Low Leakage and High Forward Current Density Quasi-Vertical GaN Schottky Barrier Diode With Post-Mesa Nitridation

Kang, Xuanwu; Sun, Yue; Zheng, Yingkui; Wei, Ke; Wu, Hao; Zhao, Yuanyuan; Liu, Xinyu; Zhang, Guoqi

DOI
10.1109/TED.2021.3050739

Publication date
2021

Document Version
Accepted author manuscript

Published in
IEEE Transactions on Electron Devices

Citation (APA)
Kang, X., Sun, Y., Zheng, Y., Wei, K., Wu, H., Zhao, Y., Liu, X., & Zhang, G. (2021). Low Leakage and High Forward Current Density Quasi-Vertical GaN Schottky Barrier Diode With Post-Mesa Nitridation. *IEEE Transactions on Electron Devices*, *68*(3), 1369-1373. Article 9334400. https://doi.org/10.1109/TED.2021.3050739

Low Leakage and High Forward Current Density Quasi-Vertical GaN Schottky Barrier Diode With Post-Mesa Nitridation

Xuanwu Kang, Yue Sun, *Graduate Student Member, IEEE*, Yingkui Zheng, Ke Wei, Hao Wu, Yuanyuan Zhao, Xinyu Liu, and Guoqi Zhang, *Fellow, IEEE*

***Abstract*—In this brief, a high-performance quasi-vertical GaN Schottky barrier diode (SBD) on sapphire substrate with post-mesa nitridation process is reported, featuring a low damaged sidewall with extremely low leakage current. The fabricated SBD with a drift layer of 1 μm has achieved a very high ON/OFF current ratio (I_{ON}/I_{OFF}) of 10^{12} with a low leakage current of $\sim10^{-9}$ A/cm^2 @-10 V, high forward current density of 5.2 kA/cm^2 at 3 V in dc, a low differential specific ON-resistance ($R_{ON,sp}$) of 0.3 m$\Omega\cdot$cm^2, and ideality factor of 1.04. In addition, a transmission-line-pulse (TLP) *I–V* test was carried out and 53 kA/cm^2 at 30 V in pulsed measurement was obtained without device failure, exhibiting a great potential for high power applications.**

***Index Terms*—GaN, high forward current density, leakage, mesa, quasi, Schottky barrier diode (SBD), transmission-line-pulse (TLP), vertical.**

I. Introduction

GaN-BASED vertical power devices have tremendous potential for high-power switching applications, because of their superior device characteristics, e.g., high voltage blocking and high frequency switching capability [1], [2]. High-performance fully vertical GaN-on-GaN p-n diodes [3]–[6] and Schottky barrier diodes (SBDs) [7]–[11] have been demonstrated for high breakdown and good thermal properties. However, as the high-quality GaN substrates are expensive and only available in small size, quasi-vertical GaN diodes on low-cost foreign substrates (e.g., silicon or sapphire) have attracted more attentions recently [12], [13]. Although high-performance GaN SBDs on foreign substrates have been demonstrated, some critical issues still limit the development of GaN quasi-vertical SBDs. One of them is the large reverse leakage current [14], which can cause OFF-state power loss and reliability problems [15]. Some literatures suggest that it is possible to inhibit the leakage currents by junction termination techniques [7], [16], [17], reducing dislocation density of GaN epitaxial layer [18]–[20], passivating the etch mesa sidewall [21], reducing the doping concentration of GaN drift layer [22], [23], and decreasing the interface defect density at the Schottky contact interface [24].

In this brief, a quasi-vertical GaN SBD on sapphire substrate was fabricated with low damaged sidewall by post-mesa nitridation process, exhibiting a state-of-the-art low leakage current of 10^{-9} A/cm^2 at -10 V, ideality factor of 1.04 and a very high forward current density of 5.2 kA/cm^2 at 3 V in dc and 53 kA/cm^2 at 30 V in transmission-line-pulse (TLP) pulsed tester.

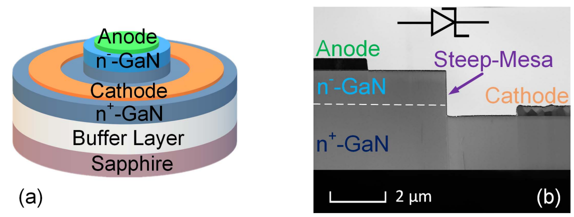

Fig. 1. (a) Schematic of the quasi-vertical GaN-on-sapphire SBD. (b) STEM cross section image of the diode with mesa structure with 6 μm spacing between the edge of anode and cathode.

II. Device Structure and Fabrication

Device schematic of the quasi-vertical GaN SBD is shown in Fig. 1(a). The epitaxial wafer was grown on a 2-in sapphire (0001) substrate by metalorganic chemical vapor deposition (MOCVD), consisting of 2-μm buffer layer, 3 μm n$^+$-GaN conducting layer (N_D: 5 $\times$ 10^{18} cm^{-3}), and 1 μm n$^-$-GaN drift layer (N_D: 1 $\times$ 10^{16} cm^{-3}). Fig. 1(b) shows the STEM

Manuscript received October 18, 2020; revised November 25, 2020 and January 6, 2021; accepted January 7, 2021. This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFB0403000, in part by the Natural Science Foundation of China under Grant 61804172 and Grant 61534007, in part by the Youth Innovation Promotion Association of the Chinese Academy of Sciences (CAS), in part by the GuangDong Province Key Technologies Research and Development Program under Grant 2019B010128001 and Grant 2019B090918006, and in part by the Science and Technology Service Network Initiative of CAS under Grant KFJ-STS-ZDTP-092. The review of this article was arranged by Editor P. J. Fay. *(Xuanwu Kang and Yue Sun contributed equally to this work.) (Corresponding authors: Guoqi Zhang; Xinyu Liu; Xuanwu Kang.)*

Xuanwu Kang and Hao Wu are with the Institute of Future Lighting, Academy for Engineering and Technology, Fudan University, Shanghai 200433, China, and also with the Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China (e-mail: kangxuanwu@ime.ac.cn).

Yue Sun is with the Shenzhen Institute of Wide Bandgap Semiconductors, Shenzhen 518000, China, also with the Department of Microelectronics, Delft University of Technology, 2628 Delft, The Netherlands, and also with the Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China.

Yingkui Zheng, Ke Wei, Yuanyuan Zhao, and Xinyu Liu are with the Institute of Microelectronics, Chinese Academy of Sciences, Beijing 100029, China (e-mail: xyliu@ime.ac.cn).

Guoqi Zhang is with the Institute of Future Lighting, Academy for Engineering and Technology, Fudan University, Shanghai 200433, China (e-mail: g.q.zhang@tudelft.nl).

Color versions of one or more figures in this article are available at https://doi.org/10.1109/TED.2021.3050739.

Digital Object Identifier 10.1109/TED.2021.3050739

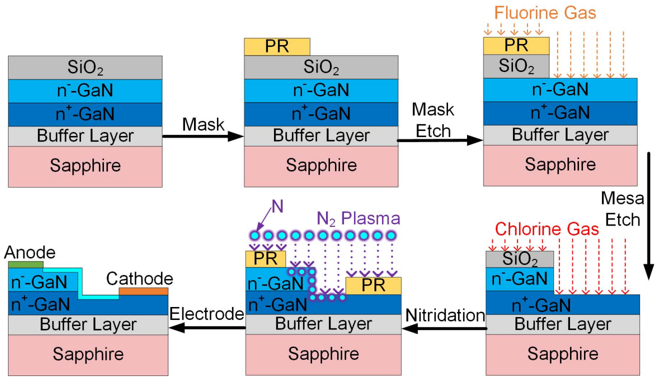

Fig. 2. Process flow diagram of the quasi-vertical GaN SBD with post-mesa nitridation.

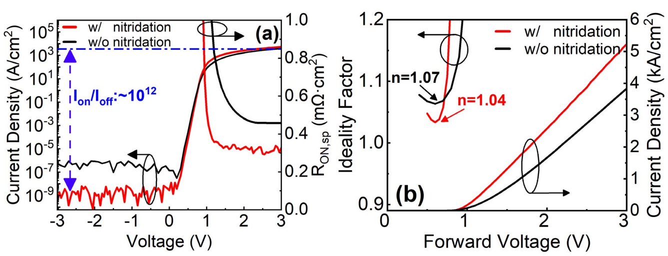

Fig. 3. Electrical characteristics of the GaN SBD with post-mesa nitridation and reference with a diameter of 100 μm. Forward J–V characteristics (a) in semi log-scale and $R_{ON,sp}$, and (b) in linear-scale and ideality factor.

cross section image of fabricated SBD. A total dislocation density of the GaN epi-wafer on sapphire was 4×10^8 cm^{-2}, which is calculated with the full-width at half-maximum of the plane rocking curve orientations.

The fabrication flow of the quasi-vertical GaN SBD is shown in Fig. 2. First, the steep mesa was formed by using an SiO_2 mask and a combination of inductively coupled plasma (ICP) dry etch with Cl_2/BCl_3 gas mixture. Next, N_2 plasma treatment was performed on the mesa for 4 min at a pressure of 0.5 Pa and an N_2 flow rate of 80 sccm to reduce the plasma etch damage. Then, the cathode metal Ti/Al/Ni/Au was deposited on the n^+-GaN layer, and annealed at 600 °C for 2 min to form an ohmic contact. Finally, circular Schottky metal was formed with Ni/Au on n^--GaN layer (drift layer) with various diameters of 100, 140, 200, and 250 μm.

The reference sample was processed without nitridation on the mesa. It is reported that not well-treated mesa sidewall can be one of the reasons to cause the high reverse leakage [25]–[27] and lead to potential reliability problems [15].

III. Results and Discussion

Fig. 3(a) and (b) shows the forward J–V characteristics in semi-log and linear scale of quasi-vertical SBD with post-mesa nitridation and the reference, both with anode diameter of 100 μm. In Fig. 3(a), the quasi-vertical GaN SBD with post-mesa nitridation has shown three orders of magnitude lower leakage current than the reference and a very high ON/OFF current ratio (I_{ON}/I_{OFF}) of 10^{12}. In Fig. 3(b), the SBD with post-mesa nitridation has reached a high forward current density of 5.2 kA/cm^2 at 3 V (normalized to the anode

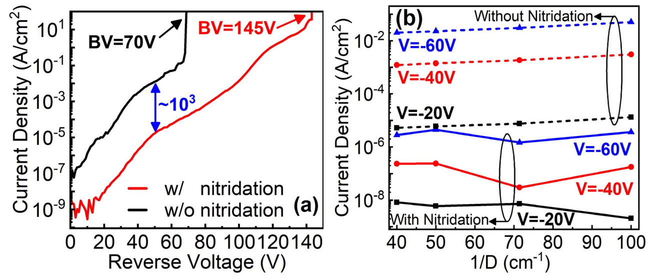

Fig. 4. (a) Reverse breakdown characteristics of GaN SBD with a diameter of 100 μm. (b) Leakage current density of SBD with and without post-mesa nitridation for different anode diameters D (D = 100, 140, 200, and 250 μm), as a function of $1/D$ at a reverse bias of 20, 40, and 60 V.

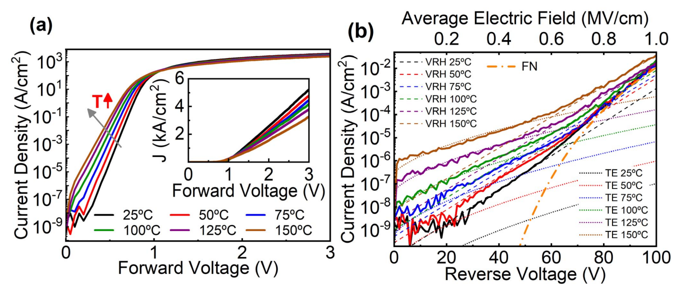

Fig. 5. Temperature dependent of (a) forward and (b) reverse J–V characteristics in semilog scale at temperatures ranging from 25 °C to 150 °C. The inset of (a) is temperature-dependent of forward J–V characteristics in a linear scale. E_{av} is the average electric field in the drift layer, which can be calculated with $E_{av} = (V_{bi}–V_r)/W_d$. W_d is the drift layer thickness. V_{bi} is the built-in voltage of GaN SBDs (~0.7 V).

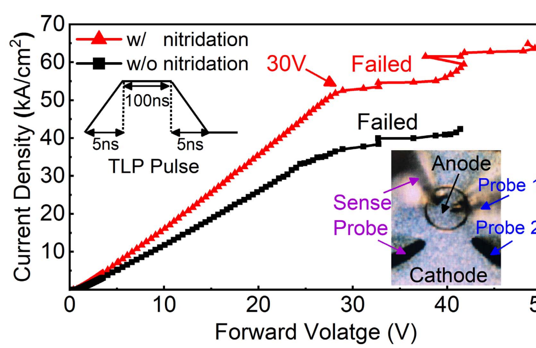

Fig. 6. Pulsed forward J–V characteristics with nitridation and w/o nitridation, under a pulsewidth of 100 ns and rise/fall time of 5 ns by a TLP tester (anode diameter is 200 μm).

area), almost by 25% higher than the reference sample. Meanwhile, it has obtained a low differential specific ON-resistance ($R_{ON,sp}$) of 0.3 mΩ·cm^2, nearly unity ideality factor (η) of 1.04, low turn-on voltage (V_{ON}) of 0.7 V (extracted at 1 A/cm^2), showing much better forward characteristics, compared to the reference. The improved forward characteristics might be attributed to the post-mesa nitridation process, leading to the reduction of additional current choke in the access region outside of mesa [16].

Fig. 4(a) shows the breakdown voltage (BV) characteristics of the GaN SBD with post-mesa nitridation and reference at room temperature. The hard-BV of SBD with post-mesa nitridation and reference are 145 and 70 V, respectively.

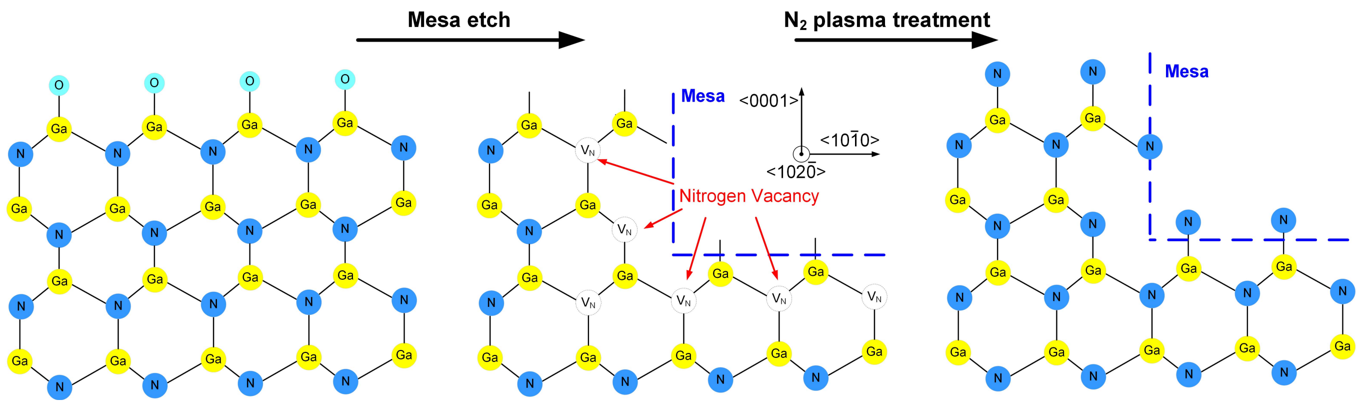

Fig. 7. Schematic of the atomic arrangement of GaN surface after mesa etch and N_2 plasma treatment.

The leakage current density of optimized SBD is $\sim 10^{-9}$ A/cm^2@10 V and 10^{-5} A/cm^2@50 V, which is three orders of magnitude lower than that of the reference, as well. Leakage current along the sidewall is one of the main leakage path for quasi-vertical GaN SBD, as ICP dry etch might create surface damage (e.g., N vacancies) [28], [29]. Therefore, post-mesa nitridation technique has been developed to remove the sidewall damage and then reduce the leakage. In addition, the slight overlap between the anode and nitridation region helps increase the Schottky barrier height around the anode periphery [30], thus reduces the leakage current. Moreover, the leakage current density, shown in Fig. 4(b), is nearly independent of the anode diameters at different reverse bias for the optimized SBD, verifying that the leakage current along sidewall is not the dominant leakage current path [16].

Fig. 5(a) shows the temperature-dependent forward J–V characteristic in log-scale of GaN SBD with post-mesa nitridation, which is dominated by thermionic emission (TE) model, with a Schottky barrier height (Φ_b) of 0.87 eV extracted based on the Richardson plot [31]. The forward current density decreases and differential $R_{\mathrm{ON,sp}}$ increases with the increased chuck temperature when forward voltage is beyond 1 V, mainly attributed to a decrease of electron mobility in the drift region. The decrease of the turn-on voltage with the increase of temperature is due to the increase of TE current at low bias (<1 V), where the effect of series resistance is small and can be neglected.

The temperature dependence of reverse characteristics is assessed as well. As shown in Fig. 5(b), a temperature increasing from 25 °C to 150 °C results in an increase of leakage current density by about two orders of magnitude. According to the leakage mechanism reported [27], [32], [33], in the low reverse bias range ($E_{\mathrm{av}} < 0.4$ MV/cm), the leakage process might be dominated by the TE mechanism. The device leakage current is beyond the limit of measurement instrument ($\sim 10^{-14}$ A) (Agilent B1500A) at low temperature, thus deviating from the TE model. For the moderate reverse bias range (0.4 MV/cm $< E_{\mathrm{av}} <$ 0.8 MV/cm), the leakage behavior shows a variable range hopping (VRH) process, which might be attributed to the threading dislocation. In the

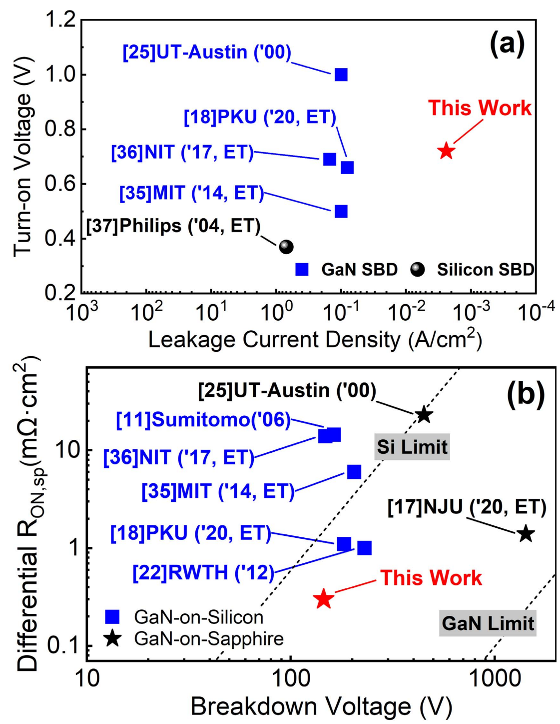

Fig. 8. (a) Benchmark of V_{ON} versus leakage current density for vertical GaN SBDs with foreign substrates and silicon SBD for the BV between 120 and 250 V. V_{ON} is the voltage extracted at 1 A/cm^2. The leakage current density is at 80% of the BV, which is defined as the correspondent voltage when leakage reaches 1 A/cm^2. (b) Differential $R_{\mathrm{ON,sp}}$ versus BV for vertical GaN SBDs with foreign substrates and silicon SBD. ET: edge termination. The differential $R_{\mathrm{ON,sp}}$ is dominated by the resistance of drift region, which is defined as the resistance for unit cross-sectional area [1].

high reverse bias region ($E_{\mathrm{av}} >$ 0.8 MV/cm), the dominant leakage mechanism is Fowler–Nordheim (FN) tunneling as a result of peak electric field crowding near the anode edge.

For the first time, TLP I–V test was carried out to assess GaN SBD characteristics under high forward bias. The SBD was measured with a pulsewidth of 100 ns and rising/falling time of 5 ns, followed by a reverse leakage measurement immediately after each pulse to assess whether the device failed. As shown in Fig. 6, the SBD with post-nitridation achieves a higher current density of 53 kA/cm^2 at 30 V than reference (37 kA/cm^2 at 30 V), while the reverse leakage current density was kept at 10^{-9} A/cm^2 at bias of -1 V in the followed reverse leakage monitoring, implying that the device is still without failure. The SBD with post-nitridation has a higher total power dissipation of 240 W than the reference sample.

As shown in Fig. 7, the native oxide was removed by dry etch while the nitrogen vacancy (V_N) was formed near the etched surface. A large amount of V_N was introduced as donor-like traps, resulting in the band bending and the increase of surface state density of the etched GaN [34]. The traps will create a primary path for leakage current along the etched mesa sidewall. During the N_2 plasma treatment on the GaN surface, nitrogen radicals were reacted with Ga atoms and then formed a new Ga–N bond, leading to a reduction of surface defect density and a significant reduction of leakage current.

The benchmark of V_{ON} versus leakage current density and differential $R_{ON,sp}$ versus BV are shown in Fig. 8(a) and (b), respectively. Our SBD with post-mesa nitridation shows a lowest leakage current density at 80% of the BV among the reported vertical GaN SBDs on foreign substrate for the BV between 120 and 250 V [18], [25], [35]–[37]. The performance of our SBD without edge termination is beyond the theoretical limit line of silicon, achieving a BV of 145 V, and a small differential $R_{ON,sp}$ of 0.3 m$\Omega\cdot$cm^2.

IV. Conclusion

In conclusion, a quasi-vertical GaN SBD on sapphire substrate with post-mesa nitridation, which can improve the performance of quasi-vertical SBD significantly, was proposed in this brief. The BV can be increased from 70 to 145 V, and leakage current density can be reduced from 10^{-7} A/cm^2 to 10^{-9} A/cm^2 at -10 V. The results suggest great potential of vertical GaN devices on sapphire for high power and low-cost applications.

References

[1] B. J. Baliga, "Gallium nitride devices for power electronic applications," *Semicond. Sci. Technol.*, vol. 28, no. 7, Jul. 2013, Art. no. 074011, doi: 10.1088/0268-1242/28/7/074011.

[2] T. Oka, "Recent development of vertical GaN power devices," *Jpn. J. Appl. Phys.*, vol. 58, Apr. 2019, Art. no. SB0805, doi: 10.7567/1347-4065/ab02e7.

[3] K. Fu *et al.*, "Demonstration of 1.27 kV etch-then-regrow GaN p-n junctions with low leakage for GaN power electronics," *IEEE Electron Device Lett.*, vol. 40, no. 11, pp. 1728–1731, 2019, doi: 10.1109/LED.2019.2941830.

[4] H. Ohta *et al.*, "Vertical GaN p-n junction diodes with high breakdown voltages over 4 kV," *IEEE Electron Device Lett.*, vol. 36, no. 11, pp. 1180–1182, Nov. 2015, doi: 10.1109/LED.2015.2478907.

[5] I. C. Kizilyalli, T. Prunty, and O. Aktas, "4-kV and 2.8-mΩ-cm^2 vertical GaN p-n diodes with low leakage currents," *IEEE Electron Device Lett.*, vol. 36, no. 10, pp. 1073–1075, Oct. 2015, doi: 10.1109/LED.2015.2474817.

[6] O. Aktas and I. C. Kizilyalli, "Avalanche capability of vertical GaN p-n junctions on bulk GaN substrates," *IEEE Electron Device Lett.*, vol. 36, no. 9, pp. 890–892, Sep. 2015, doi: 10.1109/LED.2015.2456914.

[7] S. Han, S. Yang, and K. Sheng, "High-voltage and high-I_{ON}/I_{OFF} vertical GaN-on-GaN Schottky barrier diode with nitridation-based termination," *IEEE Electron Device Lett.*, vol. 39, no. 4, pp. 572–575, Apr. 2018, doi: 10.1109/LED.2018.2808684.

[8] Y. Zhang *et al.*, "Vertical GaN junction barrier Schottky rectifiers by selective ion implantation," *IEEE Electron Device Lett.*, vol. 38, no. 8, pp. 1097–1100, Aug. 2017, doi: 10.1109/LED.2017.2720689.

[9] Y. Cao, R. Chu, R. Li, M. Chen, and A. J. Williams, "Improved performance in vertical GaN Schottky diode assisted by AlGaN tunneling barrier," *Appl. Phys. Lett.*, vol. 108, no. 11, Mar. 2016, Art. no. 112101, doi: 10.1063/1.4943946.

[10] N. Tanaka, K. Hasegawa, K. Yasunishi, N. Murakami, and T. Oka, "50 A vertical GaN Schottky barrier diode on a free-standing GaN substrate with blocking voltage of 790 v," *Appl. Phys. Exp.*, vol. 8, no. 7, Jul. 2015, Art. no. 071001, doi: 10.7567/apex.8.071001.

[11] S. Hashimoto, Y. Yoshizumi, T. Tanabe, and M. Kiyama, "High-purity GaN epitaxial layers for power devices on low-dislocation-density GaN substrates," *J. Cryst. Growth*, vol. 298, pp. 871–874, Jan. 2007, doi: 10.1016/j.jcrysgro.2006.10.117.

[12] J. Hu, Y. Zhang, M. Sun, D. Piedra, N. Chowdhury, and T. Palacios, "Materials and processing issues in vertical GaN power electronics," *Mater. Sci. Semicond. Process.*, vol. 78, pp. 75–84, May 2018, doi: 10.1016/j.mssp.2017.09.033.

[13] Y. Sun *et al.*, "Review of the recent progress on GaN-based vertical power Schottky barrier diodes (SBDs)," *Electronics*, vol. 8, no. 5, p. 575, May 2019, doi: 10.3390/electronics8050575.

[14] Y. Zhang, A. Dadgar, and T. Palacios, "Gallium nitride vertical power devices on foreign substrates: A review and outlook," *J. Phys. D, Appl. Phys.*, vol. 51, no. 27, Jul. 2018, Art. no. 273001, doi: 10.1088/1361-6463/aac8aa.

[15] S. Li *et al.*, "Reliability concern of quasi-vertical GaN Schottky barrier diode under high temperature reverse bias stress," *Superlattices Microstruct.*, vol. 130, pp. 233–240, Jun. 2019, doi: 10.1016/j.spmi.2019.04.041.

[16] Y. Zhang *et al.*, "Origin and control of OFF-state leakage current in GaN-on-Si vertical diodes," *IEEE Trans. Electron Devices*, vol. 62, no. 7, pp. 2155–2161, Jul. 2015, doi: 10.1109/TED.2015.2426711.

[17] R. Xu *et al.*, "1.4-kV quasi-vertical GaN schottky barrier diode with reverse p-n junction termination," *IEEE J. Electron Devices Soc.*, vol. 8, pp. 316–320, 2020, doi: 10.1109/JEDS.2020.2980759.

[18] Y. Li *et al.*, "Quasi-vertical GaN Schottky barrier diode on silicon substrate with 1010 high on/off current ratio and low specific on-resistance," *IEEE Electron Device Lett.*, vol. 41, no. 3, pp. 329–332, Mar. 2020, doi: 10.1109/LED.2020.2968392.

[19] Z.-K. Bian *et al.*, "High-performance quasi-vertical GaN Schottky diode with low turn-on voltage," *Superlattices Microstruct.*, vol. 125, pp. 295–301, Jan. 2019, doi: 10.1016/j.spmi.2018.09.020.

[20] C. Gupta, Y. Enatsu, G. Gupta, S. Keller, and U. K. Mishra, "High breakdown voltage p-n diodes on GaN on sapphire by MOCVD," *Phys. Status Solidi (A)*, vol. 213, no. 4, pp. 878–882, Apr. 2016, doi: 10.1002/pssa.201532554.

[21] X. Zhang, X. Zou, C. W. Tang, and K. M. Lau, "Switching performance of quasi-vertical GaN-based p-i-n diodes on Si," *Phys. Status Solidi (A)*, vol. 214, no. 8, Aug. 2017, Art. no. 1600817, doi: 10.1002/pssa.201600817.

[22] W. Witte, D. Fahle, H. Koch, M. Heuken, H. Kalisch, and A. Vescan, "Electrical properties of quasi-vertical Schottky diodes," *Semicond. Sci. Technol.*, vol. 27, no. 8, Aug. 2012, Art. no. 085015, doi: 10.1088/0268-1242/27/8/085015.

[23] A. Agarwal, C. Gupta, Y. Enatsu, S. Keller, and U. Mishra, "Controlled low Si doping and high breakdown voltages in GaN on sapphire grown by MOCVD," *Semicond. Sci. Technol.*, vol. 31, no. 12, Dec. 2016, Art. no. 125018, doi: 10.1088/0268-1242/31/12/125018.

[24] P. Reddy *et al.*, "Defect-free Ni/GaN Schottky barrier behavior with high temperature stability," *Appl. Phys. Lett.*, vol. 110, no. 1, Jan. 2017, Art. no. 011603, doi: 10.1063/1.4973762.

[25] T. G. Zhu, D. J. H. Lambert, B. S. Shelton, M. M. Wong, U. Chowdhury, and R. D. Dupuis, "High-voltage mesa-structure GaN Schottky rectifiers processed by dry and wet etching," *Appl. Phys. Lett.*, vol. 77, no. 18, pp. 2918–2920, Oct. 2000, doi: 10.1063/1.1322050.

[26] R. J. Shul *et al.*, "Inductively coupled plasma-induced etch damage of GaN p-n junctions," *J. Vac. Sci. Technol. A, Vac., Surf., Films*, vol. 18, no. 4, pp. 1139–1143, Jul. 2000, doi: 10.1116/1.582313.

[27] Y. Zhang *et al.*, "Design space and origin of off-state leakage in GaN vertical power diodes," in *IEDM Tech. Dig.*, Dec. 2015, pp. 35.1.1–35.1.4, doi: 10.1109/IEDM.2015.7409830.

[28] S. Kolli, "Vertical gallium nitride Schottky diodes for power switching applications," M.S. thesis, Dept. Elect. Comput. Eng., Univ. Louisville, Louisville, KY, USA, 2018, p. 2898, doi: 10.18297/etd/2898.

[29] M. Sugimoto, M. Kanechika, T. Uesugi, and T. Kachi, "Study on leakage current of pn diode on GaN substrate at reverse bias," *Phys. Status Solidi (C)*, vol. 8, nos. 7–8, pp. 2512–2514, Jul. 2011, doi: 10.1002/pssc.201000935.

[30] S. Han, S. Yang, and K. Sheng, "High-voltage and high-I_{ON}/I_{OFF} vertical GaN-on-GaN Schottky barrier diode with nitridation-based termination," *IEEE Electron Device Lett.*, vol. 39, no. 4, pp. 572–575, Apr. 2018, doi: 10.1109/LED.2018.2808684.

[31] D. K. Schroder, *Semiconductor Material and Device Characterization*, 3rd ed. Hoboken, NJ, USA: Wiley, 2006, doi: 10.1002/0471749095.

[32] T.-H. Yang *et al.*, "Vertical GaN-on-GaN Schottky barrier diodes with multi-floating metal rings," *IEEE J. Electron Devices Soc.*, vol. 8, pp. 857–863, Aug. 2020, doi: 10.1109/JEDS.2020.3014133.

[33] K. Fu *et al.*, "Reverse leakage analysis for as-grown and regrown vertical GaN-on-GaN Schottky barrier diodes," *IEEE J. Electron Devices Soc.*, vol. 8, pp. 74–83, 2020, doi: 10.1109/JEDS.2020.2963902.

[34] Y. J. Yoon *et al.*, "TMAH-based wet surface pre-treatment for reduction of leakage current in AlGaN/GaN MIS-HEMTs," *Solid-State Electron.*, vol. 124, pp. 54–57, 2016, doi: 10.1016/j.sse.2016.06.009.

[35] Y. Zhang *et al.*, "GaN-on-Si vertical Schottky and p-n diodes," *IEEE Electron Device Lett.*, vol. 35, no. 6, pp. 618–620, Jun. 2014, doi: 10.1109/LED.2014.2314637.

[36] K. Zhang, S. Mase, K. Nakamura, T. Hamada, and T. Egawa, "Demonstration of fully vertical GaN-on-Si Schottky diode," *Electron. Lett.*, vol. 53, no. 24, pp. 1610–1611, 2017, doi: 10.1049/el.2017.3166.

[37] C. Rochefort and R. van Dalen, "Vertical RESURF diodes manufactured by deep-trench etch and vapor-phase doping," *IEEE Electron Device Lett.*, vol. 25, no. 2, pp. 73–75, Feb. 2004, doi: 10.1109/LED.2003.822649.