Leakage Current Reduction in β-Ga_2O_3 Schottky Barrier Diodes by CF_4 Plasma Treatment

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***Abstract*— This letter reports on the suppression of reverse leakage current (I_r) in β-Ga_2O_3 Schottky barrier diodes (SBDs) through Schottky barrier modification by a low power CF_4-plasma treatment prior to Schottky metal deposition. Revealed by an x-ray photoelectron spectroscopy (XPS) analysis, the fluorine-plasma treatment brought an incorporation of fluorine ions and depletion of silicon donors in the near surface region of the β-Ga_2O_3, and thus raised its surface potential by around 0.14 eV. Furthermore, insulating GaF_x was likely created at the Schottky interface. Attributed to the fluorine-plasma- modified Schottky barrier, a reduced I_r by around four orders of magnitude and enhanced blocking voltage (V_{block}) from 150 V to 470 V at $I_r = 100\mu$ A/cm^2 have been achieved without degrading the forward characteristics. Different from the untreated device whose I_r was purely governed by the thermionic field emission (TFE), the fluorine-plasma-treated SBD showed a greatly suppressed TFE-current until a space-charge limited current (SCLC) started to dominate at around −500 V.**

***Index Terms*— β-Ga_2O_3, plasma treatment, Schottky barrier diodes, reverse leakage current, space-charge limited current.**

I. Introduction

In recent years, β-Ga_2O_3 semiconductor has attracted great research interest due to its superior material properties. The ultra-wide bandgap of ∼4.8 eV, which corresponds to a wavelength of about 260 nm, makes β-Ga_2O_3 an intrinsically suitable candidate towards high performance solar-blind deep-ultraviolet (DUV) detectors [1]–[3]. Featuring a relatively large atom density and good radiation tolerance, β-Ga_2O_3 is also promising for X-ray and high-energy particle detection applications [4]–[6]. Moreover, β-Ga_2O_3 shows a great potential for next-generation high-voltage power electronics, since its critical electric field is up to 8 MV/cm and the projected Baliga's figure of merit (BFoM) exceeds 3 GW/cm^2 [7], [8].

As a fundamentally important device, Schottky barrier diodes (SBDs) based on β-Ga_2O_3 have been extensively developed for all aforementioned applications. Remarkably, over 1 kV breakdown voltage (V_B) has been achieved in β-Ga_2O_3 power SBDs by many researchers through careful electric field management [9]–[12]. However, a relatively high reverse leakage current (I_r) in the β-Ga_2O_3 SBDs, which mainly results from an emission of majority carriers over a relatively low potential barrier (typically ∼1 eV), remains a critical challenge for both power switching and sensing applications, since it will lead to a large power consumption, high noise level, low efficiency and reliability issues. Therefore, leakage current reduction and Schottky barrier modulation are essential for developing better-performance β-Ga_2O_3 Schottky devices [13].

A previous study showed that exposure of the Pt/β-Ga_2O_3 Schottky interface to a hydrofluoric acid could increase its Schottky barrier height and decrease the I_r, in which a diffusion of fluorine (F) atoms into β-Ga_2O_3 was claimed but lacked direct confirmation [14]. On the other hand, F-based plasma treatments have been successfully adopted in GaN-based SBDs [15]–[17] and high electron mobility transistors (HEMTs) [18]–[20] for effective Schottky barrier modulation. However, performance degradation was recently observed in CF_4-plasma-treated β-Ga_2O_3 SBDs [21], [22], in terms of decreased forward current and increased ideality factor and I_r. In these studies, surface damage was likely generated due to the non-optimized treatment conditions, and it could be partially recovered by a subsequent annealing process.

In this work, through a low power CF_4-plasma surface treatment, we successfully achieved Schottky barrier modification in β-Ga_2O_3 SBDs and reduced the I_r by around four orders of magnitude, while maintaining good forward characteristics. An x-ray photoelectron spectroscopy (XPS) study confirmed the incorporation of F ions and formation of insulating GaF_x at the β-Ga_2O_3 Schottky contact after treatment.

II. Device Structure and Fabrication

The sample used in this study consisted of an 8-μm thick Si doped β-Ga_2O_3 drift layer grown on a conductive (001) β-Ga_2O_3 substrate. The non-linear $1/C^2$-V plot in Fig. 1(a) indicated a non-uniform doping in the drift layer. The net

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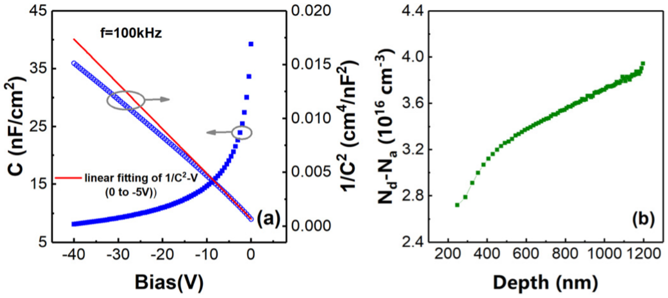

Fig. 1. (a) The measured C-V and $1/C^2$-V curves of the β-Ga_2O_3 SBD without F-plasma treatment. (b) The extracted net doping concentration (N_D-N_A) from C-V measurement.

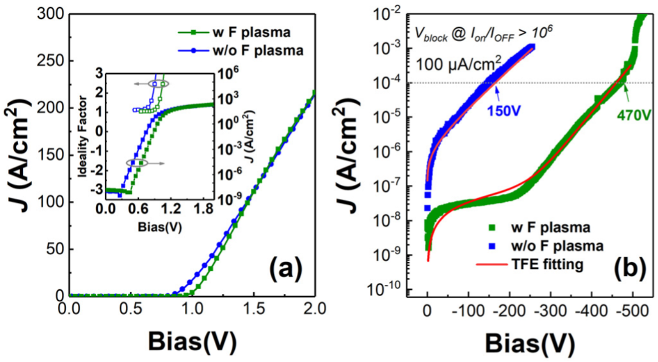

Fig. 2. Comparison of (a) forward and (b) reverse I-V characteristics for the β-Ga_2O_3 SBDs with and without F-plasma treatment.

doping concentration (N_D − N_A) was determined to be 2.8 ∼4 $\times 10^{16}$ cm^{-3}, as shown in Fig. 1(b). The fabrication process of the SBDs began with sample cleaning using acetone and isopropanol, followed by a deionized (DI) water rinse. After cleaning, the Ohmic cathode electrode (Ti/Al/Au) was deposited on backside of the sample by blanket e-beam evaporation. Then the sample was loaded into a reactive ion etch (RIE) system and a CF_4-plasma treatment was performed on the front side of the sample for 1 minute with a low RF power of 50 W. The chamber pressure and CF_4 gas flow rate were 10 mTorr and 25 sccm, respectively. Finally, circular- shaped anode electrodes with a diameter of 100 μm were formed by evaporating the Schottky metal (Ni/Au) onto the sample surface. To make comparison, a control sample without going through the F-plasma treatment process was co-prepared. Prior to the Schottky metal deposition, XPS measurements were performed on both samples to reveal how the F plasma affected the surface condition and chemical composition of the β-Ga_2O_3.

III. Results and Discussion

Fig. 2(a) plots the forward current-voltage (I-V) curves of the fabricated β-Ga_2O_3 SBDs with and without F-plasma treatment. The two devices showed quite comparable on-state performances with close-to-unity ideality factors and the forward current densities both exceeding 0.2 kA/cm^2 at a bias of +2 V. A similar specific on-resistance ($R_{on,sp}$) of ∼4.6 mΩ•cm^2 was obtained. The turn-on voltages (V_{on}), extracted at a current density of 1 A/cm^2, were 0.95 V and 0.82 V for the F-plasma-treated and untreated SBDs, respectively.

Fig. 2(b) compares the reverse I-V characteristics of the fabricated β-Ga_2O_3 SBDs with and without F-plasma treatment in a semi-log scale. The I_r in the untreated SBD increased obviously with the increase of the bias voltage and reached to $\sim 3\times10^{-4}$ A/cm^2 at −200 V. On the other hand, the F-plasma-treated SBD exhibited a I_r of $\sim 5 \times 10^{-8}$ A/cm^2 at −200 V, approximately 4 orders of magnitude lower than the untreated one. Therefore, an On/Off current ratio (I_{ON}/I_{OFF}) at −200 V as high as 4×10^9 was achieved. Moreover, the blocking voltage (V_{block}) of the device, which was defined at an I_r of 100 μA/cm^2 and corresponded to an $I_{ON}/I_{OFF} > 10^6$, was significantly enhanced by the proposed F-plasma treatment from 150 V to 470 V, among the highest in all reported β-Ga_2O_3 SBDs.

TABLE I
Benchmark of Key Parameters in Ga_2O_3 SBDs

Ref.		N_D [cm^{-3}]	$R_{on,sp}$ [mΩ·cm^2]	I_{ON}/I_{OFF} @-200V	V_{block} [V] @100μA/cm^2	E-filed manag.
[9]		3×10^{16}	2.0	5×10^6	230	FP
				1×10^2	60	No
[10]		1×10^{16}	4.7	2×10^{10}	1100	GR+FP
[11]		1.5×10^{16}	5.5	1×10^6	140	ET
				4×10^6	290	No
[12]		3×10^{16}	3.0	4×10^8	550	ET
			2.9	7×10^5	100	No
[13]		4×10^{16}	4.2	9×10^6	240	No
[14]		1.8×10^{16}	5.1	3×10^{10}	950	FP
This work	**w/o F**	**3.5×10^{16}**	**4.6**	**7×10^5**	**150**	**No**
	w F			**4×10^9**	**470**	**No**

*Field Plate (FP); Guard Ring (GR); Edge Termination (ET).

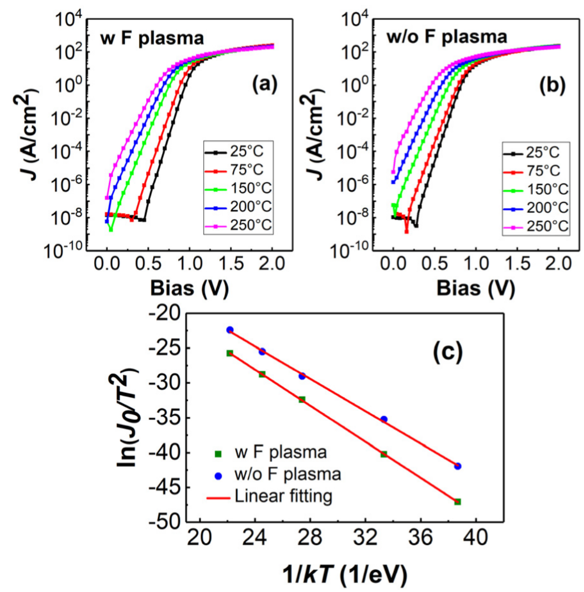

Fig. 3. T-dependent forward I-V characteristics of the β-Ga_2O_3 SBDs (a) with and (b) without F-plasma treatment, and (c) the corresponding Richardson's plots in a temperature range of 25 to 250 °C.

Table I benchmarks the device characteristics in our study with the other state-of-the-art β-Ga_2O_3 SBDs. The outstanding reverse blocking capability and well-maintained on-state performance in our device indicated that Schottky barrier modification was achieved by the proposed F-plasma treatment without degrading the quality of the Schottky contact. It should be noted that the chamber pressure in our CF_4-plasma treatment process was much lower than that in previous reports [21], [22]. The lower chamber pressure led to

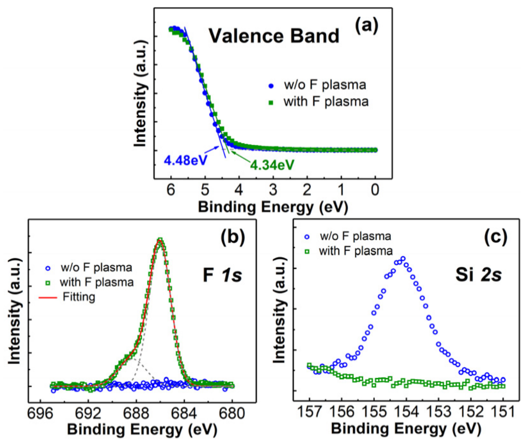

Fig. 4. (a) Valence band spectra, (b) F 1*s* core-level spectra and (c) Si 2*s* core-level spectra of the β-Ga_2O_3 samples with and without F-plasma treatment.

fewer ion-substrate collisions during treatment and less plasma damage onto the device [23].

The temperature (T)-dependent forward I-V characteristics of the β-Ga_2O_3 SBDs with and without F-plasma treatment are shown in Fig. 3, alongside with the corresponding Richardson's plots. The F-plasma-treated SBD showed an increased Schottky barrier height (SBH) of 1.31 eV compared to the untreated device of 1.18 eV, in good agreement with the 0.13 V positive shift in V_{on}. Compared to a theoretical value taking the electron effective mass of 0.342 m_0 [24], the effective Richardson's constant (A^*) extracted in our devices (20 $\sim$ 23 A/cm^{2}K^2) was relatively small. The effects of a high tunneling current could be a possible reason for the untreated SBD [25], [26], while the low A^* in the F-plasma-treated device suggested a presence of dielectric interfacial layers [27], probably GaF_x as discussed later.

Previous reports showed that the F-plasma treatment on GaN-based devices suffered from thermal stability issues, for example, threshold voltage shifting at elevating temperatures [28]. In our study, no performance degradation was observed for the F-plasma treated Ni/β-Ga_2O_3 SBDs after the high temperature test up to 250 °C. However, higher temperature stability has not been studied yet and further investigation is needed.

As shown in the valence band spectra in Fig. 4 (a), the F-plasma treatment shifted the surface Fermi level in β-Ga_2O_3 toward the valence band by ~0.14 eV, which corresponded to an increase in the surface potential and should be responsible for the higher SBH and V_{on} observed in the F-plasma-treated β-Ga_2O_3 SBD. Fig. 4 (b) and (c) compare the F *1s* and Si *2s* core-level spectra, respectively, between the β-Ga_2O_3 samples with and without F-plasma treatment. Apparently, the F *1s* peak located at ~686.0 eV with a shoulder on the higher binding energy side, which corresponded to GaF_x [29], appeared after F-plasma treatment, confirming an incorporation of F ions into the β-Ga_2O_3 and the formation of insulating GaF_x at the surface [15], [20]. On the other hand, the Si *2s* peak vanished in the F-plasma-treated sample, suggesting a removal of silicon (Si) dopant from the near surface region of the β-Ga_2O_3. During treatment, the CF_4 plasma likely reacted with Si atoms to form volatile SiF_4, which was then flushed out of the RIE chamber. Thus, it was concluded that the proposed F-plasma treatment could simultaneously enlarge the effective SBH and

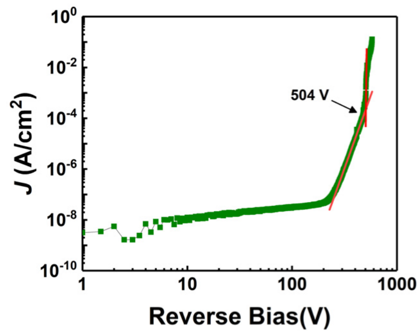

Fig. 5. The I_r of the F-plasma-treated β-Ga_2O_3 SBDs plotted in a full-log-scale.

surface depletion width in a β-Ga_2O_3 SBD, mainly due to the strong electronegativity of the incorporated F ions together with a depletion of Si dopants. The removal of Si dopant occurred only in the near surface region, much shallower than a Ni/β-Ga_2O_3 Schottky depletion depth, which would hardly affect the SBD's forward conduction.

As confirmed by the curve fitting in Fig. 2(b), a pure thermionic field emission (TFE) model well described the I_r in the untreated SBD with an SBH of 0.79 eV [32]. This value was lower than the SBH extracted from the forward I-V characteristics (1.18 eV), which could be caused by the injection of electrons into the defect mini-band rather than the conduction band [33] or the inhomogeneity of the Schottky barrier height [34], [35].

On the other hand, the I_r in the F-plasma-treated SBD showed a much smaller dependency on the bias voltage below −240 V and a hump at around −500 V, suggesting a different leakage mechanism from the untreated device. Such improvement was attributed to not only a higher and wider Schottky barrier but also the influence of the insulating GaF_x, which effectively blocked the tunneling current and might also passivate the interface states [16]. A parallel leakage path dominated the measured I_r in the F-plasma-treated SBD at a low reverse bias (<240 V), and the I_r could be fitted well up to a reverse bias of 500 V based on the TFE model including a fixed specific parallel resistance of $3 \times 10^9 \Omega cm^2$. The fitted SBH value for the F-plasma-treated SBD was 1.09 eV, obviously larger than that of the untreated device (0.79 eV), confirming a successful Schottky barrier modification by the proposed F-plasma treatment.

Fig. 5 plots the I_r of the F-plasma-treated β-Ga_2O_3 SBD in a full-log scale. It was found that the I_r showed a sudden increase at around −500 V, which could be modeled by a space-charge limited current (SCLC) conduction near the traps-filled-limit voltage (V_{TFL}) [30], [31], [33]. Under a high-level reverse bias, the electrons that injected into the depletion region could be partly captured by traps until the V_{TFL} was reached, at which point a soft breakdown usually occurred.

IV. Conclusion

A CF_4-plasma treatment process has been developed for leakage current reduction in β-Ga_2O_3 SBDs. Through an incorporation of F ions and removal of Si dopants, as well as a formation of insulating GaF_x at the Schottky interface, Schottky barrier modification was realized. The F-plasma-treated device showed significantly enhanced reverse characteristics including a ~$10^4\times$ lower I_r and > 3× higher V_{block}, while maintaining good on-state performances.

References

[1] A. S. Pratiyush, S. Krishnamoorthy, R. Muralidharan, S. Rajan, and D. N. Nath, "16-advances in Ga_2O_3 solar-blind UV photodetectors," in *Gallium Oxide*, S. Pearton, F. Ren, and M. Mastro, eds. Amsterdam, The Netherlands: Elsevier, 2019, pp. 369–399, doi: 10.1016/B978-0-12-814521-0.00016-6.

[2] A. S. Pratiyush, Z. Xia, S. Kumar, Y. Zhang, C. Joishi, R. Muralidharan, S. Rajan, and D. N. Nath, "MBE-grown β -Ga_2O_3-based Schottky UV-C photodetectors with rectification ratio $\sim 10^7$," *IEEE Photon. Technol. Lett.*, vol. 30, no. 23, pp. 2025–2028, Dec. 1, 2018, doi: 10.1109/LPT.2018.2874725.

[3] T. Oshima, T. Okuno, N. Arai, N. Suzuki, S. Ohira, and S. Fujita, "Vertical solar-blind deep-ultraviolet Schottky photodetectors based on β-Ga_2O_3 substrates," *Appl. Phys. Express*, vol. 1, no. 1, Jan. 2008, Art. no. 011202, doi: 10.1143/apex.1.011202.

[4] J. Kim, S. J. Pearton, C. Fares, J. Yang, F. Ren, S. Kim, and A. Y. Polyakov, "Radiation damage effects in Ga_2O_3 materials and devices," *J. Mater. Chem. C*, vol. 7, no. 1, pp. 10–24, 2019, doi: 10.1039/c8tc04193h.

[5] D. Szalkai, Z. Galazka, K. Irmscher, P. Tutto, A. Klix, and D. Gehre, "β-Ga_2O_3 solid-state devices for fast neutron detection," *IEEE Trans. Nucl. Sci.*, vol. 64, no. 6, pp. 1574–1579, Jun. 2017, doi: 10.1109/tns.2017.2698831.

[6] X. Lu, L. Zhou, L. Chen, X. Ouyang, B. Liu, J. Xu, and H. Tang, "Schottky X-ray detectors based on a bulk β-Ga_2O_3 substrate," *Appl. Phys. Lett.*, vol. 112, no. 10, Mar. 2018, Art. no. 103502, doi: 10.1063/1.5020178.

[7] M. Higashiwaki, A. Kuramata, H. Murakami, and Y. Kumagai, "State-of-the-art technologies of gallium oxide power devices," *J. Phys. D, Appl. Phys.*, vol. 50, no. 33, Jul. 2017, Art. no. 333002, doi: 10.1088/1361-6463/aa7aff.

[8] S. J. Pearton, F. Ren, M. Tadjer, and J. Kim, "Perspective: Ga_2O_3 for ultra-high power rectifiers and MOSFETs," *J. Appl. Phys.*, vol. 124, no. 22, Dec. 2018, Art. no. 220901, doi: 10.1063/1.5062841.

[9] N. Allen, M. Xiao, X. Yan, K. Sasaki, M. J. Tadjer, J. Ma, R. Zhang, H. Wang, and Y. Zhang, "Vertical Ga_2O_3 Schottky barrier diodes with small-angle beveled field plates: A Baliga's figure-of-merit of 0.6 GW/cm2," *IEEE Electron Device Lett.*, vol. 40, no. 9, pp. 1399–1402, Sep. 2019, doi: 10.1109/led.2019.2931697.

[10] C.-H. Lin, Y. Yuda, M. H. Wong, M. Sato, N. Takekawa, K. Konishi, T. Watahiki, M. Yamamuka, H. Murakami, Y. Kumagai, and M. Higashiwaki, "Vertical Ga_2O_3 Schottky barrier diodes with guard ring formed by nitrogen-ion implantation," *IEEE Electron Device Lett.*, vol. 40, no. 9, pp. 1487–1490, Sep. 2019, doi: 10.1109/led.2019.2927790.

[11] H. Zhou, Q. Feng, J. Ning, C. Zhang, P. Ma, Y. Hao, Q. Yan, J. Zhang, Y. Lv, Z. Liu, Y. Zhang, K. Dang, P. Dong, and Z. Feng, "High-performance vertical β -Ga_2O_3 Schottky barrier diode with implanted edge termination," *IEEE Electron Device Lett.*, vol. 40, no. 11, pp. 1788–1791, Nov. 2019, doi: 10.1109/led.2019.2939788.

[12] Y. Wang, S. Cai, M. Liu, Y. Lv, S. Long, X. Zhou, X. Song, S. Liang, T. Han, X. Tan, and Z. Feng, "High-voltage $(\bar{2}01)$ β-Ga_2O_3 vertical Schottky barrier diode with thermally-oxidized termination," *IEEE Electron Device Lett.*, vol. 41, no. 1, pp. 131–134, Jan. 2020, doi: 10.1109/led.2019.2956016.

[13] X. Lu, X. Zhou, H. Jiang, K. W. Ng, Z. Chen, Y. Pei, K. M. Lau, and G. Wang, "1-kV sputtered p-NiO/n-Ga_2O_3 heterojunction diodes with an ultra-low leakage current below 1 μ A/cm^2," *IEEE Electron Device Lett.*, vol. 41, no. 3, pp. 449–452, Mar. 2020, doi: 10.1109/led.2020.2967418.

[14] K. Konishi, K. Goto, H. Murakami, Y. Kumagai, A. Kuramata, S. Yamakoshi, and M. Higashiwaki, "1-kV vertical Ga_2O_3 field-plated Schottky barrier diodes," *Appl. Phys. Lett.*, vol. 110, no. 10, Mar. 2017, Art. no. 103506, doi: 10.1063/1.4977857.

[15] R. Chu, C. Soo Suh, M. Hoi Wong, N. Fichtenbaum, D. Brown, L. McCarthy, S. Keller, F. Wu, J. S. Speck, and U. K. Mishra, "Impact of CF_4 plasma treatment on GaN," *IEEE Electron Device Lett.*, vol. 28, no. 9, pp. 781–783, Sep. 2007, doi: 10.1109/led.2007.902849.

[16] R. Chu, L. Shen, N. Fichtenbaum, D. Brown, S. Keller, and U. K. Mishra, "Plasma treatment for leakage reduction in AlGaN/GaN and GaN Schottky contacts," *IEEE Electron Device Lett.*, vol. 29, no. 4, pp. 297–299, Apr. 2008, doi: 10.1109/led.2008.917814.

[17] W. Jin Ha, S. Chhajed, S. Jae Oh, S. Hwang, J. Kyu Kim, J.-H. Lee, and K.-S. Kim, "Analysis of the reverse leakage current in AlGaN/GaN Schottky barrier diodes treated with fluorine plasma," *Appl. Phys. Lett.*, vol. 100, no. 13, Mar. 2012, Art. no. 132104, doi: 10.1063/1.3697684.

[18] Y. Cai, Y. Zhou, K. M. Lau, and K. J. Chen, "Control of threshold voltage of AlGaN/GaN HEMTs by fluoride-based plasma treatment: From depletion mode to enhancement mode," *IEEE Trans. Electron Devices*, vol. 53, no. 9, pp. 2207–2215, Sep. 2006, doi: 10.1109/ted.2006.881054.

[19] Y. Cai, Y. Zhou, K. J. Chen, and K. M. Lau, "High-performance enhancement-mode AlGaN/GaN HEMTs using fluoride-based plasma treatment," *IEEE Electron Device Lett.*, vol. 26, no. 7, pp. 435–437, Jul. 2005, doi: 10.1109/led.2005.851122.

[20] S. Huang, H. Chen, and K. J. Chen, "Surface properties of $Al_xGa_{1-x}N$/GaN heterostructures treated by fluorine plasma: An XPS study," *Phys. Status Solidi (C)*, vol. 8, nos. 7–8, pp. 2200–2203, Apr. 2011, doi: 10.1002/pssc.201000927.

[21] J. Yang, Z. Sparks, F. Ren, S. J. Pearton, and M. Tadjer, "Effect of surface treatments on electrical properties of β-Ga_2O_3," *J. Vac. Sci. Technol. B*, vol. 36, no. 6, Nov. 2018, Art. no. 061201, doi: 10.1116/1.5052229.

[22] J. Yang, C. Fares, F. Ren, R. Sharma, E. Patrick, M. E. Law, S. J. Pearton, and A. Kuramata, "Effects of fluorine incorporation into β-Ga_2O_3," *J. Appl. Phys.*, vol. 123, no. 16, Apr. 2018, Art. no. 165706, doi: 10.1063/1.5031001.

[23] J. E. Hogan, S. W. Kaun, E. Ahmadi, Y. Oshima, and J. S. Speck, "Chlorine-based dry etching of β-Ga_2O_3," *Semicond. Sci. Technol.*, vol. 31, no. 6, Jun. 2016, Art. no. 065006, doi: 10.1088/0268-1242/31/6/065006.

[24] H. He, R. Orlando, M. A. Blanco, R. Pandey, E. Amzallag, I. Baraille, and M. Rérat, "First-principles study of the structural, electronic, and optical properties ofGa_2O_3 in its monoclinic and hexagonal phases," *Phys. Rev. B, Condens. Matter*, vol. 74, no. 19, Nov. 2006, doi: 10.1103/PhysRevB.74.195123.

[25] R. P. Tompkins, M. R. Khan, R. Green, K. A. Jones, and J. H. Leach, "IVT measurements of GaN power Schottky diodes with drift layers grown by HVPE on HVPE GaN substrates," *J. Mater. Sci., Mater. Electron.*, vol. 27, no. 6, pp. 6108–6114, Feb. 2016, doi: 10.1007/s10854-016-4536-z.

[26] L. S. Yu, Q. Z. Liu, Q. J. Xing, D. J. Qiao, S. S. Lau, and J. Redwing, "The role of the tunneling component in the current–voltage characteristics of metal-GaN Schottky diodes," *J. Appl. Phys.*, vol. 84, no. 4, pp. 2099–2104, Aug. 1998, doi: 10.1063/1.368270.

[27] C. Wu, "Interfacial layer-thermionic-diffusion theory for the Schottky barrier diode," *J. Appl. Phys.*, vol. 53, no. 8, pp. 5947–5950, Aug. 1982, doi: 10.1063/1.331384.

[28] R. Wang, Y. Cai, and K. J. Chen, "Temperature dependence and thermal stability of planar-integrated enhancement/depletion-mode AlGan/GaN HEMTs and digital circuits," *Solid-State Electron.*, vol. 53, no. 1, pp. 1–6, Jan. 2009, doi: 10.1016/j.sse.2008.09.001.

[29] A. S. Barrière, G. Couturier, G. Gevers, H. Guégan, T. Seguelond, A. Thabti, and D. Bertault, "Preparation and characterization of gallium(III) fluoride thin films," *Thin Solid Films*, vol. 173, no. 2, pp. 243–252, 1989, doi: 10.1016/0040-6090(89)90140-5.

[30] M. A. Lampert, "Simplified theory of space-charge-limited currents in an insulator with traps," *Phys. Rev.*, vol. 103, no. 6, pp. 1648–1656, Sep. 1956, doi: 10.1103/PhysRev.103.1648.

[31] A. Rizzo, G. Micocci, and A. Tepore, "Space-charge-limited currents in insulators with two sets of traps distributed in energy: Theory and experiment," *J. Appl. Phys.*, vol. 48, no. 8, pp. 3415–3424, Aug. 1977, doi: 10.1063/1.324185.

[32] M. Higashiwaki, K. Konishi, K. Sasaki, K. Goto, K. Nomura, Q. T. Thieu, R. Togashi, H. Murakami, Y. Kumagai, B. Monemar, A. Koukitu, A. Kuramata, and S. Yamakoshi, "Temperature-dependent capacitance–voltage and current–voltage characteristics of Pt/Ga_2O_3 (001) Schottky barrier diodes fabricated on n—-Ga_2O_3 drift layers grown by halide vapor phase epitaxy," *Appl. Phys. Lett.*, vol. 108, no. 13, Mar. 2016, Art. no. 133503, doi: 10.1063/1.4945267.

[33] B. Wang, M. Xiao, X. Yan, H. Y. Wong, J. Ma, K. Sasaki, H. Wang, and Y. Zhang, "High-voltage vertical Ga_2O_3 power rectifiers operational at high temperatures up to 600 k," *Appl. Phys. Lett.*, vol. 115, no. 26, Dec. 2019, Art. no. 263503, doi: 10.1063/1.5132818.

[34] N. Allen, T. Ciarkowski, E. Carlson, and L. Guido, "Characterization of inhomogeneous Ni/GaN Schottky diode with a modified log-normal distribution of barrier heights," *Semicond. Sci. Technol.*, vol. 34, no. 9, Sep. 2019, Art. no. 095003, doi: 10.1088/1361-6641/ab3071.

[35] J. H. Werner and H. H. Güttler, "Barrier inhomogeneities at Schottky contacts," *J. Appl. Phys.*, vol. 69, no. 3, pp. 1522–1533, Feb. 1991, doi: 10.1063/1.347243.