

Wide Band Gap Semiconductor Devices for Power Electronics

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It is worldwide accepted today that a real breakthrough in the Power Electronics field may mainly come 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 application to energy processing. From energy generation (carbon, oil, gas or any renewable) to the end-user (domestic, transport, industry, etc), the electric energy undergoes a number of conversions. These conversions 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. WBG 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. The performances of various rectifiers and switches, already demonstrated are also discussed. Material and process technologies of these WBG semiconductor devices are also tackled. Future trends in device development and industrialization are also addressed.

Key words: SiC, GaN, Power devices, Rectifiers, MOSFETs, HEMTs

Wide Band Gap poluvodički sklopivi za učinsku elektroniku. U današnje vrijeme napredak u polju učinske elektronike prvenstveno dolazi razvojem i uporabom *Wide Band Gap* (WBG) poluvodičkih uređaja. WBG poluvodiči kao SiC, GaN i dijamant pokazuju iznimna svojstva materijala, što omogućuje korištenje pri brzim promjenama stanja, visokim naponima i visokim temperaturama. Ova jedinstvena svojstva osiguravaju kvalitativne promjene njihovom primjenom u obradi energije. Od početnih energenata (ugljen, ulje, plin ili obnovljivi izvori) do završne faze korištenja (kućanstvo, prijevoz, industrija) električna energija prolazi kroz različite faze pretvorbe energije koje su trenutno prilično neefikasne o čemu govori podatak da se samo 20% početne energije iskoristi u konačnoj fazi. WBG poluvodiči povećavaju efikasnost pretvorbe zahvaljujući izvanrednim svojstvima materijala. U radu je dan pregled nedavnog napretka u razvoju visoko-naponskih WBG poluvodiča, posebno SiC i GaN te je dan pregled svojstava predstavljenih ispravljača i sklopki. Također u radu su opisani materijali i tehnologija WBG poluvodičkih uređaja te je opisan budući trend u razvoju uređaja i njihovom korištenju u industriji.

Ključne riječi: SiC, GaN, uređaji učinske elektronike, ispravljači, MOSFET, HEMT

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. Examples of this can be found in all ranges of power levels (from a few W to MW), and they include many types of different equipments (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. Nowadays, 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. The use of these new power semiconductor devices will allow increasing the efficiency of the electric energy transformations achieving a more rational usage of the electric energy.

Novel and innovative power devices based on WBG semiconductors 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 character-

istics (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 in the next generation of power devices. 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, 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 increasing recently. 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 in the semiconductor market with Si power diodes. On the other hand, GaN allows forming hetero-junctions (In-AlGaN alloys) and can be grown either on SiC or Si substrates. Currently, it 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.

Table 1. Physical properties of various semiconductors for power devices

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

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. In particular, WBG surface electrical properties are only partially understood. Traps, dislocations, interface states, micropipes, microcracks, 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. It is worth mentioning that diamond exhibits the best properties of all the WBG semicon-

ductors. Nevertheless, there are critical problems related with the crystal growth (small areas single crystal wafers), both p-type and n-type dopings and processing. Therefore, there is not a diamond power device in the market and it is not expected in the next decade.

SiC power devices recently reported in literature include high-voltage and high-temperature diodes, junction controlled devices (like JFETs), MOSFETs and MESFETs. 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

Si has long been the dominant semiconductor material for high-voltage applications. The situation has changed due to 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]. It has been shown that active regions of SiC-based devices overlying micropipe defects in the substrate fail to operate. Therefore, 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 that are responsible for pipe formation during SiC crystal growth. The understanding of such mechanisms has led the identification and removal of most of these defects. However, other defects, such as basal plane dislocations, are still under investigation causing poor reliability in bipolar devices. In conclusion, the most challenging approach is to grow low-doped epitaxial layers while maintaining features such as purity, surface smoothness and growth rate (epilayer thickness). Besides, minority carrier lifetime in thick epilayers appears to be long enough for conductivity modulation, as inferred from high-voltage (19 kV) reported diodes [2].

Many high-voltage experimental SiC-based two-terminal rectifiers and three-terminal switches have been demonstrated. 4H-SiC unipolar devices are expected to replace Si bipolar rectifiers in the 600-6500 V range, and power switches higher than 1.2 kV in the future [3]. Generally speaking, there are three types of power rectifiers: 1) Schottky Barrier Diodes (SBD) with extremely

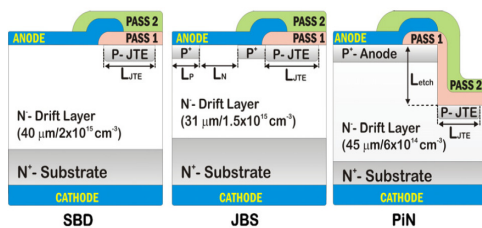


Fig. 1. Cross-section of 4H-SiC 3.3 kV Schottky, JBS and PiN diodes [5]

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 characteristics. Figure 1 shows the cross-sections of the three SiC rectifiers. Schottky and PiN diodes are the two basic types of power rectifiers. However, hybrid rectifiers such as JBS rectifiers, which combine the best 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 [4]. 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 20 A. In comparison with Si counterpart, a $\times 10$ 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 absence of reverse recovery charge in 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 25 °C and 300 °C.

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 kV [6, 7]. Infineon has presented what they call "The latest SiC Generation:

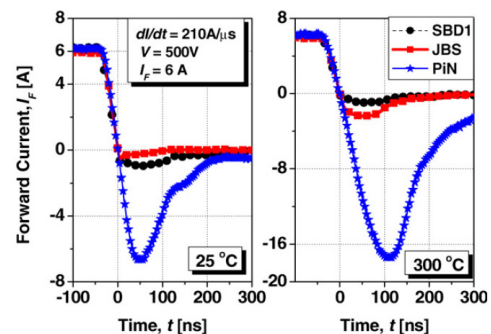


Fig. 2. Turn-off current waveforms for the 3.3 kV SiC diodes at 25 °C and 300 °C with inductive load

thinQ!TM 3G" [7] 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 [8] with a forward voltage of 3.2 V at 180 A (100 A/cm²), capable of blocking 4.5 kV with a reverse leakage current of 1 μA.

SiC power switches in the 600 V 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. In addition, there is an increasing demand of SiC high-voltage controlled switches, which opens the possibility of facing new application fields. Concerning the blocking voltage range from 1.2 kV to 1.8 kV, the Si MOSFET is not a realistic option and the Si IGBT shows high dynamic losses when requiring fast switching. SiC JFET may 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 [9]. This switch is aimed at resonant converters and power supplies. A 3mm \times 4.1mm 1.8 kV SiC JFET die has been proposed [10] 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 [11]. 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 [12]. 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 ($D_{it} = 2 \times 10^{11} \text{ eV}^{-1} \cdot \text{cm}^{-2}$ @ 0.2 eV below the conduction band edge) leading to carrier mobilities on fabricated lateral MOSFETs of $50 \text{ cm}^2/\text{V}\cdot\text{s}$ and $73 \text{ cm}^2/\text{V}\cdot\text{s}$ for thermally grown and LPCVD gate oxides, respectively [12]. Other gate dielectrics such as Al_2O_3 and high-k dielectrics have been considered as gate dielectrics in 4H-SiC devices, resulting in device mobilities over $200 \text{ cm}^2/\text{V}\cdot\text{s}$ [13]. Great improvements in MOS channel mobility by using the $\langle 1120 \rangle$ crystal face [14] rather than the more commonly used $\langle 0001 \rangle$ face have been demonstrated, with channel carrier mobilities over $200 \text{ cm}^2/\text{V}\cdot\text{s}$. A 10 kV, 5 A 4H-SiC power DMOSFET has been reported [15], which utilizes a $100 \mu\text{m}$ thick n-type epitaxial layer with a doping concentration of $6 \times 10^{14} \text{ cm}^{-3}$ for drift layer and a thermally grown gate oxide layer NO annealed. The peak effective channel mobility is $13 \text{ cm}^2/\text{V}\cdot\text{s}$. The 4H-SiC DMOSFET with an active area of 0.15 cm^2 showed a specific on-resistance of $111 \text{ m}\Omega \cdot \text{cm}^2$ 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 recently reported [16]. Both are capable of blocking 10 kV while having similar gate properties to existing Si power switches thereby simplifying their insertion into existing power systems.

Furthermore, the channel mobility of POCl_3 -annealed MOSFETs has been proved to be $\times 3$ that of NO-annealed MOSFETs [17]. In this sense, 1200 V, 67 A and 3000 V, 30 A 4H-SiC DMOSFET (Fig. 4) has been reported [18, 19] and since 2011 a 1.2 kV, 33 A SiC MOSFET is commercially available (www.cree.com). Cree has recently incorporated to its catalogue the 1200 V, 80 m Ω 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 25/100 °C [20]. Besides, Rohm has an-

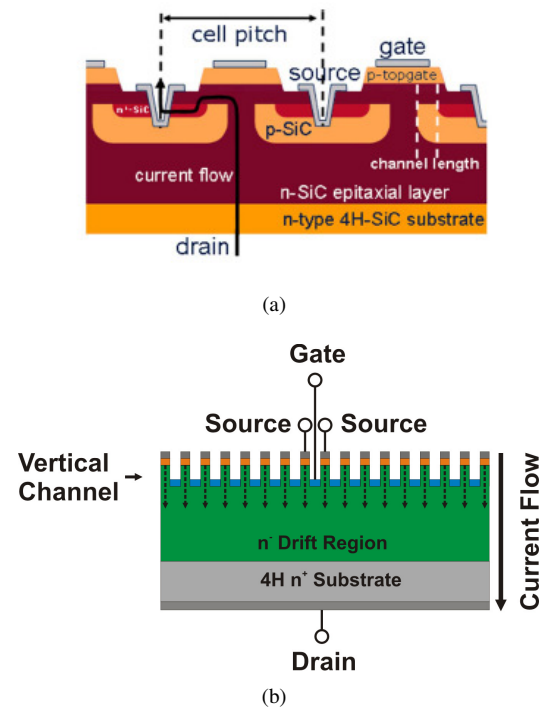


Fig. 3. Cross-sections of normally-on (a) and normally-off (b) JFETs from Infineon and SemiSouth, respectively

nounced a trench MOSFET configuration for high current density per unit area, which will make it possible to drive 300 A from a single chip [21]. Their target is $1 \text{ m}\Omega \cdot \text{cm}^2$, 1200 V. 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 [22] with a current gain of 34 in the active region, which is the result of using a double emitter structure: a low-doped n^- -layer capped with a high-doped n^+ -layer. This double emitter provides higher minority carrier lifetime in the low-doped n-layer for higher emitter efficiency, while the top

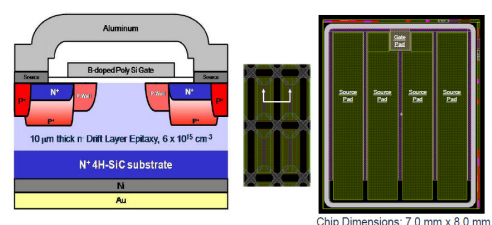


Fig. 4. 1200 V, 67 A 4H-SiC DMOSFET: Device Structure and Layout [19]

n^+ - layer provides a good ohmic contact. The chip area is $4.24 \text{ mm} \times 4.24 \text{ mm}$. It is capable of blocking 4.7 kV with a leakage current of $50 \text{ } \mu\text{A}$. 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 V_F (forward voltage) particular to bipolar devices. The state-of-the-art SICGT (SiC Commutated Gate turn-off Thyristor) has been reported [23]. The 4.5 kV, 120 A SICGT has a chip area of $8 \text{ mm} \times 8 \text{ mm}$ and was coated with a new high heat resistive resin capable of operating at $400 \text{ }^\circ\text{C}$ has a leakage current less than $5 \times 10^{-6} \text{ A/cm}^2$ at 4.5 kV and $250 \text{ }^\circ\text{C}$ and a V_F of 5 V at 120 A, and turn-on and turn-off times of 0.2 μs and 1.7 μs , respectively. A SICGT module was built by mounting a SICGT and two $6 \text{ mm} \times 6 \text{ mm}$ SiC pn diodes in a metal package. A 110 kVA PWM 3 phase inverter was developed using six SICGT modules demonstrating the electrical power capability of such a system.

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.

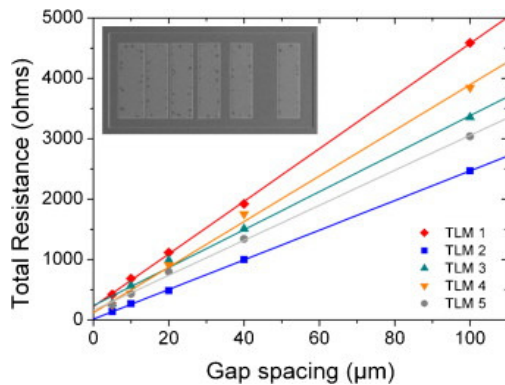
3 GAN POWER DEVICES

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.

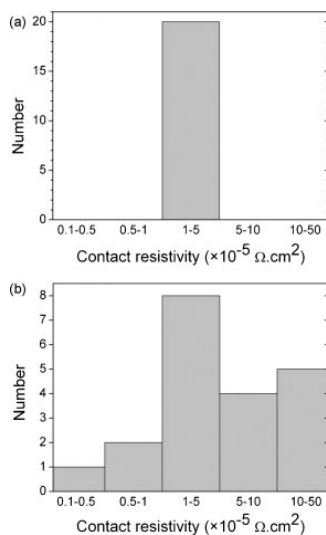
Until recently, because of the lack of electrically conducting GaN substrates, most of the GaN Schottky power diodes reported are either lateral or quasi-vertical [24]. Breakdown voltages of lateral GaN rectifiers on Sapphire substrates could be as high as 9.7 kV [25], but the forward voltage drop is 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 [26]. GaN JBS diodes could further increase the performance of GaN-based power rectifiers in the 600 V-3.3 kV range. In

this sense, we are working on the optimization of contact resistance to implanted p-type GaN [27]. 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 $4 \times 10^{-5} \text{ } \Omega \cdot \text{cm}^2$) 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. 5).

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 [28], 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 [29]. 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 [30]. 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 [31]. High voltage AlGaN/GaN HEMTs over 1 kV were reported in 2006 [32]. In this sense, a high-voltage/low R_{ON} AlGaN/GaN HEMT on semi-insulating SiC [33] has been also reported, which exhibits a record of a high-power figure of merit ($\sim 2.3 \times 10^9 \text{ V}^2/\text{W} \cdot \text{cm}^2$) 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.* [34] reported in 2011 a record breakdown voltage for HEMT fabricated on $\langle 111 \rangle$ Si by a new local Si substrate removal technology with $V_{BR} = 2.2 \text{ kV}$ for devices with gate-to-drain distances of 20 μm (buffer thickness was only 2 μm). This is a remarkable enhancement compared to the reference (on bulk Silicon), which has a saturated $V_{BR} = 0.7 \text{ kV}$. Furthermore, an extremely high blocking voltage of 8.3 kV has been achieved while maintaining relative



(a) Total resistance as function of the gap spacing for different TLM structures. Inset: SEM image of the TLM structure used to evaluate the ρ_c



(b) Statistical repartition of the ρ_c for the Si-implanted GaN annealed (a) with cap layer and (b) without cap layer

Fig. 5.

low specific on-state resistance of $186 \text{ m}\cdot\text{Wcm}^2$, via-holes through sapphire at the drain electrodes enable very efficient layout of the lateral HFET array as well as better heat dissipation [35].

It has been also demonstrated a GaN power switch [36] 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. With a high quality SiO_2/GaN interface, GaN MOSFETs are viable. Lateral GaN MOSFETs with high channel mobility ($170 \text{ cm}^2/\text{V}\cdot\text{s}$), which is correlated with the low interface state density and high blocking voltage (2.5 kV) have been demonstrated [37]. 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). 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 so that the AlGaIn layer under the gate is too thin for inducing a 2DEG, resulting in a low and positive V_{th} (threshold voltage). The enhancement mode AlGaIn HEMT was first reported by M. A. Khan et al. in 1996. [38]. 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 [39]. 3) The third approach is a p-doped GaN or AlGaIn cap layer to deplete the 2DEG underneath (Fig. 6). In 2000 Hu et al. proposed an E-mode (enhancement-mode) AlGaIn/GaN HEMT with selectively grown pn junction gate [40]. 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 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 [41] or reducing its gate leakage. 5) A combination of the previous techniques with a customized growth of the AlGaIn/GaN stack also allows improving the performances of the E-mode HEMTs [42].

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 200°C . 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

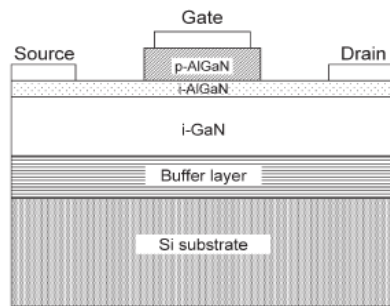


Fig. 6. Schematic cross-section of a p-type gate HEMT

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/Darlington 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 0.6-1.2 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. 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 500 °C) will certainly contribute to the market growth and industrial utilization. It will be necessary, how-

ever, to develop packages able to withstand high operating temperatures in the range of 300 °C. Finally, reliability analysis of these WBG power devices is at its 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 0.6-1.2 kV 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 AlGaIn/GaN heterostructures offering high electron mobilities (1200 cm²/V·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 switching applications, 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 200 cm²/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 AlGaIn/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 AlGaIn/GaN drift region. This hybrid MOS-HEMT has a tremendous potential to be the GaN power switch.

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