International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:11, No:8, 2017

Fabrication of High-Power AlGaN/GaN Schottky Barrier Diode with Field Plate Design

Chia-Jui Yu, Chien-Ju Chen, Jyun-Hao Liao, Chia-Ching Wu, Meng-Chyi Wu

Abstract**—**In this letter, we demonstrate high-performance AlGaN/GaN planar Schottky barrier diodes (SBDs) on the silicon substrate with field plate structure for increasing breakdown voltage V_B. A low turn-on resistance R_{ON} (3.55 mΩ-cm^2), low reverse leakage current (< 0.1 μA) at -100 V, and high reverse breakdown voltage V_B (> 1.1 kV) SBD has been fabricated. A virgin SBD exhibited a breakdown voltage (measured at 1 mA/mm) of 615 V, and with the field plate technology device exhibited a breakdown voltage (measured at 1 mA/mm) of 1525 V (the anode–cathode distance was L_{AC} = 40 μm). Devices without the field plate design exhibit a Baliga's figure of merit of V_B^2/R_{ON} = 60.2 MW/cm^2, whereas devices with the field plate design show a Baliga's figure of merit of V_B^2/R_{ON} = 340.9 MW/cm^2 (the anode–cathode distance was L_{AC} = 20 μm).

Keywords**—**AlGaN/GaN heterostructure, silicon substrate, Schottky barrier diode, high breakdown voltage, field plate, Baliga's figure-of-merit.

I. Introduction

GALLIUM nitride (GaN) is a promising material which has a wide bandgap (~3.4 eV), high critical electric field (~3.3 MV/cm), and good thermal conductivity (~1.3 W/cm·K) characteristics compared with the traditional silicon material that has been taken recently. In addition, making use of the AlGaN/GaN heterostructure not only enhanced the polarization effect but also improved electron mobility (about 1500 cm^2/V-s), that is very suitable for applying the high-speed devices, such as a SBD [1]-[5], high electron mobility transistor (HEMT) [6]-[10], and so on.

SBD is an essential element in many power conversion systems, which is also useful for the integrated power system to accelerate the operating speed of the circuit. Therefore, the device which has high power and high operating speed characteristic becomes a highly popular research topic, and there have been more and more research papers published lately. Those papers about AlGaN/GaN SBD using a silicon substrate can be divided into two parts. The first one is focusing on optimizing forward bias characteristics [11]-[14], and the second one is for reverse voltage improving [14]-[17].

The main achievement of this letter is to fabricate a lateral device which is AlGaN/GaN SBD on silicon substrate and analyzing electrical characteristics by designing different mask layout that has multiple spacing between the anode and the cathode. In order to optimize the SBD, we have found the most suitable annealing temperature for the lowest specific contact resistance on the forward bias and considered the reverse characteristics by adding the field plate technology also. Finally, we fabricate a high breakdown voltage SBD with the breakdown voltage of 1100V, turn-on resistance of 3.55 mΩ-cm^2, and Baliga's figure of merit of 340.9 MW/cm^2.

Chia-Jui Yu, Chien-Ju Chen, Jyun-Hao Liao and Chia-Ching Wu are with the Institute of Electronics Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan, R.O.C.
Meng-Chyi Wu is with the Institute of Electronics Engineering, National Tsing Hua University, Hsinchu 30013, Taiwan, R.O.C. (corresponding author, phone: +8863 5162218; fax: +88635715971; e-mail: mcwu@ee.nthu.edu.tw).

TABLE I
RELEVANT RESEARCH COMPILATION OF ALGAN/GAN SBDS

Feature of thesis	Ron [Ω-cm^2]	V_B [V]	BFOM [W/cm^2]	Reference
2nd ohmic process	-	-	-	2005 [11]
Gated ohmic anode	-	1440	-	2013 [12]
Selective Si diffusion	-	1500	-	2013 [13]
Recessed & field	5.12m	1930	727M	2015 [14]
Floating metal rings	0.38	930	2.27M	2005 [15]
Composite buffer layer	7.9m	3489	1540M	2011 [16]
O_2 treatment	2.51m	1590	1006M	2015 [17]
Recessed anode	3.8m	2070	1127M	2016 [18]
Field plate	3.55m	1100	340.9M	This work

II. Experimental

In this letter, the epi-wafers were grown by metal organic chemical vapor deposition on a high resistivity 6-inch silicon substrate. The structures consist of a 0.1 μm AlN layer, a 2.2 μm AlGaN buffer layer, a 1.4 μm carbon-doped GaN layer, a 0.5 μm un-doped GaN layer, a 10nm AlGaN layer and a 4 nm GaN cap layer from bottom to top. The Hall measurement of the fabricated devices shows a 2DEG concentration of 3.54×10^{13} cm^{-2} with a mobility (μ) about 1277 cm^2/V·s. The SBD is designed in a circular pattern, which is defined by R (diameter of Schottky metal), L_{AC} (the spacing between anode and cathode). The distance between anode and cathode (L_{AC}) was 10, 20, 30, 40, and 50 μm, respectively.

First is forming isolation region to block the 2DEG layer by using a low-damage Cl_2-based inductively coupled plasma reactive ion etching (ICP-RIE). Second, using a thermal evaporator to deposit the ohmic metal (Ti/Al/Ni/Au), and followed by rapid thermal annealing at 875 °C for 30 s in N_2 ambient. The TiN layer covered the 2DEG channel directly after high temperature annealing, resulting in enhanced carrier mobility and the specific contact resistance is 1.18×10^{-5} Ω-cm^2 were obtained by the transmission line method [19]. The third step is for preventing surface leakage and depositing 200 nm SiO_2 as a passivation layer by plasma-enhanced chemical vapor deposition (PECVD). Finally, Ni/Au is used to form Schottky contact which was deposited by a thermal evaporator.

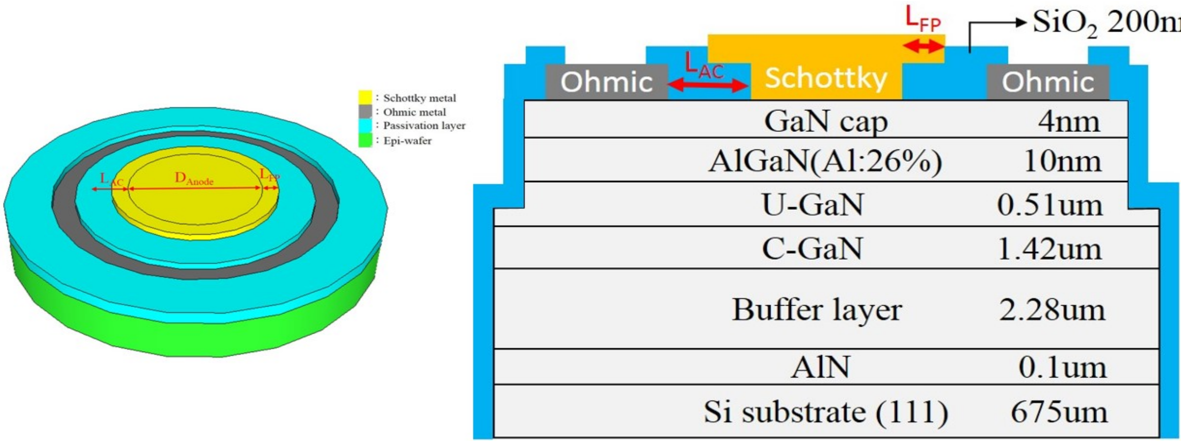

Fig. 1 Top view and cross-section schematic of SBD.

III. Results and Discussion

We fabricated the SBDs with different spacing between anode and cathode (L_{AC}=10-50 µm). The anode diameter of device is 100 µm, and the length of the field plate is 5 µm. Fig. 2 shows the forward bias I-V characteristics of the SBDs. The average turn-on voltage (calculated at 1mA/mm) of SBDs is 2±0.5 V, and the minimum turn-on resistance R_{ON} is 1.3 mΩ-cm^2. The voltage of the diode turn-on and the value of turn-on resistance have a direct relationship between anode and cathode spacing. The longer distance of L_{AC} would have a larger series resistance and led higher turn-on voltage and higher resistance characteristics of the SBD. It is observed in the semi-log plot shown in the inset of Fig. 2 that the current reaches saturation when the voltage is about 5 V.

Fig. 3 shows the reverse I-V characteristics of the SBDs. The average values of leakage current (measured at -100 V) is smaller than 0.1 µA, and it shows in the inset of Fig. 3. If the Schottky junction withstands excessive thermal budget in fabrication environment, the surface leakage current of the diodes will increase dramatically. Moreover, the breakdown voltage of SBDs has a relationship with length of space between the anode and cathode. When the length of spacing increases, the effective series resistance increases as well. Due to this reason, the longer distance of the Schottky metal to the ohmic metal possess higher breakdown voltage. The Baliga's figure of merits (BFOM) is a standard value to confirm the power device level, and it is calculated by the square of the breakdown voltage divided by turn-on resistance.

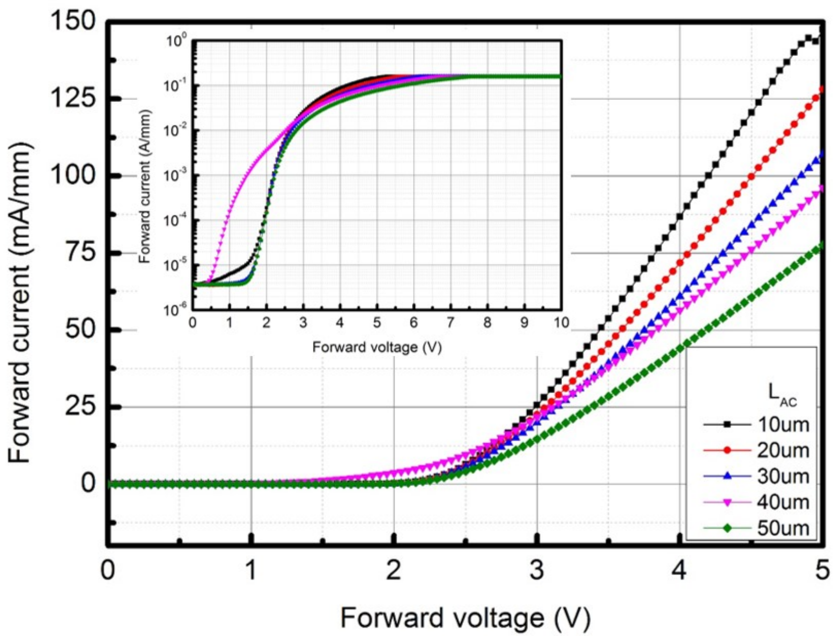

Fig. 2 Forward *I-V* characteristics in linear scale of the fabricated AlGaN/GaN SBDs with field plate design. Inset: Forward *I-V* characteristics in semi-log scale

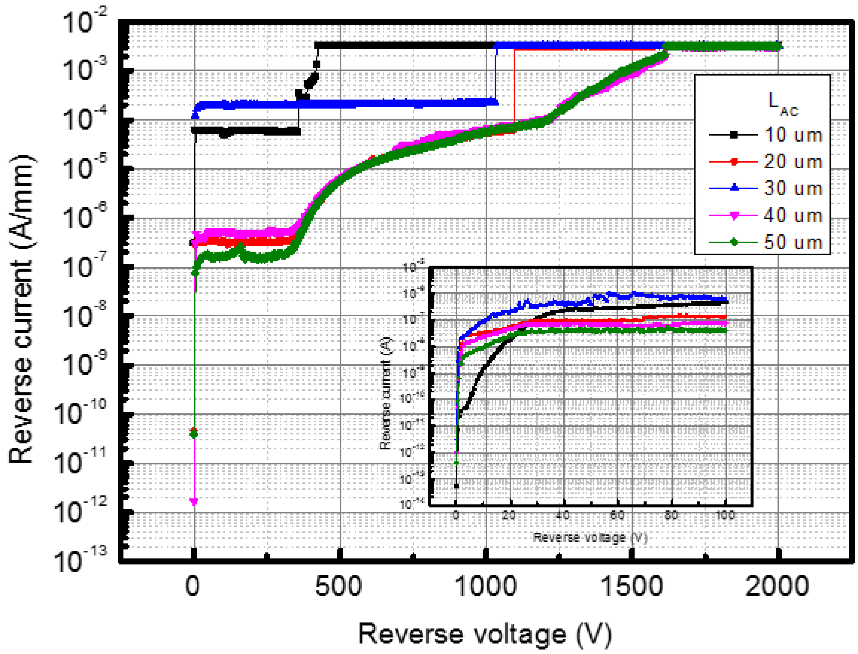

Fig. 3 Reverse *I-V* characteristics of the fabricated AlGaN/GaN/Si SBDs with field plate design. Inset: Reverse leakage *I -V* characteristics up to -100 V

In this report, the highest breakdown voltage is 1525 V with L_{AC} 40 μm (measured at 1 mA/mm), the turn-on resistance is 9.97 mΩ-cm^2, and the Baliga's figure of merit of V_B^2/R_{ON} = 233.3 MW/cm^2. Nevertheless, it is a trade-off choice between the breakdown voltage and the turn-on resistance. Therefore, the device with L_{AC} 20 μm has the best BFOM performance, which is 340.9 MW/cm^2.

Fig. 4 shows the SBD forward I-V characteristics with different temperatures from 25 °C to 175 °C, and we observed that the turn-on voltage drop from 2.25 V at 25 °C to 1.85 V at 170 °C. The reason is that the main current flow mechanism is thermionic emission, the higher temperature applied much more energy to the carrier causes a forward voltage decrease.

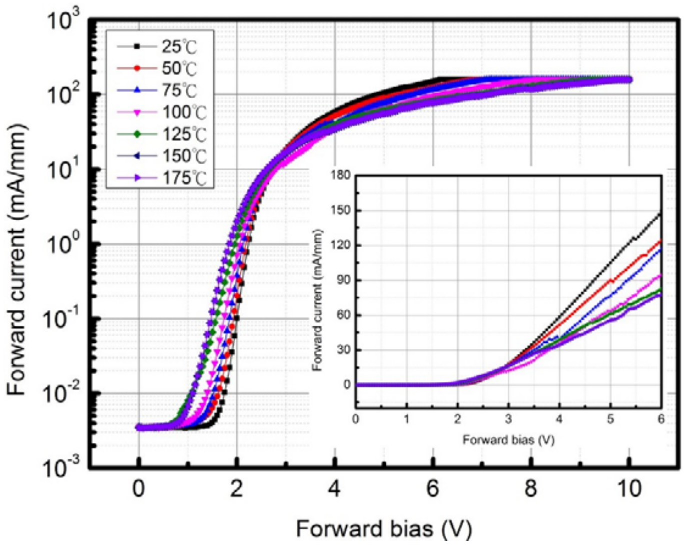

Fig. 4 Forward *I-V* characteristics in semi-log scale of the SBD with L_{AC} 20um at different temperatures. Inset: Forward *I-V* characteristics of the SBD with L_{AC} 20um in linear scale

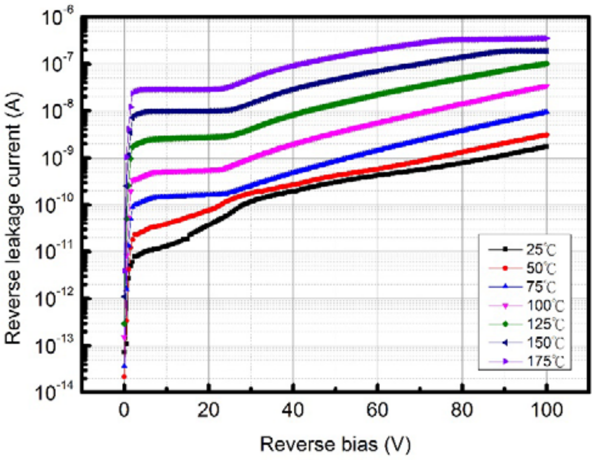

Fig. 5 Forward *I-V* characteristics in linear scale of the fabricated AlGaN/GaN SBDs with field plate design. Inset: Forward *I-V* characteristics in semi-log scale

Fig. 5 reveals the reverse I-V characteristics with different temperatures from 25 °C to 175 °C. It appears that the leakage current increases with raising operating temperature. The value of leakage current measured at 175 °C rises by two orders higher than the reverse current at room temperature. From a band diagram point of view, with temperature increasing, the electrons have greatly higher probabilities to jump from valance band to conduction band. Consequently, the reverse leakage current has positive correlation with temperature.

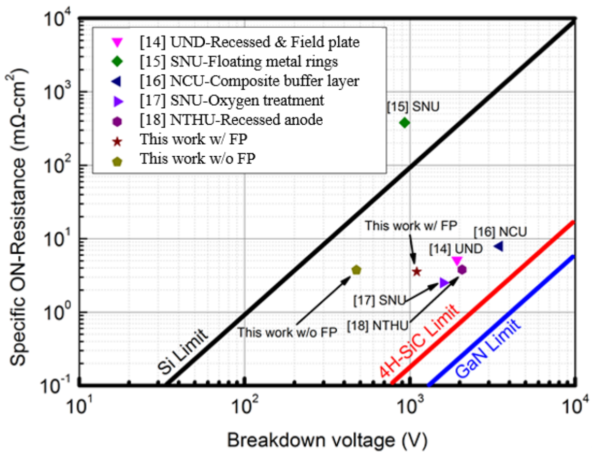

Fig. 6 The theoretical limit plot of breakdown voltage V_B versus turn-on resistance R_{ON} for various published thesis

Fig. 6 shows the turn-on resistance versus breakdown voltage as the BFOM plot for various AlGaN/GaN power SBDs. The figure shows the study features and performance of AlGaN/GaN SBDs in recent years. Zhu et al. propose recessed anode technology to reduce turn-on voltage and dual field plates design can improve the breakdown voltage in 2015 [14]. Lee et al. proposed the use of floating metal rings (FMR) designed, and it effectively enhanced the breakdown voltage from 578V to 930V in 2005 [15]. Lee et al. fabricated lateral SBD on epi-wafer which has composite AlGaN/AlN buffer layer structure, and the device breakdown voltage is up to 3489 V in 2011 [16]. Seok et al. proposed that the post-process O_2 treatment technology can reduce the leakage current about six orders, and the breakdown voltage can be increased from 808 V to 1590 V in 2015 [17]. Tsou et al. proposed the recessed-anode process can reduce turn-on voltage, and also, surface smoothing techniques can reduce the leakage current and improve the breakdown voltage in 2016 [18].

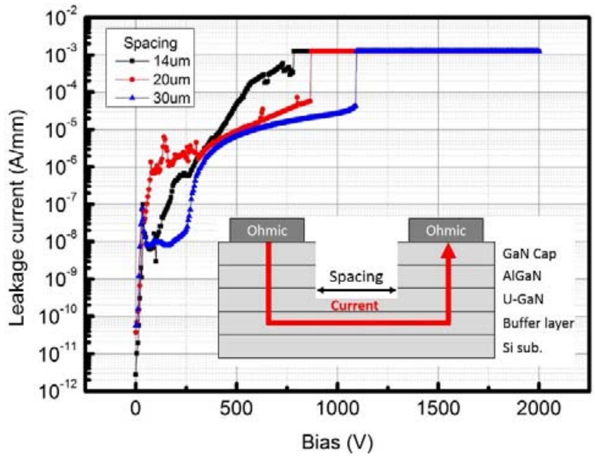

Fig. 7 *I-V* characteristics of buffer layer leakage current of the test pattern with different electrode spacing

In our work, we successfully fabricated the AlGaN/GaN planar SBD on Si substrate. The diodes with the field plate design have highly improvement in reverse bias characteristics. This design of the SBDs with the field plate is much closer to the limit line of 4H-SiC material as shown in Fig. 6. In addition, this report also makes a further discussion for the theoretical breakdown voltage of the epi-wafers which called the test-key measurement. Taking advantage of etching and deposition process only, we try to reduce the fabrication mistake and obtain the theoretical breakdown value.

Fig. 7 exhibits the larger spacing between the electrodes have a higher breakdown voltage which is the same as the SBD. It is intuitively followed by the series resistance between the two electrodes. The maximum reverse voltage is 1095 V that measured by the test-key layout when the current reaches 1 mA. In result, we compared the characteristics between the SBD, and the test-key breakdown voltage is very close to prove that our SBD has excellent electrical characteristics.

IV. Conclusions

In this letter, we have successfully fabricated the AlGaN/GaN planar SBD with field plate design on Si substrate. The highest breakdown voltage of 1525 V with L_{AC} 40 μm (measured at 1mA/mm), the turn-on resistance of 9.97 mΩ-cm^2, and the Baliga's figure of merit of V_B^2/R_{ON} = 233.3 MW/cm^2 were obstained. The average values of reverse leakage current (measured at -100V) of SBDs are smaller than 0.1 µA. Moreover, we get the high performance SBD with L_{AC} 20 µm, the breakdown voltage of 1100 V with low turn-on resistance of 3.55 mΩ-cm^2, and the Baliga's figure of merit of V_B^2/ R_{ON} = 340.9 MW/cm^2. The value of breakdown voltage increased about 2.4 times compared with the device without field plate design. Meanwhile, field plate technology was proven effective in promoting the breakdown voltage.

ACKNOWLEDGMENT

The financial support from national science council (103-2218-e-007-002- and 103-2622-e-007-009-cc2) is deeply appreciated.

REFERENCES

[1] E. B. Treidel, O. Hilt, R. Zhytnytska, A. Wentzel, C. Meliani, J. Würfl, and G. Tränkle, "Fast-switching GaN-based lateral power Schottky barrier diodes with low onset voltage and strong reverse blocking," *IEEE Electron Device Lett*, vol., 33, no. 3, Mar. 2012.
[2] T. F. Chang, C. F. Huang, T. Y. Yang, C. W. Chiu, T. Y. Huang, K. Y. Lee, and F. Zhao, "Low turn-on voltage dual metal AlGaN/GaN Schottky barrier diode," *Solid-State Electronics*, vol. 105, pp. 12-15, Mar. 2015.
[3] J. Hu, S. Stoffels, S. Lenci, N. Ronchi, R. Venegas, S. You, B. Bakeroot, G. Groeseneken, "Physical origin of current collapse in Au-free AlGaN/GaN Schottky barrier diodes," *Microelectronics Reliability*, vol. 54, pp. 2196–2199, 2014.
[4] Y. Yao, J. Zhong, Y. Zheng, F. Yang, Y. Ni, Z. He, Z. Shen, G. Zhou, S. Wang, J. Zhang, J. Li, D. Zhou, Z. Wu, B. Zhang, and Y. Liu, "Current transport mechanism of AlGaN/GaN Schottky barrier diode with fully recessed Schottky anode," Japanese Journal of Applied Physics, vol. 54, pp. 011001, 2015.
[5] M. W. Ha, M. K. Han, C. K. Hahn, "Effects of post-oxidation on leakage current of high-voltage AlGaN/GaN Schottky barrier diodes on Si(111) substrates," *Solid-State Electronics*, vol. 81, pp. 1–4, 2013.
[6] A. Minko, V. Hoël, E. Morvan, B. Grimbert, A. Soltani, E. Delos, D. Ducatteau, C. Gaquière, D. Théron, J. C. De Jaeger, H. Lahreche, L. Wedzikowski, R. Langer, and P. Bove, "AlGaN–GaN HEMTs on Si with power density performance of 1.9 W/mm at 10 GHz," *IEEE Electron Devices Lett*., vol. 25, no. 7, pp. 453–455, Jul. 2004.
[7] I. Hwang, H. Choi, J. Lee, H. S. Choi, J. Kim, J. Ha, C. Y. Um, S. K. Hwang, J. Oh, J. Y. Kim, J. K. Shin, Y. Park, U. Chung, I. K. Yoo, and K. Kim, "1.6kV, 2.9 mΩ cm^2 normally-off p-GaN HEMT device," *IEEE International Symposium on Power Semiconductor Devices and ICs Conf.*, June. 2012.
[8] J. J. Freedsman, T. Kubo, and T. Egawa, "High drain current density E-Mode Al_2O_3/AlGaN/GaN MOS-HEMT on Si with enhanced power device figure-of-merit (4×10^8 $V^2\Omega^{-1}cm^{-2}$)," *IEEE Transactions On Electron Devices*, vol. 60, no. 10, pp. 3079–3083, Oct. 2013.
[9] Q. Zhou, B. Chen, Y. Jin, S. Huang, K. Wei, X. Liu, X. Bao, J. Mou, and B. Zhang, "High-performance enhancement-mode Al_2O_3/ AlGaN/ GaN-on-Si MISFETs with 626 MW/cm^2 figure of merit," *IEEE Transactions On Electron Devices*, vol. 62, no. 3, pp. 776-781, Mar. 2015.
[10] S. Majumdar, A. Bag, and D. Biswas, "Implementation of veriloga GaN HEMT model to design RF switch," *Microwave And Optical Technology Lett*., vol. 57, no. 7, pp. 1765-1768, Jul. 2015.
[11] K. Park, Y. Park, S. Hwang, and W. Jeon, "1kV AlGaN/GaN power SBDs with reduced on resistances," *International Symposium on Power Semiconductor Devices & IC's*, pp. 223-226, 2011.
[12] J. G. Lee, B. R. Park, C. H. Cho, K. S. Seo, and H. Y. Cha, "Low turn-nn voltage AlGaN/GaN-on-Si rectifier with gated ohmic anode," *IEEE Electron Device Lett.*, vol. 34, no. 2, pp. 241-216, Feb. 2013.
[13] Y. W. Lian, Y. S. Lin, J. M. Yang, C. H. Cheng, and S. S. H. Hsu, "AlGaN/GaN Schottky barrier diodes on silicon substrates with selective Si diffusion for low onset voltage and high reverse blocking," *IEEE Electron Device Lett.*, vol. 34, no. 8, pp. 981-983, Aug. 2013.
[14] M. Zhu, B. Song, M. Qi, Z. Hu, K. Nomoto, X. Yan, Y. Cao, W. Johnson, E. Kohn, D. Jena, H. G. Xing, "1.9-kV AlGaN/GaN lateral Schottky barrier diodes on silicon," *IEEE Electron Device Lett.*, vol. 36, no. 4, pp. 375-377, Apr. 2015.
[15] S. C. Lee, M. W. Ha, J. C. Her, S. S. Kim, J. Y. Lim, K. S. Seo, and M. K. Han, "High breakdown voltage GaN Schottky barrier diode employing floating metal rings on AlGaN/GaN hetero-junction," *International Symposium on Power Semiconductor Devices & IC's*, pp. 247-250, 2005.
[16] G. Y. Lee, H. H. Liu, and J. I. Chyi, "High-performance AlGaN/GaN Schottky diodes with an AlGaN/AlN buffer layer," *IEEE Electron Device Lett*., vol. 32, no. 11, pp. 1519-1521, Nov. 2011.
[17] O. Seok, M. K. Han, Y. C. Byun, J. Kim, H. C. Shin, M. W. Ha, "High-voltage AlGaN/GaN Schottky barrier diodes on silicon using a post-process O_2 treatment," *Solid-State Electronics*, vol. 103, pp. 49–53, 2015.
[18] C. W. Tsou, K. P. Wei, Y. W. Lian, and S. H. Hsu, "2.07-kV AlGaN/GaN Schottky barrier diodes on silicon with high Baliga's figure-of-merit," *IEEE Electron Device Lett*., vol. 37, no. 1, pp. 70-73, Jan. 2016.
[19] L. Wang, D. H. Kim, and I. Adesida, "Direct contact mechanism of Ohmic metallization to AlGaN/GaN heterostructures via Ohmic area recess etching," *Appl. Phys. Lett*., vol. 95, pp. 172107, Oct. 2009.