A Survey of Wide Bandgap Power Semiconductor Devices

José Millán, *Member, IEEE*, Philippe Godignon, Xavier Perpiñà, Amador Pérez-Tomás, and José Rebollo

***Abstract*—Wide bandgap semiconductors show superior material properties enabling potential power device operation at higher temperatures, voltages, and switching speeds than current Si technology. As a result, a new generation of power devices is being developed for power converter applications in which traditional Si power devices show limited operation. The use of these new power semiconductor devices will allow both an important improvement in the performance of existing power converters and the development of new power converters, accounting for an increase in the efficiency of the electric energy transformations and a more rational use of the electric energy. At present, SiC and GaN are the more promising semiconductor materials for these new power devices as a consequence of their outstanding properties, commercial availability of starting material, and maturity of their technological processes. This paper presents a review of recent progresses in the development of SiC- and GaN-based power semiconductor devices together with an overall view of the state of the art of this new device generation.**

***Index Terms*—BJTs, diodes, GaN, HEMTs, IGBTs, JFETs, MOSFETs, power devices, SiC, thyristors, wide bandgap (WBG) semiconductors.**

I. Introduction

POWER electronics allows the efficient processing of electrical energy through means of electronic switching devices. Nowadays, 40% of the worldwide energy is consumed as electric energy, and therefore, power electronics plays a key role in its generation–storage–distribution cycle. The largest portion of the power losses in power electronic converters is dissipated in their power semiconductor devices. Currently, these power devices are based on the mature and very well established Si technology although Si exhibits some important limitations regarding blocking voltage capability, operation temperature, and switching frequency. At present, the highest commercial Si IGBT breakdown voltage capability is 6.5 kV with a limited switching performance, and not any Si-based device may operate above 200 °C. These unavoidable physical limits reduce drastically the efficiency of current power converters, which requires among others, complex and expensive cooling systems and expensive passive components. Consequently, a new generation of power devices based on wide bandgap (WBG) semiconductor materials is expected for power converters. The use of these new WBG power semiconductor devices will allow increasing the efficiency of the electric energy transformations achieving a more rational use of the electric energy together with a considerable improvement in size and robustness of power converters.

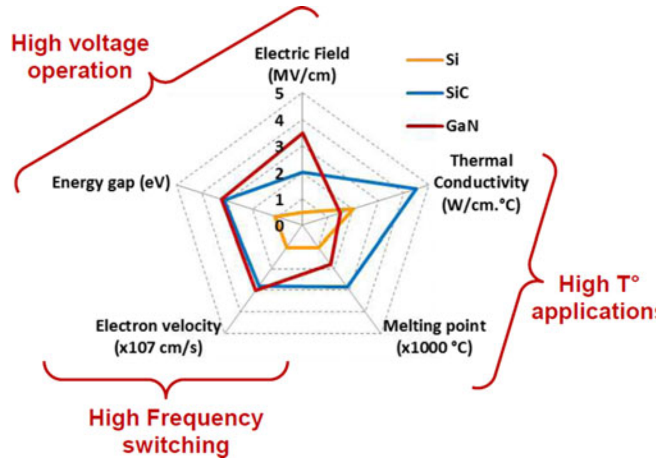

Fig. 1. Summary of Si, SiC, and GaN relevant material properties [1].

Among the possible semiconductor materials candidates, Silicon Carbide (SiC) and Gallium Nitride (GaN) show the best tradeoff between theoretical characteristics (high blocking voltage capability, high-temperature operation, and high switching frequencies), real commercial availability of the starting material (wafers and epitaxial layers), and maturity of their technological processes. Fig. 1 highlights some key material properties of WBG semiconductors candidates to replace Si [1].

GaN and, especially, SiC process technologies are by far the most mature among WBG semiconductor materials and, therefore, more attractive from the device manufacturer's perspective for high-power electronics. Although GaN theoretically offers better high-frequency and high-voltage performances, the lack of good-quality bulk substrates needed for vertical devices and the lower thermal conductivity lend SiC the better position for high-voltage devices. In fact, some SiC devices, such as Schottky diodes, are already competing with their Si counterparts. However, the industrial interest for GaN power devices is increasing steadily. In the last decade, GaN technology has been

Manuscript received February 13, 2013; revised May 13, 2013; accepted June 4, 2013. Date of current version January 10, 2014. This work was supported in part by the Spanish Ministry of Science and Innovation (Research Programs: RUE CSD2009-00046, TRENCH-SiC TEC2011-22607, THERMOS TEC2008-05577, Ramón y Cajal RYC-2008-03174, and Ramón y Cajal RYC-2010–07434). Recommended for publication by Associate Editor P. Mawby.

The authors are with the Institut de Microelectrònica de Barcelona-Centre Nacional de Microelectrònica (IMB-CNM), Consejo Superior de Investigaciones Científicas (CSIC), Universitat Autònoma de Barcelona, 08193 Barcelona, Spain (e-mail: jose.millan@imb-cnm.csic.es; philippe.godignon@imb-cnm.csic.es; xavier.perpinya@imb-cnm.csic.es; amador.perez@imb-cnm.csic.es; jose.rebollo@imb-cnm.csic.es).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TPEL.2013.2268900

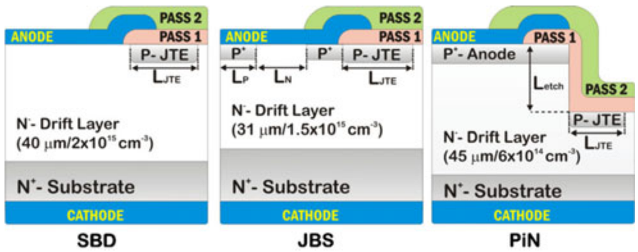

Fig. 2. Cross section of 4H-SiC 3.3-kV Schottky, JBS, and p-i-n diodes [4].

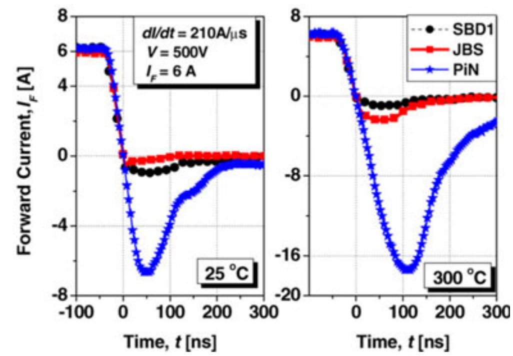

Fig. 3. 3.3-kV SiC diodes turn-off current waveforms at 25 °C and 300 °C with inductive load [4].

maturing fast, primarily due to light-emitting diodes manufacturing, but now also as a platform for high-frequency, high-voltage electronics, especially focused on GaN-based heterojunction high electron mobility transistors (HEMTs).

These novel power devices represent a real breakthrough in power electronics although many developments are still required. On the other hand, many of the material advantages are not fully exploited due to specific material quality, technology limitations, nonoptimized device designs, and reliability issues. Furthermore, the development of modeling and electrothermal characterization tools for these power devices, and the design of their packaging for high-temperature operation, drivers, and controllers need a great research effort and they represent an actual breakthrough.

This paper presents an overview of recent advances on novel SiC- and GaN-based power devices as well as expected future trends. State-of-the-art SiC devices, including high-voltage and high-temperature diodes, JFETs, MOSFETs, Thyristors, and IGBTs, are reviewed, as well as GaN-based diodes, HEMTs, and MOSFETs.

II. SiC Power Devices

The significant achievements in both SiC bulk material growth and process technology provide an excellent scenario to this semiconductor material for high-power applications. High-quality SiC wafers are mandatory for a reasonable yield of large-area SiC power devices. The progress is reflected in the achievement of very low micropipe density (0.75 cm^{-2} for a 75-mm wafer). Today, 100-mm SiC wafers are in the market, and 150-mm SiC wafers will be available in a near future [2]. Apart from micropipe formation, other defects causing poor reliability in bipolar devices, such as basal plane dislocations, are still under investigation.

A. SiC Power Rectifiers

In comparison with Si counterparts, a $\times 10$ increase in blocking voltage is possible with the same SiC drift layer thickness due to the SiC larger dielectric critical field. The high thermal conductivity of SiC is also a great advantage in comparison with Si diodes since it allows operating at higher current density ratings as well as to minimize the size of the cooling systems. There are basically three types of SiC power rectifiers [3], their cross sections being shown in Fig. 2:

1) Schottky Barrier Diodes (SBDs) showing extremely high switching speed and low on-state losses, but lower blocking voltage and high leakage current;
2) p-i-n diodes with high-voltage operation and low leakage current, but showing reverse recovery charging during switching;
3) Junction Barrier Schottky (JBS) diodes with Schottky-like on-state and switching characteristics, and p-i-n-like off-state performance.

SiC SBDs are commercially available since 2001 and have shown a continuous increase in the blocking voltage and conduction current ratings. Concretely, 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 current capabilities as high as 50 A [5], [6], these ratings being further increased in the near future. In fact, commercial 3.3-kV Schottky diodes have been already announced [7], and it is expected that they will eventually replace Si p-i-n rectifiers in the 600 V–3 kV range. Moreover, the easy SBD paralleling has allowed the introduction of commercial IGBT 600 A/1.2 kV power modules containing SiC SBDs as freewheeling diodes [8].

The ability of SiC devices for high-temperature operation makes them suitable for many applications in aerospace and space missions [9] although high-temperature reliable device packaging needs to be developed [10], [11]. Large-area 3.3-kV SBDs have been fabricated for high-temperature applications [4] with forward currents in the range of 10–20 A. An example of high-temperature operation is the 300-V, 5-A SBD diodes developed for harsh environment space applications (BepiColombo ESA mission) [12]. Besides, SiC SBDs are well suited for high switching speed applications due to the low reverse recovery charge in comparison with ultrafast Si p-i-n diodes. Thus, SiC SBDs match perfectly as freewheeling diodes with Si IGBTs. Fig. 3 displays the reverse recovery of the three SiC rectifiers at 25 °C and 300 °C.

Hybrid rectifiers, merging p-i-n and Schottky structures (JBS diodes), are particularly attractive since they combine the benefits of a high blocking voltage capability from p-i-n diodes and the low reverse recovery of SBDs (see Fig. 3). They are commercially available up to 1.2 kV, and Infineon has recently presented the thinQ!$^{\text{TM}}$ 5G generation [13] of 650-V JBS diodes based on a thin-wafer technological process showing improved surge current capability and avalanche ruggedness with a positive temperature coefficient. Besides, high-current (50 A) JBS diodes for being used as antiparallel diodes in IGBT modules are available from Cree, and 75 A–100 A/1.2 kV up to 20 A/10 kV JBS diodes have also been demonstrated [14].

Due to reliability problems (forward voltage drift mainly), there are no SiC bipolar diodes available in the market. Nevertheless, SiC state-of-the-art p-i-n diodes include that reported in [15] with a forward voltage drop of 3.2 V at 180 A (100 A/cm^2), and a blocking voltage capability of 4.5 kV with a reverse leakage current of 1 μA. In fact, p-i-n diodes will only be of interest for breakdown voltages over 2–3 kV, and structures with blocking capability up to 20 kV have been demonstrated [16]. However, their commercialization will depend on overcoming reliability problems through the improvement of the starting semiconductor material quality.

B. SiC Unipolar Power Switches

SiC-based power switches are well suited for high-voltage and, especially, high-temperature applications. Although SiC power switches in the 600 V range have two strong Si competitors; i.e., the power MOSFET (including superjunction devices) and the IGBT, they have clear advantages for higher blocking voltages. For the 1.2–1.7 kV range, the Si power MOSFET is not a realistic option due to the large conduction losses, and the Si IGBT shows high dynamic losses when requiring fast switching.

SiC JFET is an excellent alternative for this voltage range since it shows an ultralow specific on-resistance and is able to operate at high temperatures and high frequencies. Concretely, Infineon has developed a 1.5-kV, 0.5-Ω on-resistance hybrid switch aimed at resonant converters and power supplies. It consists of a 1.5-kV vertical SiC normally-on JFET (see Fig. 4) and a 60-V n-channel Si MOSFET in a cascode configuration which provides the resulting switch a normally-off behavior [18]. In addition, Infineon has recently announced a 1.2-kV, 70-mΩ on-resistance SiC JFET-based switch (CoolSiC) [19] consisting in a cascode topology including a low-voltage p-channel Si MOSFET in series with a high-voltage n-type SiC JFET. This solution allows referencing the gate driver for both the JFET and the MOSFET to the same potential, accounting for the switch ruggedness enhancement. Although these SiC JFET technologies are viable at voltages up to 4.5 kV, the hybrid switches do not show high-temperature operation due to the presence of the low-voltage Si MOSFET inside the package. New SiC normally-off trench JFETs have been developed to overcome this problem based on the high built-in voltage of SiC p-n junctions [20] although they show high resistive channels and low threshold voltages, and consequently, further improvements are still needed to get high-performance normally-off SiC JFETs. Fig. 4 shows the schematic cross sections of normally-on and normally-off JFETs.

As far as SiC MOS-gated structures are concerned, the potential candidates are the power MOSFET for breakdown voltages up to 9 kV and the IGBT for higher voltage capabilities. This voltage value results from a theoretical study to determine the voltage limit up to which the SiC power MOSFET would become attractive over the SiC IGBT in terms of a higher projected MVA rating [14], although it is commonly accepted that a lower value (around 5 kV) would be more realistic for practical devices. The development of low resistance power MOSFETs has been delayed due to the very low inversion channel mobility achieved on 4H-SiC. A great research effort in improving the MOS interface and in the integration of power MOSFETs has been done in the last years. The most remarkable advances in SiC MOS device technology have been reached by reducing the interface trap density (D_{it}) and improving surface morphology, the more effective techniques being the use of either nitrogen or $POCl_3$ during postoxidation annealing and the formation of the MOS channel on alternative crystal faces.

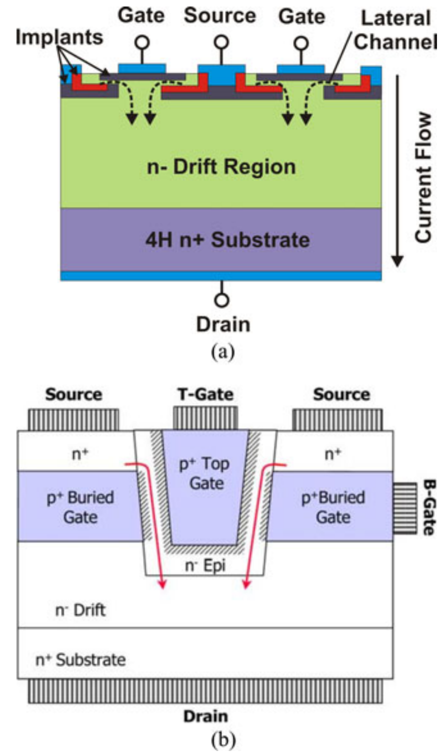

Fig. 4. Cross sections of (a) normally-on [17] and (b) normally-off JFETs [20].

Concretely, nitridation via NO and N_2O annealing of the SiC MOS interface has been proven key in decreasing D_{it} close to the conduction band edge ($D_{\mathrm{it}} = 2 \times 10^{11}$ eV$^{-1}\cdot$cm^{-2} at 0.2 eV below the conduction band edge) leading to channel mobility values on fabricated lateral MOSFETs of 50 and 73 cm^2/Vs for thermally grown and LPCVD gate oxides, respectively [21]. Besides, the channel mobility of $POCl_3$-annealed MOSFETs has been proven to be $\times 3$ that of NO-annealed MOSFETs [22]. The use of alternative gate dielectric materials such as Al_2O_3 and high-k dielectrics has also been considered, resulting in channel mobility over 200 cm^2/Vs [23]. Besides, improvements in MOS channel mobility ($>$200 cm^2/Vs) using the $\langle 1120 \rangle$ crystal face rather than the more commonly used $\langle 0001 \rangle$ face have been reported [24]. These technological achievements have allowed the appearance of SiC power MOSFETs. In fact, normally-off n-channel SiC power MOSFETs in the breakdown voltage range

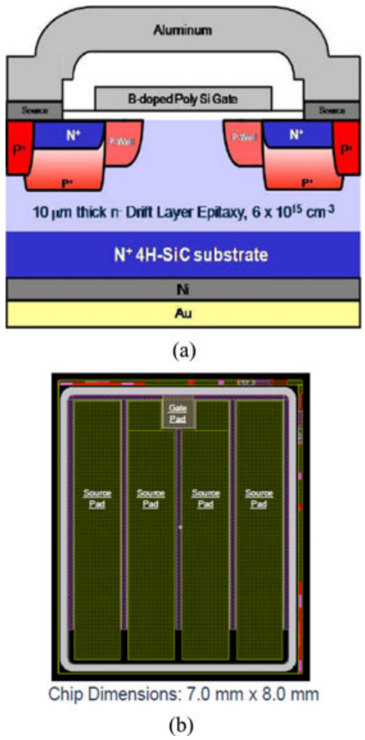

Fig. 5. 1.2-kV, 67-A 4H-SiC DMOSFET [2].

of 600 V–1.2 kV are available in the market. A 1.2-kV, 67-A (see Fig. 5) and 3-kV, 30-A 4H-SiC DMOSFET has been reported [2], [25], and since 2011, a 1.2-kV, 33-A SiC MOSFET is commercially available from Cree. This company has recently incorporated to its portfolio a 1.2-kV, 80-mΩ power MOSFET capable to attain record efficiencies with significant reliability improvement over competing Si devices with a nominal current of 42 A/24 A at 25 °C/100 °C [26]. Moreover, Rohm is currently offering 35-A/1.2-kV, 80-mΩ encapsulated MOSFETs [27], and has also announced a 1.2-kV, 1-mΩ·cm^2 trench MOSFET structure for high current density which will make it possible to drive 300 A from a single chip [28]. Besides, this company is going to introduce 120-A/1.2-kV "Full-SiC" power modules integrating SiC MOSFETs and SBDs [29] with high-frequency operation above 100 kHz. Powerex is also offering 100-A/1.2-kV all-SiC power modules [30], and a 800-A/1.2-kV prototype has been recently reported [31].

Furthermore, structures with a blocking voltage capability up to 10 kV have been recently demonstrated. For example, a 10-kV, 5-A 4H-SiC power DMOSFET has been reported in [32], utilizing a 100-μm-thick 6×10^{14} cm^{-3} doped n-type epitaxial layer, and a thermally grown gate oxide layer NO annealed. Although the peak effective channel mobility is rather low (13 cm^2/Vs), the 4H-SiC DMOSFET with an active area of 0.15 cm^2 showed a specific on-resistance of just 111 mΩ·cm^2 at room temperature.

C. SiC Bipolar Power Switches

The SiC IGBT is seen as the power switch with highest future potential for high-voltage applications since its superior on-state performance due to conductivity modulation. SiC IGBTs have received a lot of attention in recent years, and several structures with blocking voltage capabilities over 10 kV have been reported [33]. It is expected that these power switches will increase their voltage capability up to 20–30 kV in a near future [14], [34], thus widening the application field of SiC power switches. The achievements in the MOS interface quality and large channel mobilities achieved in the development of power MOSFETs are crucial for designing IGBT structures with high electrical performances. Besides, improvements in the epilayer growth process are still needed for the realization of competitive n-channel IGBT structures. Recently, Cree has reported their latest developments on ultra-high-voltage 4H-SiC IGBTs [33]. Concretely, a 4H-SiC p-channel IGBT, with a chip size of 6.7 mm $\times$ 6.7 mm, and an active area of 0.16 cm^2, exhibits a record high blocking voltage of 15 kV, while showing a room temperature differential specific on-resistance of 24 mΩ·cm^2 with a gate bias of -20 V. In addition, a 4H-SiC n-channel IGBT with the same area shows a blocking voltage of 12.5 kV, and a room temperature differential specific on-resistance of 5.3 mΩ·cm^2 with a gate bias of 20 V.

SiC BJTs are also promising although they also suffer from reliability problems similar to p-i-n junction rectifiers. These power structures have been developed over the last decade becoming a sufficiently mature technology. As an example, Cree reported a 4-kV, 10-A BJT with a current gain of 34 in the active region [35]. The chip area is 4.24 mm $\times$ 4.24 mm, and it is capable of blocking 4.7 kV with a leakage current of 50 μA, and turn-on and turn-off times of 168 and 106 ns at room temperature, respectively. However, SiC BJTs still show both current gain and forward voltage drop degradation under forward stress due to the presence of stacking faults in the base–emitter region [36], thus hindering the commercial production of these components.

Finally, some SiC-GTO structures have also been developed since they can benefit from conductivity modulation and the negative temperature coefficient of the forward voltage drop. One of the highest performance reported structure is the SiCGT (SiC Commutated Gate turn-off Thyristor) [37], whose cross section is schematically shown in Fig. 6. This SiCGT is a 4.5-kV, 120-A structure with a chip area of 8 mm $\times$ 8 mm coated with a new high heat resistive resin able to operate at 400 °C. The forward voltage drop is 5 V at 120 A, and the leakage current is less than 5×10^{-6} A/cm^2 at 4.5 kV and 250 °C, showing turn-on

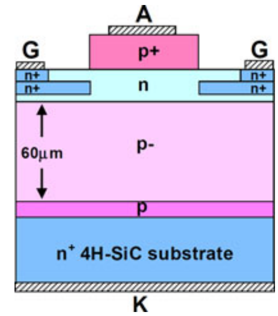

Fig. 6. Cross section of the SiCGT structure [38].

and turn-off times of 0.2 and 1.7 μs, respectively. In addition, three-phase inverter operation using a back-to-back system at dc bus of 2 kV and effective output power of 120 kW has been proven using power modules including a SiCGT and SiC p-i-n diodes [38].

III. GaN Power Devices

GaN is particularly attractive for high-voltage, high-frequency, and high-temperature applications due to its WBG, large critical electric field, high electron mobility, and reasonably good thermal conductivity. At present, GaN-based devices are already commercialized in the photonics area, while this semiconductor material is still in a first stage concerning power applications. Due to the lack of commercial high-quality free-standing GaN substrates in the past, GaN epilayers have been mainly grown on foreign substrates, particularly, SiC, sapphire, and Si. Growing high-quality, single-crystalline GaN films, which are essential for the power conversion, requires a well-defined global epitaxial relationship between the epitaxial GaN film and the substrate. Among the diverse possibilities, GaN epilayers grown on Si substrates offer a lower cost technology compared to the other substrates as well as allowing material growth on large diameter substrates up to 200 mm [39].

A. GaN Rectifiers

Most of GaN Schottky power diodes reported up to now are either lateral or quasi-vertical [40] structures due to the lack of electrically conducting GaN substrates. Breakdown voltages of lateral GaN rectifiers as high as 9.7 kV have been obtained on Sapphire substrates [41] although the forward voltage drop is still high. GaN rectifiers implemented on Si or Sapphire substrates are attracting a lot of attention because of their lower cost. Recently, with the availability of high-temperature hydride vapor phase epitaxy free-standing GaN substrates, 600-V GaN Schottky diodes are due to be launched in the market to compete with SiC Schottky rectifiers [42]. In addition, commercial GaN Schottky diodes will be available in the market in a very near future in the 600 V–1.2 kV voltage range. On the other hand, JBS GaN diodes are also being investigated which could further increase the performance of GaN-based power rectifiers in the 600 V to 3.3 kV range, although improvements in the contact resistance to implanted p-type GaN are still needed [43].

B. HEMTs and Power MOSFETs

One of the most interesting properties of GaN for power applications is the existence of a 2-D electron gas (2DEG) formed in AlGaN/GaN heterostructures due to the large conduction band discontinuity between GaN and AlGaN and the presence of polarization fields allowing a large 2DEG concentration with high electron mobility values (1200–2000 cm^2/Vs). GaN HEMTs (see Fig. 7) are intrinsically normally-on devices since a negative bias must be applied to the gate for removing the 2DEG. These devices have attracted a great attention in recent years with a remarkable tradeoff between specific on-resistance and breakdown voltage. They are well suited for high-power switching applications, with a projected $\times$100 performance advantage in the square breakdown voltage per specific on-resistance figure of merit ($V_{\rm BR}^2/R_{\rm ON}$) over silicon power devices. The combination of high speed and low-loss switching performance makes these devices very attractive for switching power supplies with ultrahigh bandwidth (in the megahertz range) and as microwave power devices for base station of cellular phone.

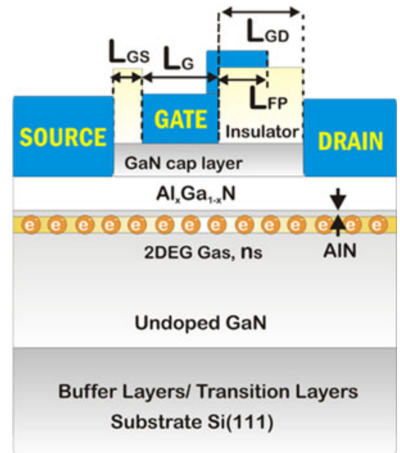

Fig. 7. Cross section of a normally-on GaN HEMT [44].

Remarkable improvements have been made since the appearance of the first GaN-based HEMT switch [45]. For instance, the output power capability at microwave frequencies of GaN-based HEMTs on both sapphire and SiC substrates has improved from initial 1.1 W/mm in 1996 up to 40 W/mm recently [46]. Moreover, the voltage capability of GaN HEMTS is approaching 10 kV and GaN-based power converters have been already demonstrated. One of the main issues in improving the electrical performance of the first HEMT structures was to suppress the drain current collapse and to increase the gate-to-drain breakdown voltage by controlling the bulk and surface trap densities [47]. In this sense, several approaches have been proposed including the surface-charge-controlled n-GaN-cap structure, the recessed gate and field-modulating plate structure, and the passivation of surface states via silicon nitride or other dielectric layers [48].

As a result, high-performance AlGaN/GaN HEMTs on Si substrates with blocking voltages higher than 1 kV [49], and high-voltage/low specific on-resistance HEMTs on semi-insulating SiC substrates [50] have been reported, the latter exhibiting a record of the $V_{\rm BR}^2/R_{\rm ON}$ figure of merit ($\sim$2.3 $\times$ 10^9 V^2/$\Omega\cdot$cm^2) exceeding the 6H-SiC theoretical limit. Concerning GaN HEMTs on Si, a significant achievement was the silicon removal approach accounting for a significant power increase of these HEMT structures. Concretely, a 2.2-kV HEMT fabricated on Si using a new local Si substrate removal technology has been recently reported [51], which represents a significant improvement in comparison with HEMT reference structure on bulk Si showing a blocking voltage capability of 700 V. Besides, GaN HEMT power switches for high-frequency, kilowatt power conversion fabricated on semi-insulating SiC substrates using field-plated gates have also been demonstrated [52].

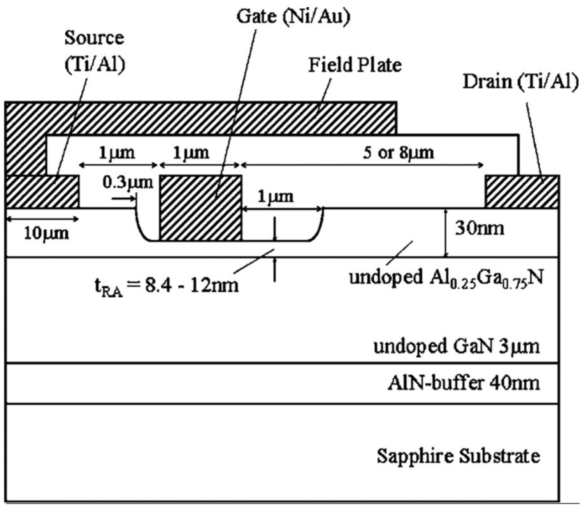

Fig. 8. Recessed-gate GaN HEMT structure [54].

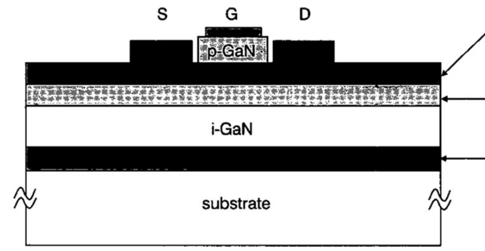

Fig. 9. Schematic cross section of a p-n gate GaN HEMT [57].

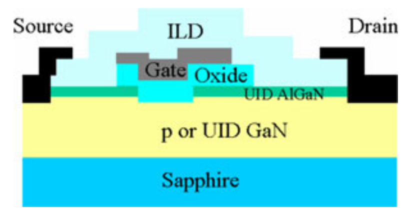

Fig. 10. Schematic cross-sectional view of a lateral GaN hybrid MOS-HFET [65].

Finally, extremely high voltage HEMTs (8.3 kV) with a low specific on-state resistance value of 186 mΩ·cm^2 have been demonstrated on a sapphire substrate with an improved heat dissipation performance by using via-holes through the sapphire at the drain electrodes [53].

As mentioned before, GaN HEMTs are basically normally-on devices, which makes difficult to use them in power systems where normally-off switches are preferred. For this reason, a research effort has been put in recent years in developing normally-off GaN HEMT structures through several approaches. One of them is the use of a recessed-gate structure (see Fig. 8), first reported in [54], in such a way that the AlGaN layer under the gate region is too thin for inducing a 2DEG, which accounts for a positive threshold voltage. Another solution for implementing a normally-off GaN HEMT is the use of a fluorine-based plasma treatment of the gate region [55] instead of reducing the AlGaN thickness as in the recessed-gate structure. The threshold voltage shift results from the incorporation of Fluor ions in the AlGaN barrier, and the damage induced by the plasma treatment is easily removed by a moderate temperature post-gate annealing. A combination of the gate recess together with a fluorine-based surface treatment has been proven as an excellent solution for getting high-performance normally-off AlGaN/GaN HEMTs [56]. Another technique for the realization of a normally-off HEMT is the selective growth of a p-n junction gate [57], [58] allowing the depletion of the 2DEG layer underneath (see Fig. 9).

Normally-on and off GaN HEMTs are commercially available with a breakdown voltage in the 20–600 V range. As examples, EPC [59] supplies normally-off GaN HEMTs from 40 V/33 A to 200 V/12 A, whereas MicroGaN [60] offers normally-on 600-V–170-mΩ GaN HEMTs, and a normally-off 600-V cascode switch based on the series connection of a normally-on GaN HEMT and a Si MOSFET.

As mentioned previously, the interest on GaN power devices is continuously increasing, and in this sense, an advanced GaN-based bidirectional super heterojunction field-effect transistor using the polarization junction concept has been recently demonstrated [61]. The fabricated HEMTs with Schottky and p-n junction gate structures are arrayed on an insulator substrate of Sapphire and the measured isolation voltage between the devices is more than 2 kV with measured on-resistances of 24 and 22 Ω·mm in the both directions, respectively. It is also worthy to remark that advances in GaN HEMT process technology enable the integration of GaN diodes, which can be used to protect the HEMTs' gate against voltage peaks. Furthermore, GaN smart power technologies are also under development allowing the monolithical integration of high-voltage power devices and low-voltage peripheral structures for sensing/protection/control purposes [62].

For high-voltage power switching applications, lateral GaN MOSFETs show the advantage of normally-off operation and large conduction band offset, which makes them less susceptible to hot electron injection and other reliability problems, in particular those related to surface states and current collapse [63], and makes them to be an alternative to SiC MOSFETs and GaN HEMTs. The high-quality of SiO_2/GaN interface has allowed the integration of lateral GaN MOSFETs with channel mobility values of 170 cm^2/Vs and high blocking voltage capability (2.5 kV) [63]. Nevertheless, these modest inversion channel mobility values, as in the SiC case, due to the presence of interface states, surface roughness, and scattering phenomena represent a major problem. To overcome this, an AlGaN/GaN heterostructure can be incorporated into the RESURF region of the GaN MOSFETs (see Fig. 10). The resulting hybrid MOS-HEMT [64]–[66] incorporates the merits of both the MOS gate control and the high mobility of the 2DEG in the AlGaN/GaN drift region and opens the possibility to implement normally-off, low on-state resistance and high blocking capability GaN power switches.

IV. Conclusion

This paper presents an overview of recent developments in power devices based on WBG semiconductor materials. The unique WBG material properties open the possibility for a future generation of more efficient power converters in applications where Si-based systems show important limitations, such as high-temperature, high-voltage, and high-frequency operation. At present, the commercial availability of high-quality wafers and the maturity of technological process made SiC and GaN the most adequate WBG semiconductor materials for these new power devices.

High-voltage SiC SBDs and JBS diodes are commercially available and they are already real competitors of Si diodes. On the other hand, SiC JFETs and MOSFETs will compete with Si IGBTs up to breakdown voltages in the range of 5 kV. JFETs are the first commercial SiC switches due to problems in improving the gate interface of SiC MOSFETs. Normally-on JFETs and normally-off hybrid cascode topologies including a normally-on SiC JFET in series with a low-voltage Si MOSFET are well established. On the contrary, normally-off SiC JFETs still suffer from high resistive channels that will need further improvements. SiC MOSFETs have been recently commercialized up to 1.2 kV. It is expected that results from improving the SiC MOSFET would be applied to the SiC IGBT that will allow the commercial development of IGBTs with breakdown voltages higher than 10 kV.

Most of GaN power devices are mainly fabricated on epitaxial GaN layers on Si, sapphire, or SiC substrates. High-voltage GaN diodes have been demonstrated and they will be commercialized in a near future. In addition, remarkable improvements on HEMTs fabricated on GaN heterostructures have been made in the last decade. The large 2DEG concentration and the high electron mobility values make these structures attractive for high-frequency switching/power applications. Although the HEMT structure is intrinsically a normally-on device, several techniques have been developed allowing the integration of normally-off HEMTs. GaN HEMTs are already commercially available up to 600 V. Finally, hybrid MOS-HEMT structures are also being considered for low-resistance, high-voltage GaN power switches.

References

[1] P. Roussel, “SiC market and industry update,” presented at the Int. SiC Power Electron. Appl. Workshop, Kista, Sweden, 2011.

[2] A. Agarwal, “Advances in SiC MOSFET performance,” presented at the ECPE SiC & GaN Forum Potential of Wide Bandgap Semicond. Power Electron. Appl., Birmingham, U.K., 2011.

[3] R. Singh, D. C. Capell, A. R. Hefner, J. Lai, and J. W. Palmour, “High-power 4H-SiC JBS rectifiers,” *IEEE Trans. Electron Devices*, vol. 49, no. 11, pp. 2054–2063, Nov. 2002.

[4] A Pérez-Tomás, P. Brosselard, J. Hassan, X Jordà, P. Godignon, M. Placidi, A. Constant, J. Millán, and J. P. Bergman, “Schottky versus bipolar 3.3 kV SiC diodes,” *Semicond. Sci. Technol.*, vol. 23, pp. 125004-1–125004-7, 2008.

[5] Application Notes CPWR-TECH1, 2005, CPWR-AN01, Rev. A, 2002 [Online]. Available: www.cree.com/power

[6] (2013). [Online]. Available: www.infineon.com/sic

[7] (2013). [Online]. Available: http://www.genesicsemi.com/index.php/sic-products/schottky

[8] FF600R12IS4 F Data Sheet (2007). [Online]. Available: www.infineon.com

[9] T. Funaki, J. C. Balda, J. Junghans, A. S. Kashyap, H. A. Mantooth, F. Barlow, T. Kimoto, and T. Hikihara, “Power conversion with SiC devices at extremely high ambient temperatures,” *IEEE Trans. Power Electron.*, vol. 22, no. 4, pp. 1321–1329, Jul. 2007.

[10] P. Ning, F. Wang, and K. D. T. Ngo, “High-temperature SiC power module electrical evaluation procedure,” *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3079–3083, Nov. 2011.

[11] R. Wang, D. Boroyevich, P. Ning, Z. Wang, F. Wang, P. Mattavelli, K. D. T. Ngo, and K. Rajashekara, “A high-temperature SiC three-phase AC-DC converter design for $>100\,^{\circ}$C ambient temperature,” *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 555–572, Jan. 2013.

[12] P. Godignon, X. Jordà, M. Vellvehí, X. Perpiñà, V. Banu, D. López, J. Barbero, P. Brosselard, and S. Massetti, “SiC Schottky diodes for harsh environment space applications,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 7, pp. 2582–2590, Jul. 2011.

[13] V. Scarpa, U. Kirchner, R. Kern, and R. Gerlach, “New SiC thin-wafer technology paving the way of Schottky diodes with improved performance and reliability,” *Power Electron. Eur.*, no. 3, pp. 30–32, 2012.

[14] R. J. Callanan, A. Agarwal, A. Burk, M. Das, B. Hull, F. Husna, A. Powell, J. Richmond, S-H. Ryu, and Q. Zhang, “Recent progress in SiC DMOSFETs and JBS diodes at Cree,” in *Proc. 34th Ind. Electron. Conf.*, 2008, pp. 2885–2890.

[15] B. A. Hull, M. K. Das, J. T. Richmond, J. J. Sumakeris, R. Leonard, J. W. Palmour, and S. Leslie, “A 180 Amp/4.5 kV 4H-SiC PiN diode for high current power modules,” in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2006, pp. 277–280.

[16] H. Niwa, G. Feng, J. Suda, and T. Kimoto, “Breakdown characteristics of 12–20 kV-class 4H-SiC PiN diodes with improved junction termination structures,” in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2012, pp. 381–384.

[17] R. Siemieniec and U. Kirchner, “The 1200 V direct-driven SiC JFET power switch,” in *Proc. Eur. Conf. Power Electron. Appl.*, 2011, pp. 1–10.

[18] D. Stephani, “Today’s and tomorrow’s industrial utilization of silicon carbide power devices,” presented at the 10th Eur. Conf. Power Electron. Appl., Toulouse, France, 2003, Paper 1199.

[19] (2012). [Online]. Available: http://www.infineon.com/cms/en/product/discretes-and-standard-products/coolsic-tm-sic-jfet/channel.html

[20] R. K. Malhan, Y. Takeuchi, M. Kataoka, A.-P. Mihaila, S. J. Rashid, F. Udrea, and G. A. J. Amaratunga, “Normally-off trench JFET technology in 4H silicon carbide,” *Microelectron. Eng.*, vol. 83, pp. 107–111, 2006.

[21] M. K. Das, “Recent advances in (0001) 4H-SiC MOS device technology,” *Mater. Sci. Forum*, vol. 457–460, pp. 1275–1280, 2004.

[22] D. Okamoto, H. Yano, K. Hirata, T. Hatayama, and T. Fuyuki, “Improved inversion channel mobility in 4H-SiC MOSFETs on Si face utilizing phosphorus-doped gate oxide,” *IEEE Electron Devices Lett.*, vol. 31, no. 7, pp. 710–712, Jul. 2010.

[23] N. G. Wright, N. Poolami, K. V. Vassilevski, A. B. Horsfall, and C. M. Johnson, “Benefits of high-k dielectrics in 4H-SiC trench MOSFETs,” *Mater. Sci. Forum*, vol. 457–460, pp. 1433–1436, 2004.

[24] C. Blanc, D. Tournier, P. Godignon, D. J. Bring, V. Souliere, and J. Camassel, “Process optimisation for $<11–20>$ 4H-SiC MOSFET applications,” *Mater. Sci. Forum*, vol. 527–529, pp. 1051–1054, 2006.

[25] S. Ryu, B. Hull, S. Dhar, L. Cheng, Q. Zhang, J. Richmond, M. Das, A. Agarwal, J. Palmour, A Lelis, B. Geil, and C. Scozzie, “Performance, reliability, and robustness of 4H-SiC power DMOSFETs,” *Mater. Sci. Forum*, vol. 645–648, pp. 969–974, 2010.

[26] (2012). [Online]. Available: http://www.cree.com/products/pdf/CMF20120D.pdf

[27] (2012). [Online]. Available: http://www.rohm.com

[28] (2012). [Online]. Available: http://www.rohm.com/products/sic/trench.html

[29] SiC Power Module - BSM120D12P2C005 (2013). [Online]. Available: http://www.rohm.com

[30] (2013). [Online]. Available: http://www.pwrx.com/summary/SiC-Modules.aspx

[31] R. A. Wood and T. E. Salem, “Evaluation of a 1200-V, 800-A all-SiC dual module,” *IEEE Trans. Power Electron.*, vol. 26, no. 9, pp. 2504–2511, Sep. 2011.

[32] S.-H. Ryu, S. Krishnaswami, B. Hull, J. Richmond, A. Agarwal, and A. Hefner, “10 kV, 5 A 4H-SiC power DMOSFET,” in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2006, pp. 265–268.

[33] S.-H. Ryu, C. Capell, C. Jonas, L. Cheng, M. O’Loughlin, A. Burk, A. Agarwal, J. Palmour, and A. Hefner, “Ultra high voltage (>12 kV),

high performance 4H-SiC IGBTs," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2012, pp. 257–260.
[34] D. A. Marckx, "Breakthrough in power electronics from SiC," Nat. Renewable Energy Lab., Golden, CO, USA, NREL/SR-500-38515, 2006.
[35] S. Krishnaswami, A. Agarwal, J. Richmond, T. P. Chow, B. Geil, K. Jones, and C. Scozzie, "4 kV, 10 A bipolar junction transistors in 4H-SiC," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2006, pp. 289–292.
[36] B. Buono, R. Ghandi, M. Domeij, B. G. Malm, C.-M. Zetterling, and M. Ostling, "Current gain degradation in 4H-SiC power BJTs," *Mater. Sci. Forum*, vol. 679–680, pp. 702–705, 2011.
[37] Y. Sugawara, Y. Miyanagi, K. Asano, A. Agarwal, S. Ryu, J. Palmour, Y. Shoji, S. Okada, S. Ogata, and T. Izumi, "4.5 kV 120 A SICGT and Its PWM three phase inverter operation of 100 kVA Class," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2006, pp. 117–120.
[38] A. Tanaka, S. Ogata, T. Izumi, K. Nakayama, T. Hayashi, Y. Miyanagi, and K. Asano, "Reliability investigation of SiC bipolar device module in long time inverter operation," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2012, pp. 233–236.
[39] B. De Jaeger, M. V. Hove, D. Wellekens, X. Kang, H. Liang, G. Mannaert, K. Geens, and S. Decoutere, "Au-free CMOS-compatible AlGaN/GaN HMET processing on 200 mm Si substrates," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2012, pp. 49–52.
[40] A. P. Zhang, G. T. Dang, F. Ren, H. Cho, K.-P. Lee, S. J. Pearton, J.-I. Chyi, T.-Y. Nee, and C.-C. Chuo, "Comparison of GaN P-I-N and Schottky rectifier performance," *IEEE Trans. Electron. Devices*, vol. 48, no. 3, pp. 407–411, Mar. 2001.
[41] A. P. Zhang, J. W. Jonson, F. Ren, J. Han, A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, J. M. Redwing, K. P. Lee, and S. J. Pearton, "Lateral $Al_x Ga_{1-x} N$ power rectifiers with 9.7 kV reverse breakdown voltage," *Appl. Phys. Lett.*, vol. 78, pp. 823–825, 2001.
[42] (2010) [Online]. Available: http://www.powdec.co.jp/Diode.pdf
[43] M. Placidi, A. Pérez-Tomás, A. Constant, G. Rius, N. Mestres, J. Millán, and P. Godignon, "Effects of cap layer on ohmic Ti/Al contacts to Si^+ implanted GaN," *Appl. Surface Sci.*, vol. 255, pp. 6057–6060, 2009.
[44] A. Fontserè, A. Pérez-Tomás, V. Banu, P. Godignon, J. Millán, H. De Vleeschouwer, J. M. Parsey, and P. Moens, "A HfO_2 based 800 V/300 °C Au-free AlGaN/GaN-on-Si HEMT technology," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2012, pp. 37–40.
[45] M. A. Khan, J. N. Kuznia, D. T. Olson, W. J. Schaff, J. W. Burm, and M. S. Shur, "Microwave performance of a 0.25 μm gate AlGaN/GaN heterostructure field effect transistor," *Appl. Phys. Lett.*, vol. 65, pp. 1121–1123, 1994.
[46] Y.-F. Wu, M. Moore, A. Saxler, T. Wisleder, and P. Parikh, "40-W/mm double field-plated GaN HEMTs," in *Proc. IEEE Device Res. Conf.*, 2006, pp. 151–152.
[47] N. Ikeda, S. Kaya, J. Li, Y. Sato, S. Kato, and S. Yoshida, "High power AlGaN/GaN HFET with a high breakdown voltage of over 1.8 kV on 4-inch Si substrates and the suppression of current collapse," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2008, pp. 287–290.
[48] T. Oku, Y. Kamo, and M. Totsuka, "AlGaN/GaN HEMTs passivated by Cat-CVD SiN Film," *Thin Solid Films*, vol. 516, pp. 545–547, 2008.
[49] S. Yoshida, J. Li, H. Takehara, H. Kambayashi, and N. Ikeda, "Fabrication of AlGaN/GaN HFET with a high breakdown voltage of over 1050 V," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2006, pp. 317–320.
[50] E. Bahat-Treidel, F. Brunner, O. Hilt, E. Cho, J. Würfl, and G. Tränkle, "AlGaN/GaN/GaN:C back-barrier HFETs with breakdown voltage of over 1 kV and low $R_{ON} \times A$," *IEEE Trans. Electron. Devices*, vol. 57, no. 11, pp. 3050–3058, Nov. 2010.
[51] P. Srivastava, J. Das, D. Visalli, M. Van Hove, P. E. Malinowski, D. Marcon, S. Lenci, K. Geens, K. Cheng, M. Leys, S. Decoutere, R. P. Mertens, and G. Borghs, "Record breakdown voltage (2200 V) of GaN DHFETs on Si with 2-μm buffer thickness by local substrate removal," *IEEE Electron Dev. Lett.*, vol. 32, no. 1, pp. 30–32, Jan. 2011.
[52] K. S. Boutros, S. Chandrasekaran, W. B. Luo, and V. Mehrotra, "GaN switching devices for high-frequency, kW power conversion," in *Proc. Int. Symp. Power Semiconductor Devices and ICs*, 2006, pp. 321–323.
[53] Y. Uemoto, D. Shibata, M. Yanagihara, H. Ishida, H. Matsuo, S. Nagai, N. Batta, M. Li, T. Ueda, T. Tanaka, and D. Ueda, "8300 V blocking voltage AlGaN/GaN power HFET with thick poly-AIN passivation," in *IEDM Tech. Dig.*, 2007, pp. 861–864.
[54] W. Saito, Y. Takada, M. Kuraguchi, K. Tsuda, and I. Omura, "Recessed-gate structure approach toward normally-off high-voltage AlGaN/GaN HEMT for power electronics applications," *IEEE Trans. Electron. Devices*, vol. 53, no. 2, pp. 356–362, Feb. 2006.
[55] Y. Cai, Y. Zhou, K. M. Lau, and K. J. Chen, "Control of threshold voltage of AlGaN/GaN HEMTs by fluoride-based plasma treatment: From depletion mode to enhancement mode," *IEEE Trans. Electron. Devices*, vol. 53, no. 9, pp. 2207–2215, Sep. 2006.
[56] T. Palacios, C.-S. Suh, A. Chakraborty, S. Keller, S. P. DenBaars, and U. K. Mishra, "High-performance E-Mode AlGaN/GaN HEMTs," *IEEE Electron. Devices Lett.*, vol. 27, no. 6, pp. 428–430, Jun. 2006.
[57] X. Hu, G. Simin, J. Yang, M. A. Khan, R. Gaska, and M. S. Shur, "Enhancement-mode AlGaN/GaN HFET with selectively grown pn junction gate," *Electron. Lett.*, vol. 36, pp. 753–754, 2000.
[58] O. Hilt, E. Bahat-Treidel, E. Cho, S. Singwald, and J. Würfl, "Impact of buffer composition on the dynamic on-state resistance of high-voltage AlGaN/GaN HFETs," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2012, pp. 345–348.
[59] (2013). [Online]. Available: http://epc-co.com
[60] (2013). [Online]. Available: http://www.microgan.com/
[61] A. Nakajima, V. Unni, K. G. Menon, M. H. Dhyani, E. M. Sankara Narayanan, Y. Sumida, and H. Kawai, "GaN-based bidirectional super HFETs using polarization junction concept on insulator substrate," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2012, pp. 265–268.
[62] K-Y Wong, W. Chen, X. Liu, C. Zhou, and K. J. Chen, "GaN smart power IC technology," *Phys. Status Solidi B*, vol. 247, no. 7, pp. 1732–1734, 2010.
[63] W. Huang, T. P. Chow, Y. Niiyama, T. Nomura, and S. Yoshida, "Lateral implanted RESURF GaN MOSFETs with BV up to 2.5 kV," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2008, pp. 291–294.
[64] H. Kambayashi, Y. Satoh, S. Ootomo, T. Kokawa, T. Nomura, S. Kato, and T. P. Chow, "Over 100 A operation normally-off AlGaN/GaN hybrid MOS-HFET on Si substrate with high-breakdown voltage," *Solid-State Electron.*, vol. 54, pp. 660–664, 2010.
[65] W. Huang, T. P. Chow, Y. Niyama, and S. Yoshida, "Enhanced-mode GaN hybrid MOS-HEMTs with $R_{on,sp}$ of 20 mΩcm^2," in *Proc. Int. Symp. Power Semicond. Devices ICs*, 2008, pp. 295–298.
[66] T. Oka and T. Nozawa, "AlGaN/GaN recessed MIS-gate HFET with high-threshold-voltage normally-off operation for power electronics applications," *IEEE Electron Device Lett.*, vol. 29, no. 7, pp. 668–670, Jul. 2008.

José Millán (M'91) was born in 1948. He received the B.Sc. degree from the University of Navarra, Pamplona, Spain, in 1971, and the Ph.D. (Hons.) degree in electronics from the Autonomous University of Barcelona (UAB), Barcelona, Spain, in 1980.

He was an Assistant Professor at the UAB during 1980–1987. In 1987, he joined the Centro Nacional de Microelectrónica (CNM), Barcelona. He became a Full Professor at the Consejo Superior de Investigaciones Científicas in 1991. He was the Deputy Director of CNM-Barcelona in February 1999–February 2003 and March 2006–June 2008. He has published more than 290 papers including regular and international conference papers. He has participated in 32 national projects, 23 European projects, and 21 industrial contracts. He also holds 12 patents. His research interests include process technologies (Si and widebandgap semiconductors) for power devices and microsystems.

Philippe Godignon was born in Lyon, France, in 1963. He received the Ph.D. degree in electrical engineering from the Institut National des Sciences Appliquées de Lyon, Lyon, in 1993.

Since 1990, he has been with the Power Device and System Group, Centro Nacional de Microelectrónica, Barcelona, Spain, where he has been working on Si and SiC IGBT/VDMOS device design and technologies. His competence covers the device technological process development and mask design as well as the electrical characterization. He has authored more than 250 publications and conference proceedings on Si and SiC power devices. He also coauthored more than ten patents. His recent works deal with SiC devices extended to high-temperature devices and sensors as well as grapheme and CNT transistors for environmental and biomedical applications.

Xavier Perpiñà received the B.S. degree in physics, the M. Phil. degree in electronic engineering, and the Ph.D. degree from the Universitat Autònoma de Barcelona, Barcelona, Spain, in 1999, 2002, and 2005, respectively.

In 1999, he was with the Institut de Microelectrònica de Barcelona–Centre Nacional de Microelectrònica (IMB-CNM), Spanish Research Council, Barcelona, where he began his research activity with the Power Devices and Systems Group until 2005. From 2005 to 2007, he was with Alstom Transport. He is currently a Ramon y Cajal Fellow at IMB-CNM. He has authored and coauthored more than 90 research papers in international conferences and journals, edited two books on railway hot topics, and hold several patents in this research field. He also belongs to THERMINIC and EUROSIME conference scientific committees. His research interests include electrothermal characterization, reliability and layout robustness improvement in power semiconductor devices, integrated circuits, and packaging for power applications.

Amador Pérez-Tomás received the B.Sc. degree in physics from the University of Barcelona, Barcelona, Spain, in 1999, and the Ph.D. degree in physics from the Autonomous University of Barcelona, Barcelona, in 2005.

He worked in the financial and banking sector from 1999 to 2001 He was a Research Fellow at the University of Warwick (U.K.) during 2006–2008. In 2008, he joined the Institut de Microelectrònica de Barcelona–Centre Nacional de Microelectrònica (IMB-CNM), Spanish Research Council, Barcelona. His research activity was primarily related to SiC and GaN devices and semiconductor heterojunctions. He has authored or coauthored more than 145 papers including regular and international conference papers. He also worked on relevant R&D industrial contracts, holds one U.S. patent and supervised several Ph.D. students.

José Rebollo was born in 1959. He received the B.S. and Ph.D. degrees in physics from the Autonomous University of Barcelona, Barcelona, Spain, in 1982 and 1987, respectively.

He was an Assistant Professor at the Autonomous University of Barcelona teaching Electronics and Physics as well as Postgraduate Microelectronic Courses. In 1989, he joined the Power Devices and Systems Group of the National Microelectronic Centre, Barcelona, where he has been working on the physics, technology, modeling, and reliability of power semiconductor devices. He has published more than 200 papers in scientific journals and conferences, and holds several patents in these fields. He has participated and managed several EU-funded projects, and industrial contracts including technology transfer, as well as R&D projects funded by the Spanish Administration.