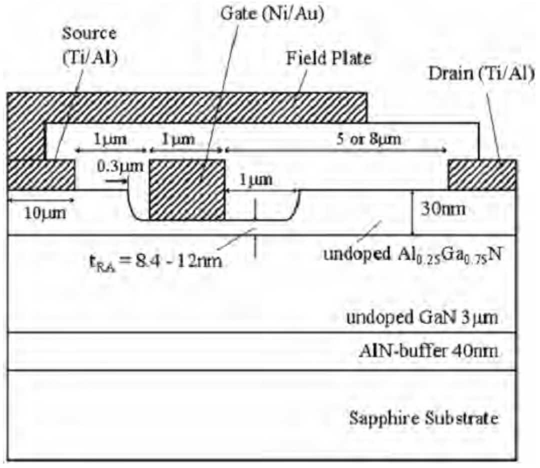
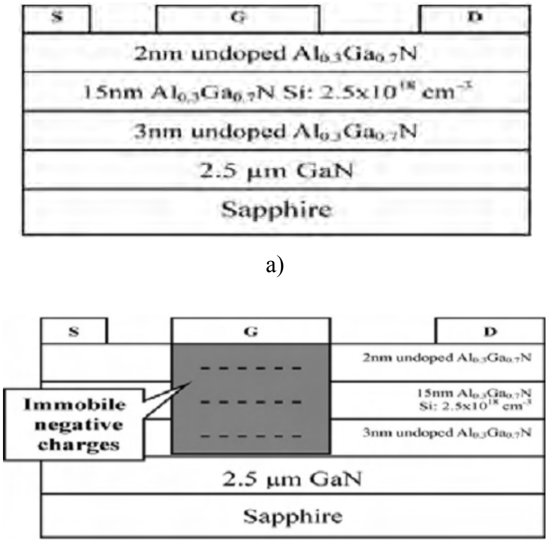


**Fig. 6.** Schematic cross- section of a a recessed-gate structure GaN HEMT [41].

2) A second approach is to use fluorine-based plasma to dope the semiconductor beneath the gate metal, so that acceptors are formed in this region, effectively depleting the 2DEG [42].



a)

b)

**Fig. 7.** Schematic cross- section of a fluorine-gate GaN HEMT [42].

3) The third approach is to introduce a p-doped GaN or AlGaN cap layer to deplete the 2DEG underneath (Fig. 8). In 2000 Hu *et al.* proposed an E-mode AlGaN/GaN HEMT with selectively grown pn junction gate [43].

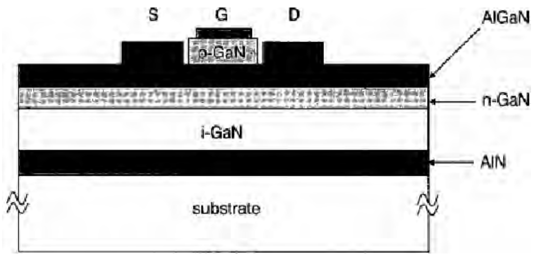


**Fig. 7.** Schematic cross- section of a pn-gate GaN HEMT.

4) It is also possible to include the MOS-HEMT as a technique for getting an E-HEMT as a structure combining the HEMT 2DEG current capability and the MOS normally-off operation. Recessed MIS-HEMTs (Fig. 8) have been also proposed but the objective of the reported devices is not to make the device normally-on but increase the transconductance of MIS-HEMTs [44] or reducing its gate leakage.

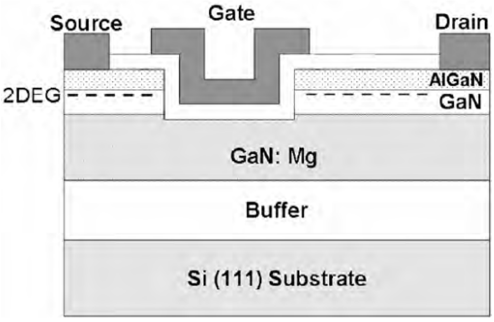


**Fig. 8.** Schematic cross- section of an AlGaN/GaN hybrid MOS-HFET [45].

5) A combination of the previous techniques with a customized growth of the AlGaN/GaN stack also allows improving the performances of the E-mode HEMTs [46].

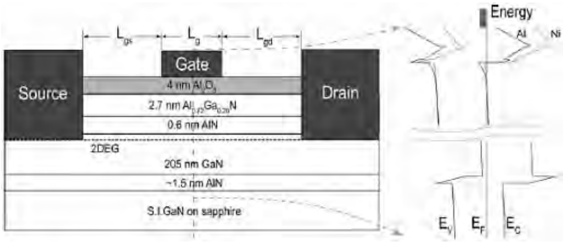


**Fig. 9.** Schematic cross-section of a Nonpolar AlGaN/GaN Metal-insulator-semiconductor heterojunction field-effect transistors [47].

## 4. FUTURE TRENDS

The new generation of power devices for power converters will be based on Wide Band Gap semiconductors to replace traditional silicon power devices. Currently the highest breakdown voltage capability of the commercial dominant power switch (Si IGBT) is 6.5 kV. In any case, a Silicon-based device could not operate over 200ºC. These inevitable physical limits reduce drastically the efficiency of current power converters, which requires among others, complex and expensive cooling systems. The use of these new power semiconductor materials will allow increasing the efficiency of the electric energy transformations for a more rational use of electric energy, thus reducing carbon footprint. The most promising WBG semiconductor materials for this new generation of power semiconductor devices are SiC and the GaN.

SiC Schottky and JBS diodes are commercially available up to 1.2 kV. PiN diodes will be only relevant for breakdown voltages over 3 kV. PiN diodes with outstanding blocking capability up to 20 kV have been demonstrated. However, they still need to overcome a reliability problem (forward voltage drift) before commercialisation. Recent results in this sense are encouraging. Regarding SiC switches, despite the successful demonstration of the cascode pair consisting of a high voltage, normally-on SiC JFET and a low-voltage Si MOSFET, more reliable normally-off SiC switches are expected although improvements in process technology are still needed. The potential candidates are the SiC MOSFET (<5 kV) and the SiC IGBT (>5 kV). Also, even though BJTs/Darlingtons are promising they also suffer from reliability problems similar to PiN junction rectifiers. In any case, a normally-off SiC power MOSFET in the breakdown voltage range of 600V-1.2 kV is available in the market. SiC n-channel power switches (the n-MOSFET and the n-IGBT) capable of blocking 10 kV have been demonstrated recently. In this case, their gate properties are similar to existing Si power switches thereby simplifying their insertion into existing power systems. It is also expected that the blocking capability of these n-channel power switches will increase up to 20-30 kV in a future, widening the application field of SiC power switches. Recently Cree has [48] presented their latest developments in ultra-high voltage 4H-SiC IGBTs. Concretely, a 4H-SiC P-IGBT, with a chip size of 6.7mm × 6.7 mm and an active area of 0.16 $cm^2$ exhibiting a record high blocking voltage of 15 kV, while showing a room temperature differential specific on-resistance of 24 $m\Omega \cdot cm^2$ with a gate bias of -20 V. And a 4H-SiC N-IGBT with the same area showed a blocking voltage of 12.5 kV, and demonstrated a room temperature differential specific on-resistance of 5.3 $m\Omega \cdot cm^2$ with a gate bias of 20V.

Other topics linked to the back-end process, such as passivation, are of crucial relevance since they can affect the efficiency of the edge termination. Suitable high k-dielectrics can play a main role. Moreover, the high operating temperature of SiC power devices (demonstrated over 500ºC) will certainly contribute to the market growth and industrial utilization. It will be necessary, however, to develop packages able to withstand high operating temperatures in the range of 300ºC. Finally, reliability analysis of these WBG power devices is at is very early stage (especially for GaN devices).

GaN devices are already commercialised in the photonics area but it is in an embryonic state regarding power applications. Due to the fact that GaN can be grown on Si substrates, there is a part of the scientific community that supports the idea that GaN can deliver the SiC performance with the Si cost. However, it is also wide spread the view that GaN devices must be implemented on SiC in order to get competitive devices, hence annulling the cost argument. Commercial power 0.6-1.2kV GaN Schottky diodes will be available in the market in a very near future. One of the most interesting properties of GaN for power application is the high electron mobility of the 2DEG gas formed in AlGaN/GaN heterostructures offering high electron mobilities (1200 $cm^2/V \cdot s$). The material and device properties (breakdown field, mobility and speed) of GaN HEMTs lend themselves to high power switching applications, with a projected ×100 performance advantage ($V_{BR}^2/R_{ON}$) over silicon power devices. The combination of high speed and low-loss switching performance enabled by GaN devices is particularly suited for an emerging type of switching power supplies with ultra-high bandwidth (in the MHz range). The breakdown capability of GaN HEMTS is approaching 10 kV and power converters have been already demonstrated. However, HEMT devices are generally normally-on devices and it is extremely difficult to convince power systems designers and final users to use these normally-on switches. For high voltage power switchingapplications, GaN MOSFET has the advantages of normally-off operation without current collapse problematic. However, GaN

MOSFET currently exhibits -and probably it will be an unsolved major problem as in the case of SiC-modest inversion channel mobility (below 200cm$^2$/V·s) due to the presence of interface states, surface roughness and other scattering mechanisms. A way to around this could be the incorporation of AlGaN/GaN hetero-structure into the RESURF region of GaN MOSFETs. A hybrid MOS-HEMT has the advantage of both the MOS gate control and the high mobility 2DEG in AlGaN/GaN drift region. This hybrid MOS-HEMT has a tremendous potential to be the GaN power switch.

Furthermore, Au-free CMOS compatible GaN technologies are also reported [49], which allow the fabrication of GaN HEMTs in CMOS lines. The GaN hybrid MOS-HEMT and the pn-gate GaN HEMT [50] have a promising future.

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