High-Voltage SiC Devices: Diodes and MOSFETs

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Abstract — This paper reviews recent achievements on high-voltage SiC-based devices aimed at Wind Power and Solid-State Transformer applications. SiC diodes with voltage ranges between 1.7kV and 9kV have been designed and fabricated. On the other hand, SiC JFETs and, specially, SiC MOSFETs are also under development, and preliminary prototypes of 3.3 kV SiC MOSFETs are reported.

Keywords—Wide Band Gap Semiconductors, SiC, SiC diodes, SiC transistors, high-voltage applications.

1. Introduction

The demand of modern wide band gap semiconductor devices for high efficient energy conversion systems can open new and increased performance of these systems [1]. Silicon Carbide (SiC) diodes are available in the market for more than 15 years, becoming key components in various applications like power supplies or solar power conversion systems. Nevertheless, SiC transistors are relatively new in the market and system's designers are becoming familiar with these power switches.

However, the SiC high-voltage (HV) capability is not fully exploited. While SiC rectifiers with breakdown voltages in excess of 3.3kV are getting close to becoming commercially available, only SiC switches with a voltage range of 1.2-1.7kV are in the market. In this sense, there are EU funded initiatives to increase the voltage level of SiC devices. In the framework of the European Project SPEED [2], a group of companies and research institutions is focusing on SiC power devices for specific applications in addition to the already addressed fields. The current roadmap for SiC semiconductor industry is the introduction of 3-6.5kV SiC devices into the market in a medium term.

SPEED aims at a breakthrough in SiC technology along the whole supply chain:

• Growth of SiC substrates and epitaxial layers.

• Fabrication of power devices (rectifiers and switches) in the 1.7kV / 10kV range.

• Packaging and reliability of these devices.

• SiC-based highly efficient power conversion cells, including the design and optimization of the auxiliary circuitry needed for controlling and protecting the SiC devices for the two selected applications. This includes the selection of the power converters' configurations and the cells optimization to fulfil the desired functionalities.

• Real-life applications and field-tests in close cooperation with two market-leading manufacturers of HV devices and major electrical utility as final users.

To this end, suitable SiC substrates, epitaxial layers and HV devices are being developed and implemented in two demonstrators: A costefficient Solid-State Transformer (SST) to support advanced grid smartness and power quality, and a windmill power converter with improved capabilities for generating AC and DC power. At present, there are no SSTs in the market due to the high cost associated with power electronic converters when compared to conventional 50 Hz transformers. It is expected that SiC devices will facilitate the SST commercial introduction improving their properties and system-level advantages. On the other hand, the use of SiC devices in wind power applications with high frequencies during the power conversion will result in reducing power losses due to the inherent low SiC devices' dynamic losses. The main objective of SPEED project is to evaluate the advantage of SiC rectifiers and switches in terms of efficiency increase, power density, reduced converters' complexity, plus the adaptation of the involved technologies for optimizing cost performance solutions for both applications.

2. SiC power devices for Wind Power Applications

It has to be pointed out that wind power applications normally use 1.7kV components. Therefore, in the framework of this project 1.7kV SiC rectifiers and switches, especially adapted for this application, are under development.

A. Schottky Barrier Diodes

It is well known that unipolar devices are limited in handling overcurrent events due to their inherent resistive I(V) characteristic. In SPEED, special devices are under development for this specific application. The idea is to use the so called merged PiN Schottky diodes, MPS, (or Junction Bipolar Schottky, JBS) [3, 4]. Fig. 1 shows the basic principle of this merged diode, in which the current flow under nominal current conditions is managed by the Schottky area. Hence, it results in a low forward voltage drop (V_F). However, under overcurrent conditions the Schottky component alone will not be able to withstand it, and the rectifier's PiN area allows the overcurrent flow. Although pure SiC PiN diodes would be able to support high currents due to conductivity modulation, V_F (in the range of 3V in SiC) is too high to compete with Si PiN diodes.

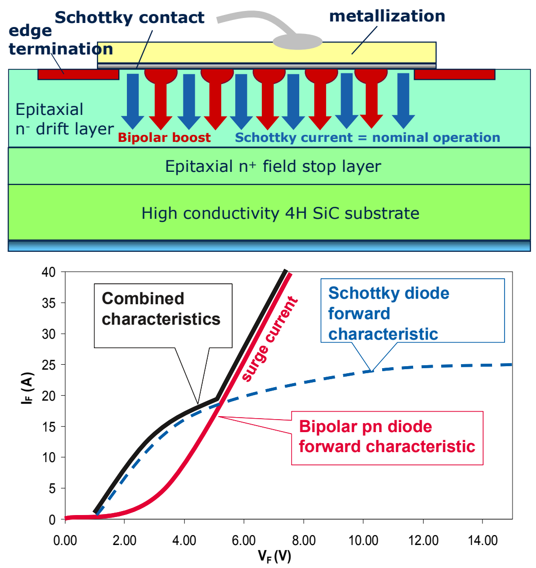


Fig. 1. Cross-section, functionality and I(V) forward characteristic for a merged PiN-Schottky diode in SiC.

This solution comes from the monolithic integration of both structures with a smart layout of the Schottky component that combines the benefits of both concepts (low V_F plus overcurrent capability, adding the breakdown capability of a PiN diode).

A drawback of SiC Schottky barrier diodes compared to Si PiN diodes comes from the V_F increase with temperature, due to the fact that the active region is purely resistive. The conduction losses of SiC based Schottky diodes are much lower compared to the Si-based PiN counterparts, which usually do not show a change with temperature in forward voltage drop at a rated current. Therefore, suitable SiC JBS structures with an optimized V_F/temperature behaviour trade-off must consider a smart Schottky/PiN area ratio, especially at operating temperatures between 125ºC and 150ºC junction temperature. Fig. 2 shows the achieved progress for the most recent 1.2kV diodes from Infineon.

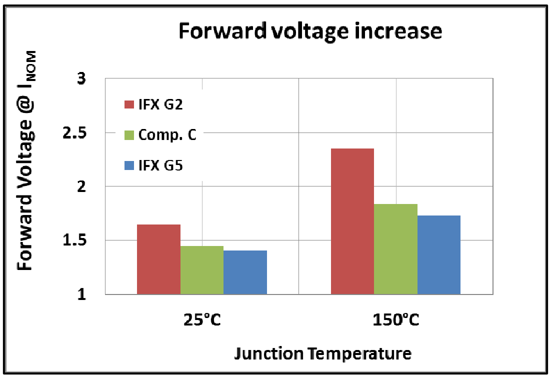


Fig. 2. Forward voltage drop of SiC 1.2kV diodes at rated current, left at room temperature, right at 150ºC. Comparison between Infineon's old and new generation diodes and a competitor's device.

Not just V_F at room temperature could be improved, but also at high temperature could be also reduced significantly. The baseline for this improvement is a doping engineering. It should be noted that there are very few 1.7kV SiC components commercially available. Regarding power modules, only few products can be found in the market [5] made up of SiC rectifiers and Si IGBTs. In fact, especial designs have been realized recently to extend the devices' blocking capability towards 1.7kV. After analyzing first prototype modules with a current handling capability of about 1kA developed within the project, the achievable system benefit was estimated. The lack of any storage charge in SiC Schottky diodes results in a significant reduction of the IGBTs turn-on losses in half bridge configuration, which is the most common arrangement in commercial applications [6]. However, static losses of SiC Schottky diodes are higher than that exhibit by Si PiN diodes.

Fig. 3 shows the reduction in turn-on losses for different DC bus voltages with the most recent Si IGBT4 generation (Trenchstop technology) [6]. Taking into account the total loss balance considering other contributions (SiC diode recovery energy and Si IGBT turn-off losses plus conduction losses for both components) a saving of about 30 to 40% compared to the full Si based configuration is possible, depending on the final switching frequency.

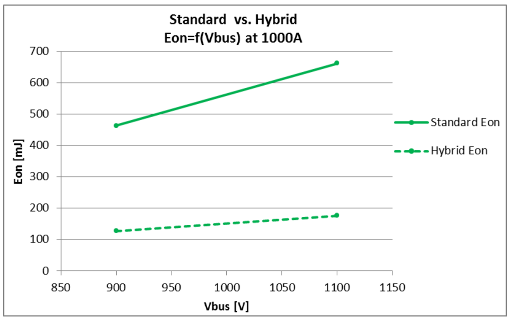


Fig. 3. Reduction of dynamic losses (turn on – Eon) by using SiC freewheeling diodes (hybrid) in combination with Si IGBTs (standard).

B. SiC Transistors

As far as switches are concerned, both MOSFETs and JFETs rated at 1.7 kV are contemplated within SPEED project with special emphasis in reducing the conduction and dynamic losses. For the conduction loss reduction, the lack of a knee voltage compared to Si IGBTs is the most prominent advantage. Many applications, as in wind power generators, operate most of their time not at full load, but only at 30 to 60% of the full rated current. Then, the linear I(V) characteristic of unipolar SiC transistors can allow achieving a significant save in this mode compared to Si IGBTs based solutions. In addition, these SiC transistors can also be designed to include an internal body diode, which can replace the external freewheeling diode used today with Si IGBTs. Although this internal diode is a PiN-based structure, it is expected a very small reverse recovery current due to the thin drift zone of a 1.7kV SiC transistor. Regarding the conduction losses of this internal diode it can be considered that the always present parallel channel of the transistor can be turned on, thus offering a knee free I(V) characteristic for the diode mode, ending up with a further reduction in conduction losses of the complete circuit.

3. SiC power devices for Solid-State Transformers

Classical line frequency transformers are key elements in power distribution systems. Transformers are relatively cheap and reliable devices based on a well-establish technology. However, they suffer from several limitations, including low power density (large weight/volume for a certain power), large losses with light loads, sensitivity to harmonics, offset and imbalances and no effective overload protection. Solid State Transformers (SSTs) are an alternative to classical transformers [7-10]. The use of fast-switching power semiconductor devices allows a significant decrease of the volume/weight of the transformer core. Even more important, SSTs often provide control and some energy storage capability. This enables the integrated implementation of additional functionalities [8] that include: 1) automatic continuous on-load voltage regulation, contributing to a smoothing effect for the voltage profile through the grid; 2) provision of reactive power compensation; 3) on-demand definition of the wave shape, including harmonic compensation; 4) environmental benefits: the oil free SSTs will be more environmental friendly in comparison with conventional oil immersed transformers, while in comparison with the conventional dry-type transformers, the SSTs are expected to be more efficient (in terms of lower losses).

Nevertheless, SSTs need to develop new high-voltage power devices, with SiC being the most suitable material. However, to apply SiC devices in this application it is necessary to significantly increase the blocking voltage and the current ratings of the devices. HV range diodes will be developed for the targeted application in SPEED. 3.3kV, 6.5kV and 10kV class diodes of JBS and PiN type and their corresponding switches, with current ratings of up to 30A per chip (depending on the voltage class) are targeted, which is well above the current state of the art.

C. SiC Diodes

This work has been developed on the basis of previous research [11-15]. The main effort has been focussed on adapting the previous experience to these specific application requirements.

1) 3.3kV

There are basically three types of SiC power rectifiers, their cross-sections being shown in Fig. 4: 1) Schottky Barrier Diodes (SBD) showing 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.

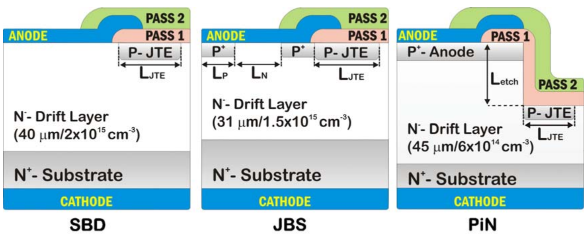


Fig. 4. Cross-section of manufactured 4H-SiC 3.3 kV Schottky, JBS and PiN diodes.

3.3 kV class 4H-SiC SBD, JBS and PiN diodes were manufactured, characterized and compared. The diodes were characterized in forward, reverse and switching modes in the 25ºC–300ºC temperature range. Fig. 5 shows the experimental I(V) characteristics in the forward mode. It is not straightforward to choose a clear 3.3 kV winning rectifier for power converter applications. JBS diodes definitely exhibit the best on-resistance versus reverse recovery properties for forward current densities up to 100 A/cm^2. In the 100–500 A/cm^2 forward current density range, JBS is still competing with PiN because its reverse recovery charge is much lower (an order of magnitude). Above 1000 A/cm^2, the PiN diode forward characteristics significantly outperform those from a JBS, especially at room temperature. JBS behaves like a SBD or like a PiN depending on many factors, especially the temperature. The blocking capability of fabricated SiC diodes is shown in Fig. 6. As expected SBDs clearly show a higher leakage current than JBS and PiN diodes. Fig. 7 displays the reverse recovery of the three SiC rectifiers at 25ºC and 300ºC. As it can be seen, SBD and JBS diodes show a negligible reverse recovery and independent of temperature.

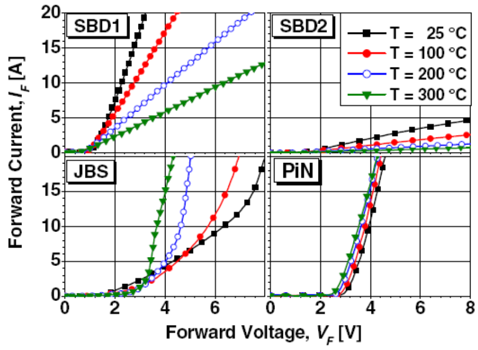


Fig. 5. Forward I(V) curves of the fabricated 3.3 kV SiC diodes in the 25ºC-300ºC temperature range. Active areas: SBD1= 25 mm^2; SBD2, JBS and PiN = 2.6 mm^2.

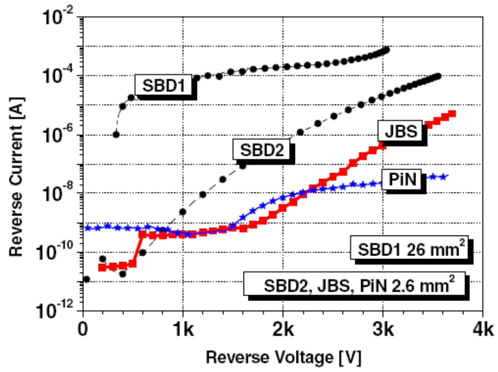


Fig. 6. Blocking characteristics of the fabricated 3.3kV SiC diodes at room temperature.

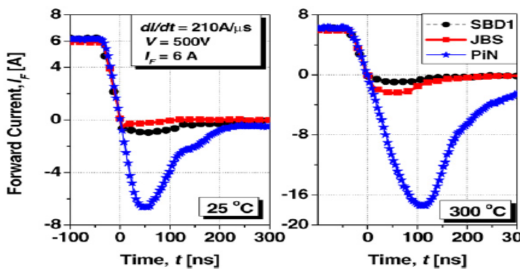


Fig. 7. Turn-off current waveforms for 3.3 kV SiC diodes in the 25ºC-300ºC temperature range.

However, the SiC epilayer could be degraded under bipolar operation. PiN and JBS diodes suffer from forward voltage drift after a dc stress, due to stacking fault (SF) formation. As it is inferred from Fig. 8, 3.3kV SBD diodes, with such a thick epilayer, appear only to outperform JBS and PiN in terms of reliability or in applications where the switching speed, at high temperatures, is paramount. SPEED is also developing high quality (SF free) thick epilayers suitable for bipolar conduction.

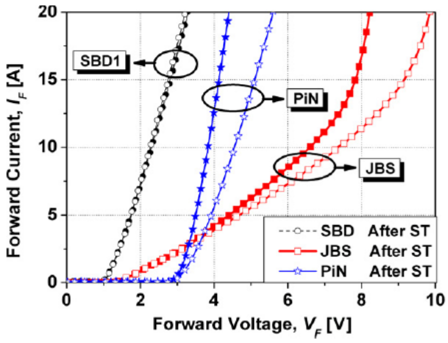


Fig. 8. Evolution of forward I(V) characteristics of 3.3 kV diodes after DC stress (20-60 hours @ 10 A, 25ºC-225ºC).

2) *5kV/6kV-9kV*

The devices have been fabricated on an 8° off 3-inch 4H-SiC substrates. A 90μm thick epilayer doped at $5{\cdot}10^{14}cm^{-3}$ was grown. The design of the devices is fully planar [15]. Fig. 9 shows a schematic view of a vertical cut in the center of the JBS diode, showing the active area and the termination design. The active area of the diodes, delimited by the field channel stopper, measures $2.1{\times}2.1mm^2$.

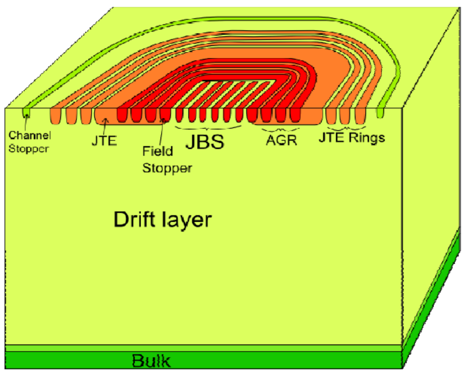


Fig. 9. Schematic view of a JBS diode with guard ring assisted resurf termination.

The termination extension is 350μm long and the total die area is $3.25{\times}3.25mm^2$ including the dicing tracks. The JBS diodes design consists of p-type stripes of 3μm width 4μm spaced. The p stripes are created via the implantation of aluminum impurities at different energies to create a 200nm deep box profile doped at $1{\times}10^{19}cm^{-3}$. This implantation was also used to create assisting guard rings of the termination.

The termination is a guard rings assisted resurf made of a 220μm long JTE with 3 assisting guard rings (AGR) and 5 JTE Rings. The ring spacing and size, and the JTE dose were optimized by simulation.

The forward characteristics of the diodes were measured on the whole wafer with probes in Kelvin configuration, with a forward voltage from 0 to 3V (fig. 10). The specific on-resistance of all the diodes ranges from $85m\Omega{\cdot}cm^2$ to $141m\Omega{\cdot}cm^2$ depending on the diode type and design, but also on the position on the wafer, which accounts for the lack of uniformity of epilayer parameters. Indeed, lower on-resistances are obtained at the wafer periphery. We can estimate that the epitaxial layer is 30% thicker at the centre of the wafer than at the periphery.

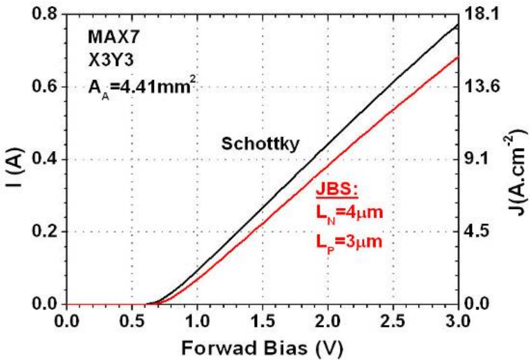


Fig. 10. Forward characteristics of 9kV Schottky and JBS diodes.

Concerning the reverse I(V) characteristics, the wafer was immersed in a Galden bath and the diodes were reverse bias up to their maximum capability. Reverse characteristics of several diodes are shown in Fig. 11.

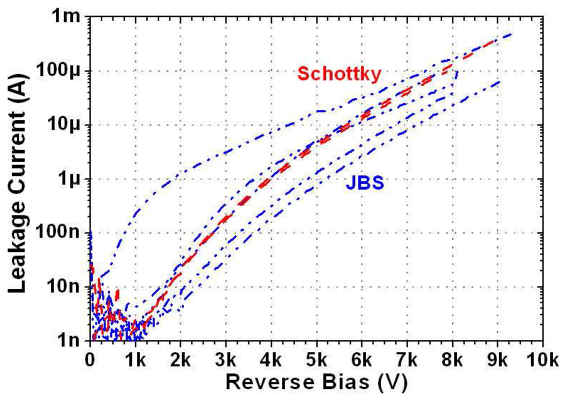
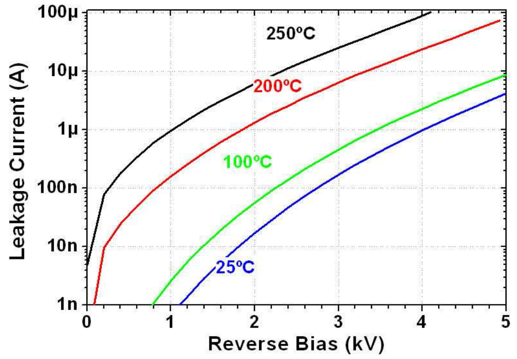
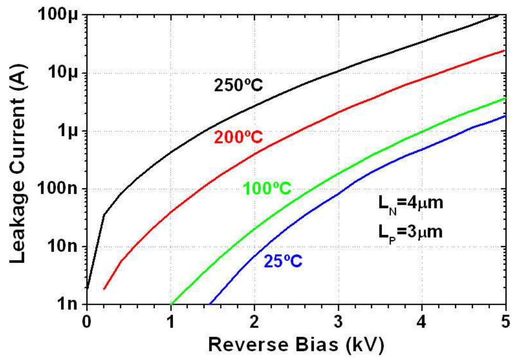


Fig. 11. Reverse characteristics of 9kV diodes at room temperature in Galden bath.

Diodes at the centre of the wafer were capable to support up to 9.2kV. Generally, our diodes withstand up to 8kV, the difference of blocking capability coming partially from the difference of drift layer thickness. Surprisingly, the Schottky diodes present a leakage current in the same range as the JBS diodes, especially at high reverse bias.



(a)



(b)

Fig. 12. Reverse characteristics of 9kV Schottky (a) and 9kV JBS (b) diodes. Temperature range: 25ºC-250ºC.

To avoid the Galden bath influence from the characterization methodology, the diodes were measured again under vacuum. The chuck was also connected to a thermostat, which allows controlling the wafer temperature up to 500ºC. At room temperature under vacuum, the measured leakage current and breakdown voltage of the diodes were similar to previous measurements in Galden. It indicates that the leakage current and breakdown voltage of the diodes are due to the diode structures themselves and not to the measurement set-up.

The reverse characteristics of several JBS and Schottky diodes at different temperatures, up to 250ºC, for a reverse bias up to 5kV were also measured. The results are plotted on Fig. 12.

In relation with 5kV diodes the epitaxial properties were a thickness of 50µm with a doping level of 10^{15} cm^{-3}. The forward characteristics of a 5kV Schottky diodes vs temperature are plotted on Fig. 13. Table 1 summarizes the V_F of a 5kV Schottky diode at different temperatures at a nominal current of 10A. The reverse I(V) characteristics of these diodes at shown in Fig. 14. As expected the JBS diodes are able to withstand higher voltages than the Schottky diodes.

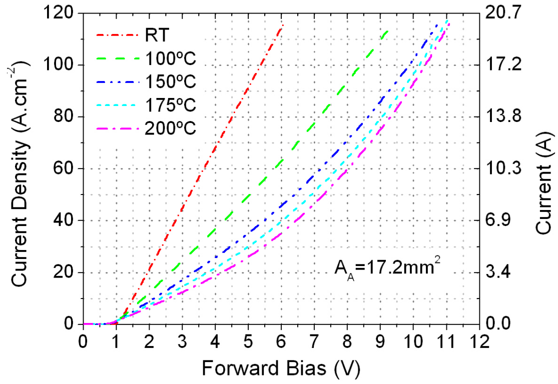


Fig. 13. Forward I(V) characteristic of a 5kV Schottky diode at different temperatures.

Table 1. V_F of a 5kV Schottky diode at different temperatures and locations on the wafer. Nominal current: 10A.

	RT	100ºC	150ºC	175ºC	200ºC
X5 Y7	3.4V	5.5V	7.0V	7.5V	7.9V
X6 Y7	3.5V	5.6V	7.0V	7.5V	7.9V
X9 Y7	3.6V	5.8V	7.1V	7.5V	7.8V

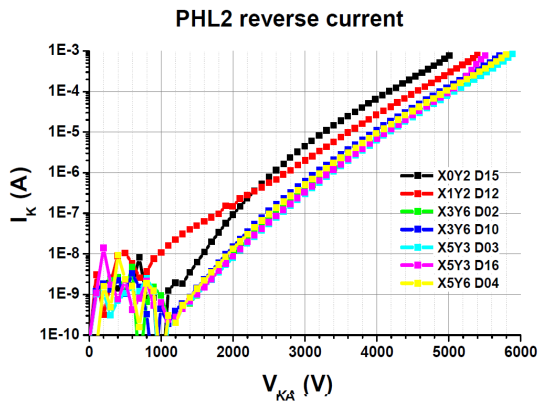
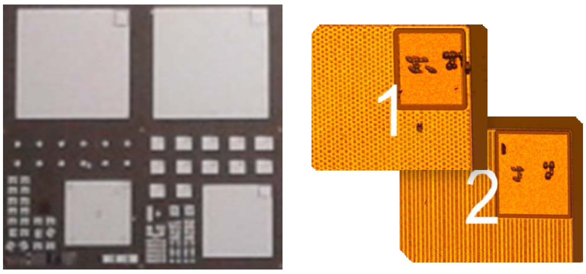


Fig. 14. Reverse I(V) characteristic of 5kV-6kV Schottky and JBS diodes. (black: Schottky, other colours: JBS)

D. SiC Transistors

Concerning high voltage SiC MOSFETs, a process technology has been defined and first prototypes have been integrated [16]. They have a self-aligned active channel, which is defined by a polysilicon layer through which both p and n-type impurities are implanted. After the p-type implantation, the polysilicon layer is oxidized and then the n-type implantation is performed. Therefore, the lateral length of the oxidized polysilicon defines the submicron channel length. The 40 nm thermal gate oxide is grown in N_2O ambient for improving the interface quality, allowing both the channel mobility increase and the threshold voltage stability.

Small (1 mm^2) and large area (9 and 25 mm^2) SiC MOSFETs have been fabricated with stripe and hex-cell designs. A photo of the design reticle showing both small and large area MOSFETs is depicted in Fig. 15.



(a) (b)

Fig. 15. (a) Photo of the fabricated SiC MOSFETs; (b) top view of the active area showing both stripes and hex-cell designs.

The experimental breakdown voltage is in the range of 1.7kV since the device edge termination has not been optimized for the first prototypes. It is expected that next devices will reach 3.3kV in the blocking mode. Fig. 16. shows the output characteristics of a large area SiC MOSFET, showing a large current capability although the devices are unpackaged.

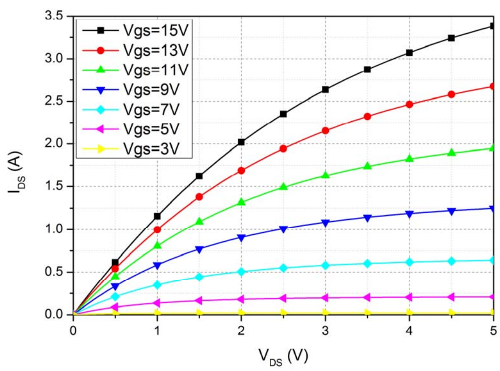


Fig. 16. Experimental output characteristics of fabricated MOSFETs.

4. Conclusions

SiC is an excellent semiconductor material for power electronics. This paper overviews SiC diodes and switches aimed at Wind Power and Solid-State Transformer applications developed within the EU funded SPEED project. 1.7 kV JBS diodes have been designed and successfully checked for Wind Power applications. Switches of this voltage class are currently under development. As far as Solid-State Transformers are concerned, Schottky, JBS and PiN diode prototypes with voltage range between 3kV and 9kV have been fabricated. These rectifiers are currently under optimisation. Moreover, preliminary prototypes of 3.3 kV SiC MOSFETs are also reported for this application.

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References

[1] J. Millán, P.Godignon, X.Perpiñà, A.Pérez-Tomás and J.Rebollo., “A survey of wide band gap power semiconductor devices”, IEEE Trans. on Power Electronics, vol.29, no. 5, pp. 2155-2163, 2014.

[2] www.speed-fp7.org

[3] F. Dahlquist , J. O. Svedberg , C. M. Zetterling , M. Ostling , B. Breitholtz and H. Lendenmann. "A 2.8 kV, 2V Forward Drop JBS Diodes with Low Leakage", Proceedings of the International Conference of Silicon Carbide and Related Materials (ICSCRM), 1999.

[4] R. Singh, S. Ryu, J. W. Palmour, A. R. Hefner and J.-S. Lai, "1500 V, 4 A 4H-SiC JBS Diodes", Proceedings of IEEE International Symposum on Power Semiconductor Devices and ICs (ISPSD), 2000.

[5] URL:http://www.infineon.com/cms/en/product/productType.html?productType=db3a30442f298676012f44599b5b0dea.

[6] P. Friedrichs. “Silicon Carbide Devices for Wind Power Applications”, Proceedings of the 39th Workshop on Compaound Semiconductor Devices and Integrated Circuits (WOCSDICE 2015), pp. 81-82.

[7] S. Falcones, M. Xiaolin and R. Ayyanar, "Topology comparison for Solid State Transformer implementation, "Power and Energy Society General Meeting, 2010 IEEE, vol., no., pp.1-8, 25-29 July 2010.

[8] Intelligent Solid State Transformers (SSTs): A Key Building Block of Future Smart Grid Systems. Tutorial J.W. Kolar

[9] A. Abedini and T. Lipo, "A novel topology of solid state transformer," Power Electronic & Drive Systems & Technologies Conference (PEDSTC), 2010 1st , vol., no., pp.101,105, 17-18 Feb. 2010

[10] S. Xu, S. Lukic, A. Q. Huang, S. Bhattacharya and M. Baran, "Performance evaluation of solid state

transformer based microgrid in FREEDM systems," Applied Power Electronics Conference and Exposition (APEC), 2011 Twenty-Sixth Annual IEEE , vol., no., pp.182-188, 6-11 March 2011.

[11] P. Brosselard, N. Camara, V. Banu, X. Jordà, M. Vellvehi, P. Godignon and J. Millan, "Bipolar conduction impact on electrical characteristics and reliability of 1.2-and 3.5-kV 4H-SiC JBS diodes". IEEE Transactions on Electron Devices, vol. 55, no. 8, 2008, pp. 1847-1856.

[12] A. Pérez-Tomás, P. Brosselard, J. Hassan, X. Jordà, P. Godignon, J. Millán and J. P. Bergman, "Schottky versus bipolar 3.3 kV SiC diodes", Semiconductor Science and Technology, vol. 23, 125004 (7pp), 2008.

[13] P. Brosselard, A. Pérez-Tomás, J. Hassan, N. Camara, X. Jordà, M. Vellvehí, P. Godignon, J. Millán and J. P. Bergman, "Low loss, large area 4.5 kV 4H-SiC PiN diodes with reduced forward voltage drift", Semicond. Sci. Technol. 24 (2009) 095004 (7pp). doi:10.1088/0268-1242/24/9/095004.

[14] H. Bartolf, V. Sundaramoorthy, A. Mihaila, M. Berthou, P. Godignon and J. Millán, "Study of 4H-SiC Schottky Diode Designs for 3.3 kV Applications". Materials Science Forum, Vols 778-780 (2014), pp 795-799. doi:10.4028/www.scientific.net/MSF.778-780.795.

[15] M. Berthou, P. Godignon, B. Vergne and P. Brosselard, "High temperature capability of high voltage 4H-SiC JBS". Materials Science Forum Vol. 711 (2012), pp. 124-128. doi:10.4028/www.scientific.net/MSF.711.124.

[16] V. Soler, M. Berthou, P. Godignon, J. Montserrat, M. Florentin, J. Rebollo and J. Millán, "Design and Fabrication of High Voltage 4H-SiC MOS Transistors". SAAEI 2015.