1.1-kV Vertical GaN p-n Diodes With p-GaN Regrown by Molecular Beam Epitaxy

Zongyang Hu, Kazuki Nomoto, *Member, IEEE*, Meng Qi, Wenshen Li, Mingda Zhu, Xiang Gao, Debdeep Jena, *Senior Member, IEEE*, and Huili Grace Xing, *Senior Member, IEEE*

***Abstract*— High-voltage vertical regrown p-n junction diodes on bulk GaN substrates are reported in this letter with molecular-beam-epitaxy regrown p-GaN on metalorganic-chemical-vapor-deposition grown n-GaN drift region. The highest breakdown voltage is measured at 1135 V, and the differential on-resistance is 3.9 mOhm.cm^2 at room temperature. The forward I–Vs show a turn-ON voltage near 3.9 V and an ideality factor of 2.5. Electroluminescence measurement of regrown p-n junctions shows ∼30 times reduced emission intensity compared with as-grown p-n junctions, indicating presence of excessive non-radiative recombination centers introduced by the regrowth process. Temperature dependent reverse I–V measurements suggest that variable range hopping inside the depleted regrown p-GaN layer is likely the mechanism of the reverse leakage. This is the first high-voltage vertical regrown p-n junction ever reported in the GaN system.**

***Index Terms*— p-n junction, molecular beam epitaxy, regrowth, breakdown voltage, specific on-resistance, ideality factor, bulk gallium nitride (GaN), avalanche, power electronics.**

I. INTRODUCTION

VERTICAL GaN power devices based on bulk GaN substrates are capable of delivering high breakdown voltage, low power loss and fast switching performance due to the unique combination of wide band gap, large critical electric field, high electron mobility and polarization effects of GaN. Recently, vertical GaN power p-n diodes with record high Baliga's figure of merit (BFOM) and critical electric field have been demonstrated [1]–[5]. However, in order to achieve the best theoretical performance and flexibility in device structure design, selective area doping of either n or p type regions is needed, so that current apertures in forms of lateral p-n junctions or embedded p-n junctions can be created in vertical switches.

Selective epitaxial regrowth has been an effective way to form critical junctions in GaN devices. MOCVD regrowth of either the n-type channel [6] or the p-type current blocking layer [7] has resulted in fabrication of vertical power switches with varied degree of success. However, it has been reported that impurity incorporation has strong dependence on crystal orientation [8], and non-planar regrowth always resulted in large leakage currents at high drain biases [7]. In addition, there are critical challenges associated with MOCVD regrowth. First, the Mg memory/diffusion effect necessitates special procedures to minimize Mg tail in the subsequent n-GaN layers during MOCVD regrowth [9]. It has been observed that a 2D electron channel cannot be formed unless an Mg blocking layer [10] or a thick Mg tail layer is incorporated to lower the Mg concentration near the hetero-interface [11]. Second, hydrogen passivation is a known problem in MOCVD as-grown Mg-doped GaN [12]. Moreover, activated Mg dopants in p-GaN can be re-passivated by high temperature (>600°C) annealing in NH_3 gas or hydrogen plasma [13], [14]. It is also known that hydrogen has a very low diffusivity due to an extremely high diffusion barrier in n-GaN [14], which becomes a major challenge for activating Mg in buried p-GaN. Alternatively, MBE growth of GaN:Mg renders sharp Mg profiles, and does not require Mg activation thanks to the low hydrogen growth environment. To this end, we have explored MBE regrowth of p-GaN on top of thick MOCVD n-GaN drift layer, demonstrating high-voltage vertical p-n diodes with breakdown voltage (BV) >1.1 kV. To the best of our knowledge, this is the first report of high-voltage GaN p-n diodes with a regrown junction.

II. EPITAXIAL (RE)GROWTH AND DEVICE FABRICATION

The original epitaxial structure contains 8 μm GaN with a target Si doping concentration of $\sim 2 \times 10^{16}$ cm^{-3} grown by MOCVD on a commercial bulk GaN substrate, which is of similar quality in the near ideal p-n diodes reported earlier [3]. Device fabrication started with a cleaning in HCl, followed by MBE growth of 400 nm GaN:Mg with a doping concentration of $\sim 1 \times 10^{18}$ cm^{-3} and a 20 nm p^{++} GaN capping layer.

The complete diode fabrication processes follow the baseline recipe described in [2], [3], and [15]. The device structure includes a beveled mesa etched into the n- GaN layer, Pd/Au anode ohmic contacts and Ti/Au cathode contacts, a spin-on-glass (SOG) passivation layer and a field plate

Manuscript received June 9, 2017; accepted June 22, 2017. Date of publication June 29, 2017; date of current version July 24, 2017. This work was supported by the ARPAe SWITCHES Project, monitored by I. Kizilyalli and T. Heidel. The review of this letter was arranged by Editor D.-H. Kim. *(Corresponding authors: Zongyang Hu; Huili Grace Xing.)*

Z. Hu, K. Nomoto, W. Li, and M. Zhu are with the School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853 USA (e-mail: zh249@cornell.edu).

M. Qi was with the Department of Electrical Engineering, University of Notre Dame, Notre Dame, IN 46556 USA. He is now with Uber Technologies Inc., San Francisco, CA 94103 USA.

X. Gao is with IQE RF LLC, Somerset, NJ 08873 USA.

D. Jena and H. G. Xing are with the School of Electrical and Computer Engineering and the Department of Materials Science and Engineering, Cornell University, Ithaca, NY 14853 USA (e-mail: grace.xing@cornell.edu).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2017.2720747

0741-3106 © 2017 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission.
See http://www.ieee.org/publications_standards/publications/rights/index.html for more information.

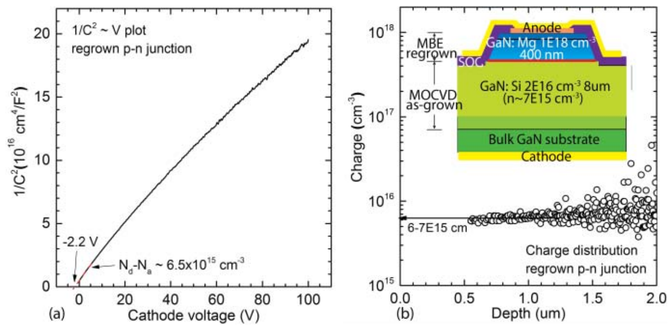

Fig. 1. (a) $1/C^2$ as a function of reverse voltage measured on the regrown GaN p-n diodes and (b) extracted net doping concentration in the n-GaN drift layer. Inset: schematic cross-section of the completed device.

edge termination connected to the anode, extending outside of the mesa edge. The transfer length measurement (TLM) on the p-GaN layer determines a specific contact resistance of $\sim 2 \times 10^{-4}\Omega\cdot\text{cm}^2$ and a sheet resistance of $\sim$89 k$\Omega/\square$ at room temperature. The schematic cross-section of the diode is shown in the inset in Fig. 1(b).

III. Results and Discussion

Capacitance–voltage ($C - V$) measurements were used to analyze the net doping concentration of the n- GaN region. Figure 1(a) shows $1/C^2$ versus cathode voltage, where the apparent built-in voltage is extracted to be $\sim$2.2 V. This value is lower compared to those of as-grown p-n junctions, which typically have a built-in voltage of $\sim$3.2 V primarily determined by the band gap of GaN [3]. Though the exact mechanism is not understood, this could be caused by extra band bending due to impurities and defects at the regrowth interface. The net doping (N_D-N_A) concentration in n-GaN is $\sim 6.5\times10^{15}$ cm^{-3}, which is consistent with the value extracted on the Schottky barrier diodes (SBDs) fabricated on the same MOCVD n-GaN without p-GaN regrowth.

Figure 2 shows the temperature (T)-dependent I-Vs of a representative regrown p-n diode with a mesa bottom diameter of 107 μm along with an as-grown p-n diode with similar dimensions from [3]. R_{on} is calculated using a diode effective diameter of 127 μm by assuming a current spreading radius of 10 μm based on previous device simulations [2], [15]. Compared to the as-grown p-n diode, the regrown diode shows a higher leakage prior to turn-on and a lower output current after turn-on. Nonetheless, the on/off current ratio of the regrown diode is over 11 orders of magnitude. The leakage current at $<$ 1 V is below the measurement range of the test equipment. The sub-threshold current increases and the forward turn-on voltage reduces with temperature, similar to as-grown p-n junctions [3], [15], which are characteristics of conduction by thermally activated carriers. The recombination current exceeds the diffusion current before the diode turns on. The high recombination current, along with a large series resistance and minor shunt leakage currents, lead to a turn-on voltage $>$ 3.2 V and an ideality factor $>$2.0 at all bias voltages in the regrown diodes. In addition, electroluminescence (EL) measurements (not shown) show that the regrown diodes have $\sim$30 times lower integrated emission intensity over the range of 300-600 nm compared to the as-grown ones

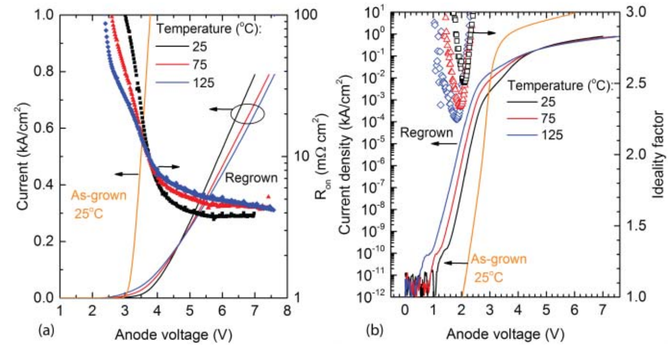

Fig. 2. (a) T-dependent forward I-V characteristics with differential R_{on} of a regrown GaN p-n diode, in comparison with an as-grown p-n diode from [3]. The mesa bottom diameter of both diodes is 107 μm. (b) Diode forward I-V characteristics in semi-log scale with extracted ideality factors.

at the same current density. This is another direct evidence that the regrown interface contains much more non-radiative recombination centers than the bulk material.

The differential on-resistance (R_{on}) of the regrown p-n diode increases with increasing temperature. This trend suggests that the dominant component of R_{on} in the regrown diode is the n-layer resistance (r_n), since electron mobility in the lightly doped n-GaN with low dislocation densities is significantly limited by phonon scattering, thus decreasing with increasing temperature [16], [17]. The dramatic reduction of conductivity modulation in the regrown diodes, supported by the EL measurement, provides an explanation to the higher R_{on} observed in the regrown diodes than the as-grown ones; at the same current density of 800 A/cm^2, $R_{on-regrown}$ is $\sim$3.9 m$\Omega\cdot$cm^2 while $R_{on-asgrown}$ is $\sim$ 0.6 m$\Omega\cdot$cm^2. The R_{on} behavior of these diodes merits further scrutiny thus insight on possible junction quality improvement, which is beyond the scope of this work.

The highest breakdown voltage measured on these regrown GaN p-n junction diodes is 1136 V, as shown in the reverse I-V plot in Fig. 3(a). The diode has a mesa diameter of 107 μm and reaches a leakage current of 0.1 A/cm^2 before breakdown. This is the highest BV ever reported for regrown GaN p-n diodes. However, most breakdown events were destructive and no avalanche breakdown behavior could be measured, unlike in the as-grown p-n diodes [3]. In order to provide information on the mechanism of leakage currents, the same I-V curve is re-plotted in the inset of Fig. 3(a): $\ln(J/J_0)$ as a function of the average electric field E (the applied reverse bias over the depletion width), where J_0 is the current density at 0 V. Following the same analysis in [18] and [19], for E $<$ 0.2 MV/cm ($<$160 V), the leakage current increases slowly with reverse voltage with a slope of $\sim$0.5, suggesting the dominant conduction mechanism is Frenkel-Poole, i.e. field assisted thermionic emission over potential barriers. For E $>$0.2 MV/cm and before breakdown, the leakage current increases steeper with bias with a slope of $\sim$1.0, suggesting the variable range hopping (VRH) inside the depletion region is dominant.

Figure 3(b) shows the T-dependent I-V characteristics of another regrown GaN p-n diode measured up to 600 V. The inset shows the slope d $\log(ln(J/J_0))/$d $\log(E)$ versus voltage.

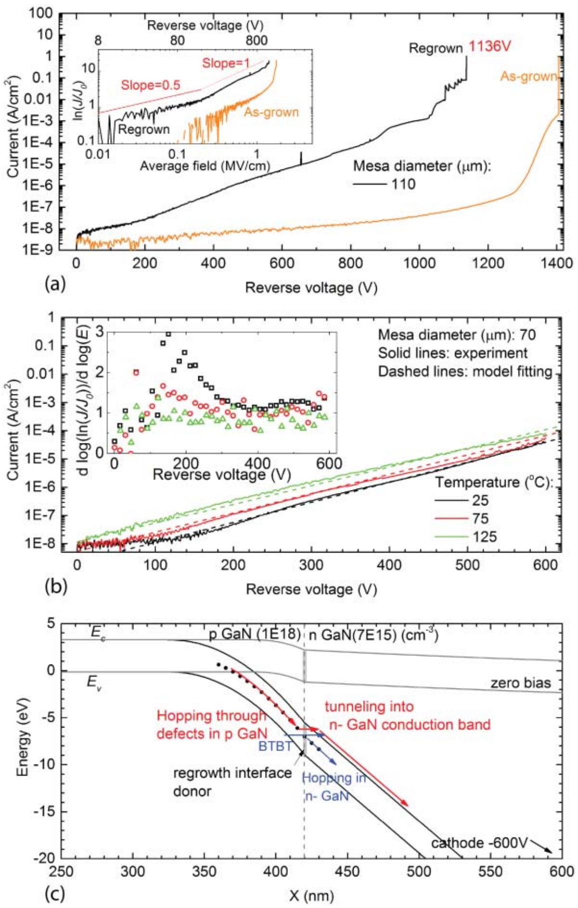

Fig. 3. (a) Reverse *I-V* characteristics of a regrown GaN p-n diode in comparison with those of an as-grown p-n diode. Inset: the log-log plot of $\ln(J/J_0)$ versus the average electric field. (b) T-dependent reverse *I-V* characteristics (solid) of a regrown GaN p-n diode and fitting results (dashed) using field and T-dependence of the VRH model. Inset: d $\log(\ln(J/J_0))$/d $\log(E)$ as a function of reverse voltage. (c) Simulated band diagram using a Mg doping of 10^{18} cm^{-3}, an n-doping of 7×10^{15} cm^{-3} and an interface donor concentration of $\sim 2.8\times10^{12}$ cm^{-2}, with the dominant leakage paths illustrated in red and the minor leakage paths in blue.

It is found that from 25 °C to 125 °C, the slope all starts from ~0.5 at low field and ends around 1.0 at high field, following $\ln\ (I) \propto E/T^{\alpha}$. The temperature dependence can be fitted reasonably well by α ~0.25, consistent with Mott VRH conduction $\ln(\sigma) \propto T^{-1/4}$, although the applied electric field has exceeded the low-field region [20]. Considering the regrown p GaN layer near the p-n junction interface is likely defective due to initial broken/dangling bonds, defects and impurities on the surface of the n-GaN, defect-assisted hopping conduction in regrown p GaN might be the dominant leakage mechanism.

A proposed band diagram is simulated using a 1D Poisson solver and shown in Fig. 3(c) along with the possible leakage paths. The donor-like defects/impurities at the regrown interface are modeled as a sheet of n type dopants. When fully activated under junction electric field, they increase the electric field and band bending in p-GaN, and also lead to a lower apparent built-in potential in *C-V* measurements. The interfacial charge density is determined to be $\sim 2.8\times10^{12}\text{cm}^{-2}$ to account for the apparent built-in potential of 2.2 V. Existence of such interface charge and defects heavily impacts the reverse leakage currents. At a poorly controlled interface, (trap-assisted) band-to-band tunneling (BTBT) usually results in much higher leakage currents at relatively low reverse biases (< 200 V), which have been observed in some regrown p-n diodes. In Fig. 4, breakdown voltages and on-resistances of GaN p-n diodes on various substrates are plotted. The regrown GaN p-n diodes presented in this work have comparable power performance to the best as-grown GaN p-n diodes on sapphire. However, it is understood that the limiting factors in these regrown diodes are the homoepitaxial regrowth interface and the subsequent epitaxial layer, not dislocations generated in heteroepitaxy on foreign substrates. Similar issues have been reported by other work in both MOCVD and MBE regrown structures. Special interface cleaning and growth conditions have been used to control the interface charge [31]–[33]. To this end, improved understanding and implementation of homoepitaxy or regrowth conditions that result in lower defect densities near the epitaxial regrowth interface are needed to further improve the diode characteristics.

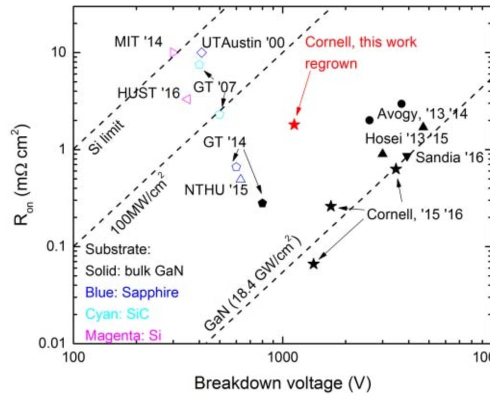

Fig. 4. On-resistance versus breakdown voltage benchmark plot of state-of-the- art high voltage GaN p-n diodes on GaN, SiC, sapphire and Si substrates. All literature data points are as-reported values from references [21]–[30], except that the Cornell '15 '16 data are recalculated following the diode area definition used in [5], [29], and [30], i.e. the anode electrode area, for a direct comparison.

IV. Conclusion

High-voltage vertical GaN p-n diodes with MBE regrown p-GaN on MOCVD grown n-GaN are demonstrated in this work. These diodes show a BV up to 1136 V, and a differential R_{on} of 3.9 mΩ·cm^2 at RT, thus a BV^2/R_{on} ~0.33 GW/cm^2; in comparison, at the same on-current level of 800 A/cm^2, the as-grown p-n diode boasts a BV^2/R_{on} ~4.1 GW/cm^2. It has been found that the regrowth interface results in significantly higher R_{on} and recombination current compared to as-grown junctions. It is suggested that the higher than as-grown reverse leakage is due to defect-assisted conduction in the regrown p GaN layer and the regrown p/n interface. This work serves as an important step towards understanding the conduction mechanism in regrown junctions and improving selective doping technique for high performance vertical GaN switches.

References

[1] I. C. Kizilyalli, A. P. Edwards, H. Nie, D. Bour, T. Prunty, and D. Disney, "3.7 kV vertical GaN PN diodes," *IEEE Electron Device Lett.*, vol. 35, no. 2, pp. 247–249, Feb. 2014, doi: 10.1109/LED.2013.2294175.

[2] K. Nomoto, Z. Hu, B. Song, M. Zhu, M. Qi, R. Yan, V. Protasenko, E. Imhoff, J. Kuo, N. Kaneda, T. Mishima, T. Nakamura, D. Jena, and H. G. Xing, "GaN-on-GaN p-n power diodes with 3.48 kV and 0.95 mΩ-cm^2: A record high figure-of-merit of 12.8 GW/cm2," in *IEDM Tech. Dig.*, Dec. 2015, pp. 9.7.1–9.7.4, doi: 10.1109/IEDM.2015.7409665.

[3] Z. Hu, K. Nomoto, B. Song, M. Zhu, M. Qi, M. Pan, X. Gao, V. Protasenko, D. Jena, and H. G. Xing, "Near unity ideality factor and Shockley-Read-Hall lifetime in GaN-on-GaN p-n diodes with avalanche breakdown," *Appl. Phys. Lett.*, vol. 107, pp. 243501-1–243501-5, Dec. 2015, doi: 10.1063/1.4937436.

[4] M. Qi, K. Nomoto, M. Zhu, Z. Hu, Y. Zhao, V. Protasenko, B. Song, X. Yan, G. Li, J. Verma, S. Bader, P. Fay, H. G. Xing, and D. Jena, "High breakdown single-crystal GaN p-n diodes by molecular beam epitaxy," *Appl. Phys. Lett.*, vol. 107, pp. 232101-1–232101-4, Dec. 2015, doi: 10.1063/1.4936891.

[5] A. M. Armstrong, A. A. Allerman, A. J. Fischer, M. P. King, M. S. van Heukelom, M. W. Moseley, R. J. Kaplar, J. J. Wierer, M. H. Crawford, and J. R. Dickerson, "High voltage and high current density vertical GaN power diodes," *Electron. Lett.*, vol. 52, no. 13, pp. 1170–1171, Jun. 2016, doi: 10.1049/el.2016.1156.

[6] 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-mΩ-cm^2 vertical GaN transistors on bulk-GaN substrates," *IEEE Electron Device Lett.*, vol. 35, no. 9, pp. 939–941, Sep. 2014, doi: 10.1109/LED.2014.2339197.

[7] R. Yeluri, J. Lu, C. A. Hurni, D. A. Browne, S. Chowdhury, S. Keller, J. S. Speck, and U. K. Mishra, "Design, fabrication, and performance analysis of GaN vertical electron transistors with a buried p/n junction," *Appl. Phys. Lett.*, vol. 106, pp. 183502-1–183502-5, May 2015, doi: 10.1063/1.4919866.

[8] S. C. Cruz, S. Keller, T. E. Mates, U. K. Mishra, and S. P. DenBaars, "Crystallographic orientation dependence of dopant and impurity incorporation in GaN films grown by metalorganic chemical vapor deposition," *J. Cryst. Growth*, vol. 311, no. 15, pp. 3817–3823, Jul. 2009, doi: 10.1016/j.jcrysgro.2009.02.051.

[9] H. Xing, D. S. Green, H. Yu, T. Mates, P. Kozodoy, S. Keller, S. P. DenBaars, and U. K. Mishra, "Memory effect and redistribution of Mg into sequentially regrown GaN layer by metalorganic chemical vapor deposition," *Jpn. J. Appl. Phys.*, vol. 42, pp. 50–53, Sep. 2003, doi: 10.1143/JJAP.42.50.

[10] S. Chowdhury, B. L. Swenson, J. Lu, and U. K. Mishra, "Use of sub-nanometer thick AlN to arrest diffusion of ion-implanted Mg into regrown AlGaN/GaN layers," *Jpn. J. Appl. Phys.*, vol. 50, pp. 101002-1–101002-5, Oct. 2011, doi: 10.1143/JJAP.50.101002.

[11] M. Zhu, B. Song, Z. Hu, K. Nomoto, M. Pan, X. Gao, D. Jena, and H. Xing, "Comparing buffer leakage in PolarMOSH on SiC and free-standing GaN substrates," in *Proc. IEEE Lester Eastman Conf. (LEC)*, Aug. 2016, pp. 27–30, doi: 10.1109/LEC.2016.7578926.

[12] S. Nakamura, T. Mukai, M. Senoh, and N. Iwasa, "Thermal annealing effects on P-type Mg-doped GaN films," *Jpn. J. Appl. Phys.*, vol. 31, no. 2B, pp. L139–L142, Feb. 1992, doi: 10.1143/JJAP.31.L139.

[13] S. Nakamura, N. Iwasa, M. Senoh, and T. Mukai, "Hole compensation mechanism of P-type GaN films," *Jpn. J. Appl. Phys.*, vol. 31, no. 5A, pp. 1258–1266, May 1992, doi: 10.1143/JJAP.31.1258.

[14] W. Götz, N. M. Johnson, J. Walker, D. P. Bour, H. Amano, and I. Akasaki, "Hydrogen passivation of Mg acceptors in GaN grown by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 67, no. 18, pp. 2666–2668, Oct. 1995, doi: 10.1063/1.114330.

[15] K. Nomoto, B. Song, Z. Hu, M. Zhu, M. Qi, N. Kaneda, T. Mishima, T. Nakamura, D. Jena, and H. G. Xing, "1.7-kV and 0.55-m$\Omega\cdot$cm^2 GaN p-n diodes on bulk GaN substrates with avalanche capability," *IEEE Electron Device Lett.*, vol. 37, no. 2, pp. 161–164, Feb. 2016, doi: 10.1109/LED.2015.2506638.

[16] M. Zhu, M. Qi, K. Nomoto, Z. Hu, B. Song, M. Pan, X. Gao, D. Jena, and H. G. Xing, "Electron mobility in polarization-doped $Al_{0-0.2}$GaN with a low concentration near 10^{17} cm^{-3}," *Appl. Phys. Lett.*, vol. 110, pp. 182102-1–182102-5, May 2017, doi: 10.1063/1.4982920.

[17] D. Jena, "Polarization induced electron populations in III-V nitride semiconductors: Transport, growth, and device applications," Ph.D. dissertation, Dept. Elect. Comput. Eng., Univ. California, Santa Barbara, CA, USA, 2003, p. 47.

[18] D. P. Han, C. H. Oh, H. Kim, J. I. Shim, K. S. Kim, and D. S. Shin, "Conduction mechanisms of leakage currents in InGaN/GaN-based light-emitting diodes," *IEEE Trans. Electron Devices*, vol. 62, no. 2, pp. 587–592, Feb. 2015, doi: 10.1109/TED.2014.2381218.

[19] Y. Zhang, H.-Y. Wong, M. Sun, S. Joglekar, L. Yu, N. A. Braga, R. V. Mickevicius, and T. Palacios, "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.

[20] N. Apsley and H. P. Hughes, "Temperature- and field-dependence of hopping conduction in disordered systems, II," *Philos. Mag.*, vol. 31, pp. 1327–1339, Apr. 1975, doi: 10.1080/00318087508228686.

[21] Y. Zhang, M. Sun, D. Peidra, M. Azize, X. Zhang, T. Fujishima, and T. Palacios, "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.

[22] X. Zou, X. Zhang, X. Lu, C. W. Tang, and K. M. Lau, "Fully vertical GaN $p-i-n$ diodes using GaN-on-Si epilayers," *IEEE Electron Device Lett.*, vol. 37, no. 5, pp. 636–639, May 2016, doi: 10.1109/LED.2016.2548488.

[23] D. Yoo, J. B. Limb, J.-H. Ryou, W. Lee, and R. D. Dupuis, "Epitaxial growth and device design optimization of full-vertical GaN $p-i-n$ Rectifiers," *J. Electron. Mater.*, vol. 36, no. 4, pp. 353–358, Apr. 2007, doi: 10.1007/s11664-006-0069-1.

[24] J. B. Limb, D. Yoo, J.-H. Ryou, S. C. Shen, and R. D. Dupuis, "Low on-resistance GaN pin rectifiers grown on 6H-SiC substrates," *Electron. Lett.*, vol. 43, no. 6, pp. 67–68, Mar. 2007, doi: 10.1049/el:20070065.

[25] T. G. Zhu, D. J. H. Lambert, B. S. Shelton, M. M. Wong, U. Chowdhury, H. K. Kwon, and R. D. Dupuis, "High-voltage GaN pin vertical rectifiers with 2 μm thick i-Layer," *Electron Lett.*, vol. 36, no. 23, pp. 1971–1972, Nov. 2000, doi: 10.1049/el:20001329.

[26] T.-T. Kao, J. Kim, T.-C. Lee, M.-H. Ji, T. Detchprohm, R. D. Dupuis, and S.-C. Shen, "Homojunction GaN $p-i-n$ rectifiers with ultra-low on-state resistance," in *Proc. CSMANTECH Conf.*, May 2014, pp. 157–160, doi: N/A.

[27] B.-S. Zheng, P.-Y. Chen, C.-J. Yu, Y.-F. Chang, C.-L. Ho, M.-C. Wu, and K.-C. Hsieh, "Suppression of current leakage along mesa surfaces in GaN-based $p-i-n$ diodes," *IEEE Electron Device Lett.*, vol. 36, no. 9, pp. 932–934, Sep. 2015, doi: 10.1109/LED.2015.2458899.

[28] I. C. Kizilyalli, A. P. Edwards, H. Nie, D. Disney, and D. Bour, "High voltage vertical GaN p-n diodes with avalanche capability," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3067–3070, Oct. 2013, doi: 10.1109/TED.2013.2266664.

[29] Y. Hatakeyama, K. Nomoto, A. Terano, N. Kaneda, T. Tsuchiya, T. Mishima, and T. Nakamura, "High-breakdown-voltage and low-specific-on-resistance GaN p-n junction diodes on free-standing GaN substrates fabricated through low-damage field-plate process," *Jpn. J. Appl. Phys.*, vol. 52, pp. 028007-1–028007-3, Jan. 2013, doi: 10.7567/JJAP.52.028007.

[30] H. Ohta, N. Kaneda, F. Horikiri, Y. Narita, T. Yoshida, T. Mishima, and T. Nakamura, "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.

[31] H. Xing, S. P. DenBaars, and U. K. Mishra, "Characterization of AlGaN/GaN p-n diodes with selectively regrown n-AlGaN by metal-organic chemical-vapor deposition and its application to GaN-based bipolar transistors," *J. Appl. Phys.*, vol. 97, no. 11, pp. 113703-1–113703-4, May 2005, doi: 10.1063/1.1914952.

[32] G. Koblmüller, R. M. Chu, A. Raman, U. K. Mishra, and J. S. Speck, "High-temperature molecular beam epitaxial growth of AlGaN/GaN on GaN templates with reduced interface impurity levels," *J. Appl. Phys.*, vol. 107, pp. 043527-1–043527-9, Feb. 2010, doi: 10.1063/1.3285309.

[33] Y. Cao, T. Zimmermann, H. Xing, and D. Jena, "Polarization-engineered removal of buffer leakage for GaN transistors," *Appl. Phys. Lett.*, vol. 96, pp. 042102-1–042102-3, Jan. 2010, doi: 10.1063/1.3293454.