Advances and Challenges in WBG Devices and their Applications in Power Conversion and Conditioning

O. Bouketir

Department of Electrical Engineering,
University Ferhat Abbes Setif 1

***Abstract*—Investigations into silicon carbide (SiC) and gallium nitride (GaN) devices are being gaining much attention and attracting many research institutions in current decades due to their great properties and superiority over traditional silicon (Si) materials (higher power ratings, and much higher operating temperature). This paper attempts to track the developments of these switching power devices and their applications in recent years. Applications, whether in electronic drives, renewable energy or different power conversion types are explored. Modelling of some devices and simulation of some systems which use these new switches are also inspected. Challenges and difficulties specially in fabrication processes are stated.**

***Index Terms*—GaN, Power Conversion, SiC, WBG.**

1. Introduction

Researchers worldwide believe that wide bandgap (WBG) semiconductors will definitely stimulate exciting innovations in power electronics, energy-saving applications and other applications in different industrial and commercial sectors. WBG semiconductor industry will demand the development of pioneering manufacturing techniques that can produce adequate WBG materials, devices, and modules at a reasonable cost.

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 [1].

Semiconductors materials like SiC, and GaN, have excellent properties. Such properties permit the operation of their devices at very high frequency, very large voltage and elevated temperature. These exceptional characteristics allow the replacement of the current Si switching devices with higher efficiency in different power electronics applications. The main advantages of replacing the existing silicon power devices in power electronics applications by WBG semiconductor switches are the remarkable increase in the power-to-size ratio, the ability of withstanding harsh conditions (e.g. very high temperature applications), high voltage blocking capability and extended life-time of the converters built around these devices.

Nevertheless, the WBG power devices made on silicon carbide (SiC) and gallium nitride (GaN) that are currently available in the market still did not find the success that Si-based switching devices have enjoyed for the past five decades. Whereas the cost of a WBG power device ($/A for a given voltage application) is much higher compared to a silicon device with identical voltage and current ratings, it may be possible to offset the higher chip cost with increased energy efficiency and system level cost and robustness benefits [2].

So far, SiC and GaN materials among WBG materials exhibit the better trade-off between theoretical characteristics (high-voltage blocking capability, high-temperature operation and high switching frequencies), and real commercial availability of the initial materials and the advancement of their fabrication procedures.

Economic viability of wide bandgap materials-based devices is limited because their price is about 3 to 5 times higher than silicon semiconductor devices. However, the materials contribute about 40% of the total device cost depending on availability, quality, and performance. Other factors that drive the WBG devices' price so high are, design, fabrication, and packaging procedures and techniques [3].

2. WBG Material Properties and Limitations

A. Properties

Semiconductors made of WBG make power electronic circuits smaller, operate faster, more reliable especially in harsh environment, and more efficient than their silicon Si-based devices. These capabilities make it possible to reduce weight, volume, and life-cycle costs in a wide range of power applications. Exploiting these potentials can result in:

- a great energy savings in industrial processing and consumer appliances,
- broad use of EV and fuel cells, and
- facilitating the integration of renewable energy systems and the electric grid.

Wide bandgap semiconductors are materials that possess bandgaps much greater than those of *silicon (Si)* and *germanium (Ge)* the traditional semiconductor materials as shown in Table 1[4].

TABLE I

Bandgap Energy of Some Semiconductor Materials [4]

Material	Symbol	Bandgap Energy (eV)
Germanium	Ge	0.7
Silicon	Si	1.1
Gallium Arsenide	GaAs	1.4
Silicon Carbide	SiC	3.3
Zink Oxide	ZnO	3.4
Gallum Nitride	GaN	3.4
Diamond	C	5.5

Si devices stop working at about 150°C, because the power loss increases due to the increase in the leakage current at off state when its temperature rises. WBG devices will operate over 200ºC, because the energy bandgaps of GaN and SiC are wider than that of Si [5]. Table II shows and compares physical properties of different semiconductors materials. Diamond has the largest bandgap energy which implies the greatest electric breakdown field.

TABLE II [6].
Physical Properties of Some Semiconductors Materials

Material	*Eg(eV) @300K*	μ_p *x10*	μ_n	v_{sat} $x10^7$	E_c $x10^6$	λ	ε_r
Si	1.12	145	450	2	0.3	1.3	11.7
GaAs	1.4	850	400	2.5	0.4	0.54	12.9
3C-SiC	2.3	100	45	2	2	5	9.6
6H-SiC	2.9	41.5	90	2	2.5	5	9.7
4H-SiC	3.2	95	115	2	3	5	10
GaN	3.39	10	35	2	5	1.3	8.9
GaP	2.26	25	150	-	10	1.1	11.1
Diamond	5.6	220	1800	3	56	20	5.7

Eg: Bandgap energy
μ_p: Hole mobility (cm^2/V.s)
μ_n: Electron mobility (cm^2/V.s)
v_{sat}:Saturated Electron Drift Velocity (cm/s)
E_c:Electric Field Breakdown (kV/cm)
λ: Thermal Conductivity (W/cm.K)
ε_r: Dielectric constant.

SiC material can be found in a various polymorphic crystalline structures called polytypes for example, 3C-SiC, 6H-SiC, 4H-SiC. SiC polytypes and GaN have similar bandgaps and electric breakdown fields. Currently, 4H-SiC is generally preferred in practical power device manufacturing over 6H-SiC because the mobilities in 4HSiC are identical along the two planes of the semiconductor contrary in the 6H-Sic are not the same. Single-crystal 4H-SiC wafers of 3 inches to 6 inches in diameter are commercially available [7].

Higher breakdown field and higher carrier concentration in SiC materials allows SiC-based MOSFET to have the three important properties of power switch, which are high voltage, low on-resistance, and high operating frequency.

At present time, SiC is considered to have the best trade-off between properties and commercial maturity with considerable potential for both HTE and high power devices. However, the industrial interest for GaN power devices is a fact. For this reason, SiC and GaN are the more attractive candidates. 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 [6].

B. Limitations

WBG power semiconductor community faces many challenges and difficulties in the R&D and industry fields as well. The high cost, poor performance and degraded reliability are some of these difficulties. These problems originate from the material used in the manufacturing process as it is too expensive compared to silicon, and it includes very much undesirable defects in its crystal. Much efforts should be put forward in the R&D field in order to determine the effects of these defects on the performance and reliability of the switching components, especially under the excited state of the condensed matter where most power devices are operated. The excited state may be caused by a combination of high-level charge injection, high temperature, and high electric field. This information is critical in order to optimize the manufacturing technology and also to develop new low-temperature materials synthesis techniques that result in low defect density at high throughput rates [2].

Crystal defects introduce local potentials in the semiconductor crystal lattice that strongly distort the energy-band structure of WBG semiconductors and cause severe degradation in electrical parameters in the excited state of the condensed matter. However, fundamental understanding of the exact phenomena of the excited state of condensed matter is lacking. This phenomenon is particularly important in high-voltage (> 6.5 kV) bipolar SiC power devices where in addition to threading screw dislocations (TSDs) and threading edge dislocations

(TEDs), point defects such as the carbon vacancy (VC) have been found to have catastrophic effects on high-voltage bipolar power diodes [2].

One of a real superiority of Si device over a SiC counterpart is the safe operating area. Fig. 1[2] illustrates a measure of a 1200V/30A Si MOSFET which is bigger than those of two SiC MOSFETs having almost the same ratings.

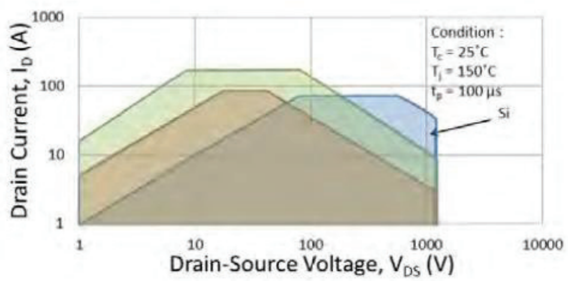

Fig. 1. Measured safe operating area (SOA) of 1,200V/30A silicon power MOSFET, and 1,200V/32A and 1,200V/45A SiC power MOSFETs at Tj=25°C [2].

3. LATEST DEVELOPMENTS IN WBG DEVICES

Despite the shortcomings of their materials stated in the previous sections, various types of WBG switching device have been manufactured and ultimately commercialized during the last two decades worldwide. Researchers have been able to develop and test diodes, thyristors and transistors made from SiC and GaN materials. They demonstrated their superiority over traditional Si switches in various applications. In this section we attempt to trace the latest developments in WBG devices and their applications.

A. Diodes

As early as year 2000, a 2kV GaN Shottky diode, a 6kV GaN pn diodes, a 4.9kV SiC Shottky diode and 19.2kV SiC pn diode were reported [8]-[9].

Ozpenici *et al.*[10], have tested and characterized commercial Si pn and SiC Schottky diodes. Their behavioral static and loss models were derived at different temperatures, and they were compared with respect to each other. Four samples of diodes based on their doping materials were prepared and their doping densities were calculated and the I-V curves were extracted. I-V characteristic of one of these samples is given in Fig. 2.

An example of a better characteristic of SiC diode as compared to the Si diode is the reverse recovery waveforms as shown in Fig. 3. This study showed that using SiC diodes and MOSFETs in electric hybrid vehicle (EHV) traction drive have saved space and weight of the overall system compared to the Si-based drive system. However, the system cost is increased.

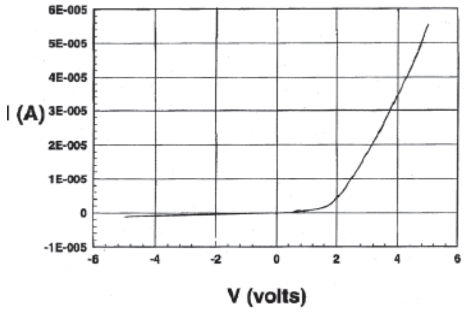

Fig. 2. I-V characteristics of a Schottky diode (p-type epi) implanted with silicon and boron as reported in [10]

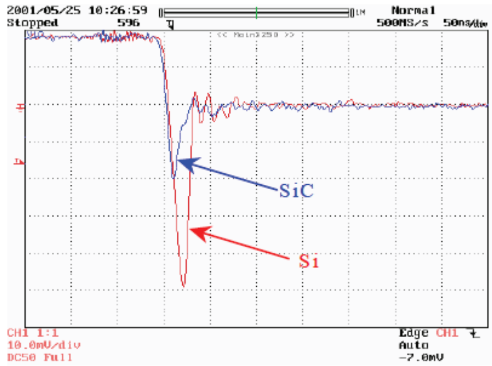

Fig. 3. Typical reverse recovery waveforms of the Si pn and SiC Schottky diode [10]

Usually, the voltage rating of Si-based Schottky diodes is less than 200V. However, the ratings of SiC Schottky diode could be found from 600V/20A to 1700V/25A. For the power diodes ratings from 600V to 1200V, compared to Si ultrafast power diodes, SiC Schottky diodes switch even faster and have smaller ON-resistance. Table III compares several key characteristics among different diodes with similar rating (around 600V/30A) at junction temperature Tj of 25^{o}C [11].

TABLE III [11]
Characteristics of Some Diodes with Similar Ratings 600V/30A

Reference	Type	V_F(V)	I_R(μA)	Q_{rr} or Q_c(nC)
ISL9R3060G2	Si	1.7	3	450
DPH30IS600HI	Si	2.2	< 1	450
C3D10060G	SiC	1.6	10	25
SCS230AE2	SiC	1.35	3	23
IDW20G65C5	SiC	1.3	0.3	29

Evolvement and developments of SiC power diodes followed during the following decade and took it step further by integrating it in a whole power module for specific application as it will be seen in the following sections. In order to integrate SiC diodes and predict their behavior, models of several diodes were developed and integrated into simulation software [12]-[13].

B. Power Transistors

The first commercial WBG power transistor was SiC junction Field Effect Transistor (JFET), which is a unipolar power device. Nowadays, the SiC JFETs developed in laboratories or commercialized ones are with the blocking voltage around 1200V and nominal current up to 40A. It is worth to note that this power rating is much bigger than a Si unipolar power device. The blocking voltages of Si MOSFET is usually below 1000V. [11].

The first SiC power MOSFET was introduced in 1994 in the form of a vertical trench gate structure (UMOSFET) (Fig. 4.) This MOSFET had a breakdown voltage of 150 V and specific on-resistance of 3.3 mΩ·cm2. The breakdown voltage of the device was restricted by the high electric field in the gate oxide at the trench corner [14].

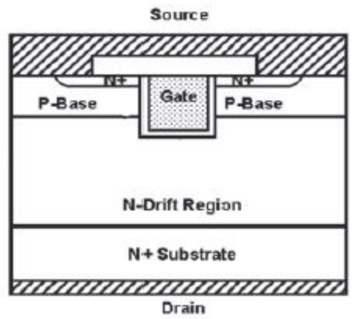

Fig. 4. UMOSFET cross section [14]

In 2004, a 6H-SiC MOSFET having a planar gate with a p-base formed by a double implantation MOS process was fabricated (DMOSFET) to overcome the high electric field in UMOSFET. 6H-SiC DMOSFET has a breakdown voltage of 760V based on a 10μm-thick and 6.5×10^{15} cm^{3}-doped n-type drift layer [15]. SiC-based power metal semiconductor field effect transistors (MESFETs) have also been reported [16]-[17]. Hui *et al.* [18] reported a vertical GaN transistors with breakdown voltages of 1.5kV fabricated on pseudo-bulk GaN substrates (Fig. 5). The transistors had a positive threshold voltage and exhibited a specific on-resistance of 2.2 mΩ.cm^2. Some other efforts in developing MSOFETs based on SiC were reported in [19]-[21].

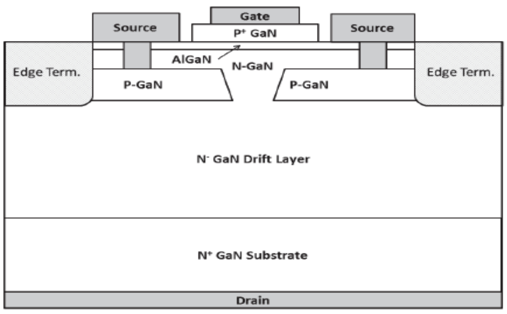

Fig. 5. Schematic cross-section of the vertical GaN transistor on bulk GaN[18].

SiC BJT exhibits 20~50 times lower than Si BJT in switching losses and ON-state voltage [22]. To improve the current gain and switching speed, the base region and collector region are made very thin because of the large critical electric field of SiC material. A 4H-SiC BJT with 44 of current gain, and 3.2 kV of blocking voltage, and specific ON-resistance of 8.1 mΩ.cm^2 was reported in[23].

Above 1000V, Si bipolar power transistor like IGBT is widely used in power converters. In 2007, Purdue University fabricated a p-IGBT with a p-region width of 175μm, as high as 20kV in blocking voltage . This IGBT could provide approximately twice the ON-state current as MOSFETs at 177°C, which is superior to the IGBT based on the Si [22]. In the same year, company *Cree* reported a SiC n-IGBT with a blocking voltage of 12 kV, and its switching characteristic is shown in Fig. 6. in comparison with that of Si-IGBT [22]. In 2014, Arun *et al.* [24] reported that a company named *Cree* successfully built a SiC 15 kV/20 n-IGBTs. The authors extracted the turn-on and turn-off characteristics of the IGBT up to 11kV and its static characteristics up to 25A and 12kV.

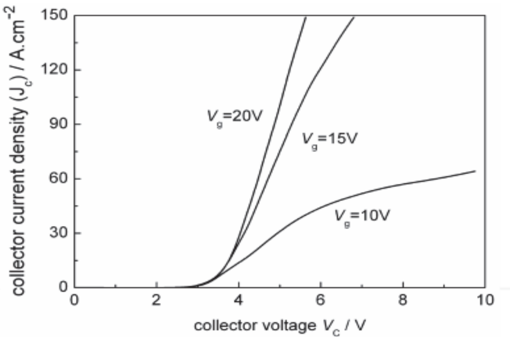

Fig. 6. 12kV 4H-SiC n-IGBT ON-state characteristics[22]

SiC-based gate turn-off thyristors (GTO) can conduct higher current and block very large voltage compared to IGBT. They also possess fast turn-off capabilities, and lower forward voltage drop than the IGBT-based switch at high injection-level currents, which results in lower power losses under normal operation.

Lin Cheng *et al.* [25], reported a developed $1cm^2$, 15kV, 4H-SiC-p-type GTO with very low, $R_{(ON,diff)}$ of 4.08mΩ.cm^2 at high injection-current density of 600~710A/cm^2. The thyristor was characterized and its leakage current at its blocking voltage was measured. Cheng *et al*. [26] also reported another SiC-based GTO with higher ratings (20kV) but larger area ($2cm^2$) and 11mΩ.cm^2 for advanced power applications. The blocking capabilities of this GTO at room temperature is depicted in Fig. 7.

Simulation models of WBG semiconductors have been reported in numerous works [27]-[32].

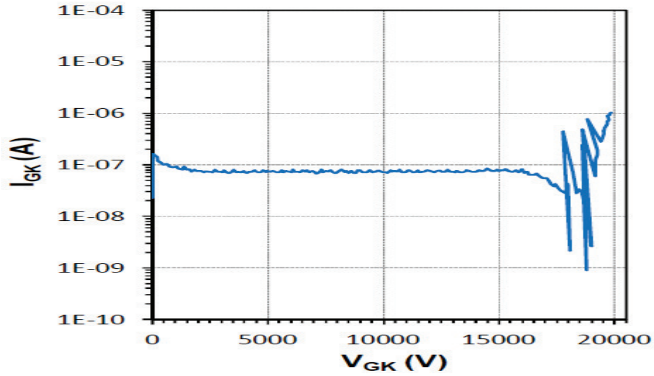

Fig. 7. Blocking capabilities of the SiC GTO reported in [26]

Arribas *et al*. [29] developed simulation models of a high-voltage MOSFET and Shottky barrier diodes (SBDs) and validated used and used them in a buck-boost bidirectional dc-dc converter, with and without an antiparallel SBDs. A trade-off between the cost and the efficiency of the converter was achieved.

An extensive research work has been carried out in order to develop equivalent device models based on gallium nitride (GaN) and silicon carbide (SiC) (GaN HFETs, SiC MOSFETs) [33]. These models were implemented in SaberRD and MATLAB software. Transient switching characteristics were analyzed and the effects of the parasitic capacitances on detrimental circuit behavior such as "overshoot," "ringing," and "false turn-on" were investigated. The modeled results were validated with experimental characterization of the devices in various power conversion circuits (Buck converter and PV system).

4. SiC-based Modules and Applications

Currently, much of the research efforts have been directed to the goal of developing all-SiC-based modules for specific applications. This section traces the latest of such endeavors in recent years.

Fun Xu *et al*. [34] presented an all SiC 7.5-kW high-efficiency three-phase buck rectifier with 480-$V_{ac,rms}$ input line-to-line voltage and 400-V_{dc} output voltage using SiC MOSFETs and Schottky diodes. The authors claimed that an efficiency of 98.5% was achieved.

Juan *et al*. [35] presented the design process of a 312kVA three-phase silicon carbide inverter using ten parallel-connected metal-oxide-semiconductor field-effect-transistor power modules in each phase-leg. They reported an estimated efficiency of about 99.3% of the inverter at rated power.

A power module based on 50A SiC-MOSFET was introduced in [36] and used in power conditioner for solar photovoltaic cells up to 4kW output. A conversion efficiency of 97.7% was reported which is better according to authors than a similar module based on Si-IGBT by 1.5%. This module, beside it had very good thermal conductivity, it possessed very low inductance (24nH) and high slew rate up to 5kA/us.

The development of the world's first all-SiC traction inverter as claimed in [37] was reported in 2015. This 4H-traction module is based on SiC MOSFET and SiC SBD had ratings of 3.3kV/1500A. It had conduction losses similar to that of Si-IGBT inverter and 55% lesser switching losses compared to conventional Si inverter. The I-V characteristics of such inverter at two different temperature values are given in Fig. 8.

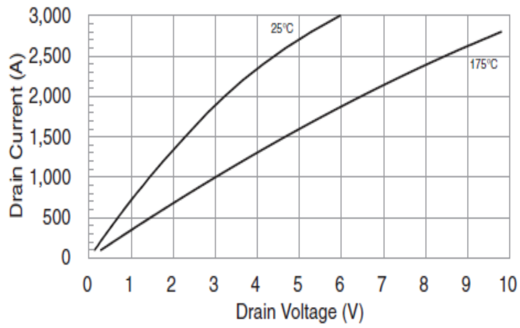

Fig. 8. I_{DS}–V_{DS} characteristics of the developed 3.3kV=1500A all-SiC power module [37].

A 1.2kV/400A SiC MOSFET/SBD dual modules were used to construct a 750V-100-kW-20-kHz bidirectional isolated dual-active-bridge dc-dc converter [38]. An efficiency of 98.7% at 42kW operation was achieved.

An all-SiC high-frequency boost DC–DC converter was reported in [39] using SiC MOSFET/SBD module. The output of the converter was 800V with 1kW power and frequency of 800kHz. The breakthrough in this design was the steady-state junction temperature of the SiC MOSFET that could reach as high as 320°C. Noritho *et al*. [40], presented an all All-SiC power module for photovoltaic Power Conditioner System (PCS). The All-SiC module has SiC-MOSFET) and SiC-SBD sandwiched between SiN (Silicon Nitride) substrate and power circuit board to achieve high power density. A ¼ of volume downsizing and 99.0% of efficiency were achieved on 20kW PV PCS.

5. Conclusion

Switching power electronics devices made of Silicon are currently approaching their limits as determined by the material properties. New materials with superior characteristics are needed in order to fulfil the requirements of advanced applications of power electronics in power conversion and conditioning in harsh conditions with higher efficiencies. SiC and GaN are promising materials because mainly of their wide bandgap energy (WBG). Various devices have been developed based on these two materials. These devices have been, characterized, modeled and new converters for different applications have been built and their results were compared with the conventional Si-based converters. This paper traced these developments in WBG-based devices and applications. Their results according to the efforts listed in the literature are very encouraging with high temperature operation and high efficiency and reduced size. However, there are still many challenges before these devices fully replace the silicon-based ones and make them totally obsolete.

REFERENCES

[1] J. Millán, P. Godignon, A. P. Tomás, “Wide bandgap semiconductor devices for power electronics,” *AUTOMATIKA*, vol. 53(2), pp. 107–116, 2012.

[2] K. Shenai, “Basic research needs in wide bandgap (WBG) power semiconductors,” in *Proc. 2014 Workshop on Defects in Wide Band Gap Semiconductors*, pp 53-56, 2014.

[3] Oak Ridge National Laboratory, “Wide band gap devices for the next generation of electric traction drive systems,” *ORNL 2012_G01058 / LAM.*, US Department of Energy, Available: http://web.ornl.gov/sci/ees/transportation/pdfs/WBGBroch.pdf

[4] Advanced Manufacturing Office, “Wide bandgap semiconductors: pursuing the promise,” *DOE/EE-0910 • April 2013*, US Department of Energy, Available: https://www1.eere.energy.gov/manufacturing/rd/pdfs/wide_bandgap_semiconductors_factsheet.pdf.

[5] H. Ueda, M. Sugimoto, T. Uesugi , and T. Kachi, “Wide-bandgap semiconductor devices for automobile applications”, *in Proc. 2006 CS MANTECH Conf.,* pp 37-40. Available: http://www.csmantech.org/Digests/2006/2006%20Digests/3A.pdf

[6] J. Millán, “A review of WBG power semiconductor devices,” *in Proc. 2012* CAS *International Semiconductor Conf.* vol.1. pp 57-66.

[7] ROHM Semiconductor, “SiC power devices and modules” application Note. *14103EBY0.,* August 2014, Available: http://rohmfs.rohm.com/en/products/databook/applinote/discrete/sic/common/sic_appli-e.pdf

[8] A. P. Zhang, F. Ren, X. A. Cao, S. J. Pearton, H. Cho, J. Han, J. I. Chyi, C. M. Lee, C. C. Chuo, S. N. G. Chu, R. G. Wilson, “High voltage GaN Schottky rectifiers,” *IEEE Transactions on Electron Devices*, Vol. 47(4), pp.692-696, Apr. 2000.

[9] M. Trivedi and K. Shenai, “Performance evaluation of high-power wide band-gap semiconductor rectifiers,” *Journal of Applied Physics,* Vol. 85(9), pp. 6889-6897, May 1999.

[10] B. Ozpineci, L. M. Tolbert, S. K. Islam and F. Z. Peng, “Testing, characterization, and modeling of SiC diodes for transportation applications,” *in Proc. 2002 IEEE 33rd Annual Power Electronics Specialists Conf. pesc 02.* Vol.4, pp1673-1678.

[11] K. Li, "Wide bandgap (SiC/GaN) power devices characterization and modeling: application to HF power converters," Ph.D. dissertation, Universite Lille 1-Sciences et Technologies, Ecole Doctorale Sciences pour l'Ingenieur, 2014.

[12] T. R. McNutt, A.R.Hefner, H. A. Mantooth, J. Duliere, D. W. Berning, and R. Singh, “Silicon carbide PiN and merged PiN Schottky power diode models implemented in the Saber circuit simulator," *IEEE Transactions on Power Electronics,* vol. 19 (3), pp. 573-581, May 2004.

[13] S. Bellone, F. Corte, L. Di Benedetto, and G. Licciardo, “An analytical model of the switching behavior of 4H-SiC p^{+}-n-n^{+} diodes from arbitrary injection conditions," *IEEE Transactions on Power Electronics*, vol. 27(3), pp. 1641-1652, Mar. 2012.

[14] J. N. Shenoy, J. A. Cooper, and M. R. Melloch, “High-voltage double implanted power MOSFET’s in 6H-SiC,” *IEEE Electron Device Lett.*, vol. 18(3), pp. 93-95, Mar. 1997.

[15] S.-H. Ryu, S. Krishnaswami, M. O'Loughlin, J. Richmond, A. Agarwal, J. Palmour, and A. R. Hefner, “10kV, 123mΩ-cm^2 4H-SiC power DMOSFETs,” *IEEE Electron Device Letters*, vol. 25, pp. 556-558, Sep. 2004.

[16] X. J. Zhang, Y. T. Yang, B. X. Duan, B. Chen, C. C Chai, and K. Song, "New 4H silicon carbide metal semiconductor field effect transistor with the buffer layer between the gate and channel,” *Chinese Physics B*, vol. 21, pp. 017201-017207, Jan 2012.

[17] K. Song, C. C. Chai, Y. T. Yang, X. J. Zhang, and B. Chen, "Improvement in breakdown characteristics of 4H-SiC MESFET with a gate-drain surface epi-layer and optimization of the structure," *Acta. Phys. Sin.*, vol. 61, pp. 27201-27206, Jan 2012.

[18] H. Nie, Q. Diduck, B. Alvarez, A. P. Edwards, B. M. Kayes, M. Zhang, G. Ye, T. Prunty, D. Bour, and I. C. Kizilyalli, “1.5-kV and 2.2-m-cm^2 vertical GaN transistors on bulk-GaN substrates” *IEEE Electron Device Letters*, Vol. 35 (9), pp 939-941,Sep. 2014.

[19] J. W. Palmour, L. Cheng, V. Pala, E. V. Brunt, “Silicon carbide power MOSFETs: Breakthrough performance from 900 V up to 15kV”, in *Proc. 2014 IEEE 26th International Symposium on Power Semiconductor Devices & IC's (ISPSD)*, pp. 79-82.

[20] K. Shenai, “Switching megawatts with power transistors,” *The Electrochemical Society Interface,* pp. 47-53, Spring 2013

[21] M. Kitabatake, “Developments of SiC DioMOS (Diode Integrated SiC MOSFET)”. *In Proc.* 2014 MRS Vol.1693. pp 19-24.

[22] Y. Yang, B. Duan, S. Yuan and H. Jia, “Novel developments and challenges for the SiC power devices”, in E. S., Saddow and F. L. Via *Advanced Silicon Carbide Devices and Processing*, InTech. 2015, pp.176-195. Available: http://dx.doi.org/10.5772/61123.

[23] S. Krishnaswami, A. Agarwal, J. Richmond, C. Capell, S. H. Ryu, J. Palmour, B. Geil, D. Katsis, C. Scozzie, "High temperature characterization of 4H-SiC bipolar junction transistors," in *Proc. 2005 Materials Science Forum,* vol. 527-529, pp. 437-440.

[24] A. Kadavelugu, S. Bhattacharya, S. Ryu, E. V. Brunt, “Characterization of 15 kV SiC n-IGBT and its application considerations for high power converters,” in *Proc. 2014 16th IEEE on Electronics Packaging Technology Conf. (EPTC)*, pp 31-35, Dec. 2014.

[25] L. Cheng, A. K. Agarwal, C. Capell, M. O'Loughlin, K. Lam, J. Zhang, J. Richmond, A. Burk, J. Palmour, A. A. Ogunniyi, H. K. O'Brien, and C. J. Scozzie, “15 kV, large area (1cm^2) 4H-SiC p-type gate turn-off thyristors,” in *Proc. 2013 9th European Conference on Silicon Carbide and Related Materials (ECSCRM’12), Mat. Sci. Forum*, Vols. 740-742, pp. 978-981.

[26] L. Cheng, A. K. Agarwal, C. Capell, M. O'Loughlin, K. Lam, J. Richmond, E. VanBrunt, A. Burk, J. W. Palmour, H. O'Brien, A. Ogunniyi, and C. Scozzie, “20 kV, 2 cm^2, 4H-SIC gate turn-off thyristors for advanced pulsed power applications”. in *Proc. 2013 19th IEEE Pulsed Power Conference (PPC),* pp. 1-4.

[27] T. R. McNutt, A. R. Hefner, H.A. Mantooth, D. Berning, and S.-H. Ryu, "Silicon carbide power MOSFET model and parameter extraction sequence," *IEEE Transactions on Power Electronics*, vol. 22(2), pp. 353-363, Mar. 2007

[28] Y. Cui, M. S. Chinthavali, F. Xu, L. M. Tolbert, “Characterization and modeling of silicon carbide power devices and paralleling operation,” *in Proc. 2012 IEEE International Symposium on Industrial Electronics (ISIE),* pp 228-233.

[29] A. P. Arribas, F. Shang, M. Krishnamurthy, and K. Shenai, “Simple and accurate circuit simulation model for SiC power MOSFETs,” *IEEE Transactions on Electron Devices,* Vol.62(2), pp 449-457, Feb. 2015.

[30] Z. Chen, D. Boroyevich, R. Burgos, and F. Wang, "Characterization and modeling of 1.2 kV, 20A SiC MOSFETs," in *Proc. 2009 IEEE Energy Conversion Congress and Exposition,* pp. 1480-1487.

[31] Z. Chen and D. Boroyevich, "Modeling and simulation of SiC MOSFET fast switching behavior under circuit parasitics," in *Proc. 2010 Conf. on Grand Challenges in Modeling and Simulation*, pp. 352-359.

[32] A. Nakajima, K. Takao, and H. Ohashi, "GaN power transistor modeling for high-speed converter circuit design," *IEEE Transactions on Electron Devices*, vol. 60(2), pp. 646-651, Feb. 2013.

[33] R. Khanna, “ Characterizing and modeling of transient behavior in power electronic circuits with wide bandgap semiconductors and in maximum power point tracking for photovoltaic systems”, Ph.D. dissertation, Swanson School of Eng., Univ. of Pittsburgh, 2014.

[34] F. Xu ; B. Guo, L. M. Tolbert, and F. Wang, “An all-SiC three-phase buck rectifier for high-efficiency data center power supplies,” *IEEE Transactions on Industry Applications,* Vol. 49(6), pp.2662–2673. May 2013.

[35] J. Colmenares, D. Peftitsis, G. Tolstoy, D. Sadik, “High-efficiency three-phase inverter with SiC MOSFET power modules for motor-drive applications,” in *Proc. 2014 IEEE Energy Conversion Congress and Exposition (ECCE)*. pp 468-474.

[36] H. Okumura, H. Harima, T. Kimoto, M. Yoshimoto, H. Watanabe, T. Hatayama, H. Matsuura, T. Funaki and Y. Sano, "SiC power module for compact power conversion equipment," in *Proc. 2013. Materials Science Forum*, Vol. 778-780. pp 1096-1099.

[37] K. Hamada1, S. Hino, N. Miura, H. Watanabe, S. Nakata, E. Suekawa, Y. Ebiike, M. Imaizumi, I. Umezaki, and S. Yamakawa, "3.3kV/1500 A power modules for the world's first all-SiC traction inverter," *Japanese Journal of Applied Physics*, pp. 1-4, 2015.

[38] H. Akagi, T. Yamagishi, N. M. L. Tan, S-I. Kinouchi, "Power-loss breakdown of a 750-V 100-kW 20-kHz bidirectional isolated DC–DC converter using SiC-MOSFET/SBD dual modules," *IEEE Transactions on Industry Applications,* 51(1). pp 420-428.

[39] X. Zhong, X. Wu, W. Zhou, K. Sheng, "An all-SiC high-frequency boost DC–DC converter operating at 320 °C junction temperature", *IEEE Transactions on Power Electronics*, Vol.9(10), pp. 5091-5096.

[40] N. Nashida, Y. Hinata, M. Horio, R. Yamada, "All-SiC power module for photovoltaic power conditioner system," in *Proc. 2014 IEEE 26th International Symposium on Power Semiconductor Devices & IC's (ISPSD)*, pp.342-345