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Surge Current Ruggedness in Vertical GaN-on-GaN PiN Diode: Role of Conductivity Modulation

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***Abstract*—In this work, we investigate the surge current ruggedness and role of the conductivity modulation in the vertical GaN-on-GaN PiN diode. With varying t_{surge} (5 μs~10 ms) and I_{peak} up to 10 kA/cm², the evolvement of surge current capability of vertical GaN-on-GaN PiN diode has been systematically investigated. Owing to the desirable photon- and thermally-enhanced conductivity modulation in the direct-bandgap GaN, a high surge energy density of 282 *J*/cm² has been realized in the vertical GaN-on-GaN PiN diode, showing great potential of vertical GaN-on-GaN PiN diodes for high power electronic applications.**

***Keywords*—Conductivity modulation, GaN-on-GaN, PiN diode, surge current ruggedness.**

I. Introduction

Compared with the conventional lateral GaN HEMTs grown on foreign substrate, vertical GaN-on-GaN power devices are promising to extend the voltage/power ratings with superior dynamic performance [1-4], benefiting from thick homo-epitaxial GaN drift layer with reduced dislocation density, and the vertical configuration that is more suitable for high current capability and less sensitive to surface trapping.

Power diodes would undergo a high surge current from circumstances of current overshoot/oscillation in switching converters, circuit failure or electrostatic discharge [5]. For indirect-bandgap bipolar devices with relatively long minority carrier lifetime (~10^{-6}–10^{-3} s for Si [6] and ~10^{-6} s for SiC [7]), minority carrier injection and conductivity modulation play an important role in their surge current capability [8]. In recent years, there are also reports demonstrating surge current capability of vertical GaN-on-GaN and quasi-vertical GaN-on-sapphire diodes, which mainly focus on the evaluation of the peak current (I_{peak}) at a certain surge pulse width (t_{surge}) [9-12]. However, the evolvement of surge current capability with varying I_{peak} and t_{surge}, as well as the underlying mechanism, has been seldom investigated to date. On the other hand, whether the minority carrier injection in direct-bandgap GaN with an ultrashort intrinsic lifetime of ~10^{-8} s [13] and the conductivity modulation [3] can play a role in the surge current capability remain unclear.

In this work, we systematically investigate the evolvement of surge current capability of vertical GaN-on-GaN PiN diode with varying t_{surge} (5 μs~10 ms) and I_{peak} up to 10 kA/cm², in which the role of photon- and thermally-enhanced conductivity modulation in direct-bandgap GaN has also been analyzed. Vertical GaN-on-GaN PiN diode exhibits enhanced conduction capability with hole injection and consequently anti-clockwise hysteresis in the double-sweep dynamic *I-V* curves which are extracted from surge current characterizations. The I_{peak}/t_{surge}-dependent surge current capability of vertical GaN-on-GaN PiN diode is attributed to photon- and thermally-enhanced conductivity modulation.

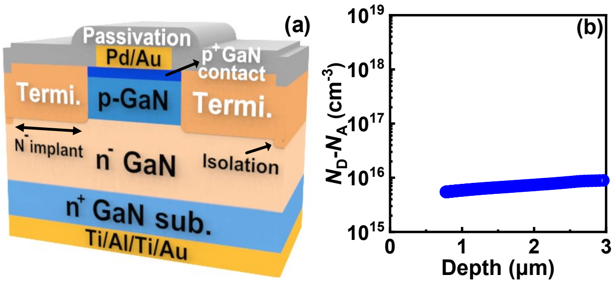

Fig. 1: (a) Schematic cross section of the vertical GaN-on-GaN PiN diode. (b) Net doping concentration (N_D-N_A) extracted from *C-V* measurements at 100 kHz in the n⁻ GaN drift layer.

II. Device Structure and Quasi-Static Performance

Fig. 1(a) shows the schematic cross section of the vertical GaN-on-GaN PiN diode, which primarily consists of Pd/Au anode, p⁺-GaN contact layer, 500-nm p-GaN layer, 15-μm n⁻-GaN drift layer, n⁺-GaN substrate, Ti/Al/Ti/Au cathode and nitrogen-implanted termination at the junction edge. The epitaxial structure was grown by metal-organic chemical vapor deposition. The net doping concentration (N_D-N_A) of the n⁻-GaN drift layer is ~6×10^{15} cm^{-3} (Fig. 1(b)), which is extracted from the *C-V* measurements at 100 kHz. The nitrogen-implanted termination can effectively suppress the electric field crowding at the junction edge and enhance the breakdown voltage up to ~2000 V in vertical GaN-on-GaN PiN diode.

Fig. 2(a) shows the forward *I-V* characteristics with the extracted specific differential R_{ON} ($R_{ON,sp}$) of the vertical GaN-on-GaN PiN diode. The calculated $R_{ON,sp}$ (Fig. 2(b)), consisting of contact resistance to p-GaN ($R_{C\_p\text{-}GaN}$), p-GaN

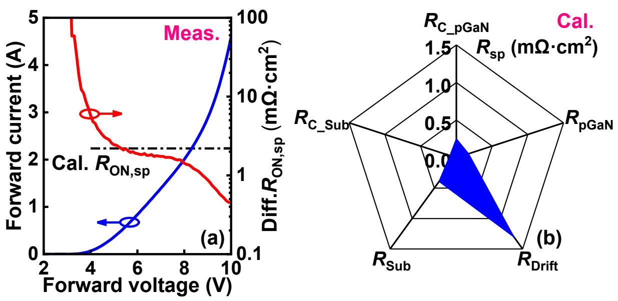

Fig. 2: (a) Measured *I-V* characteristics and corresponding differential $R_{ON,sp}$ of the vertical GaN-on-GaN PiN diode. (b) Calculated $R_{ON,sp}$ components.

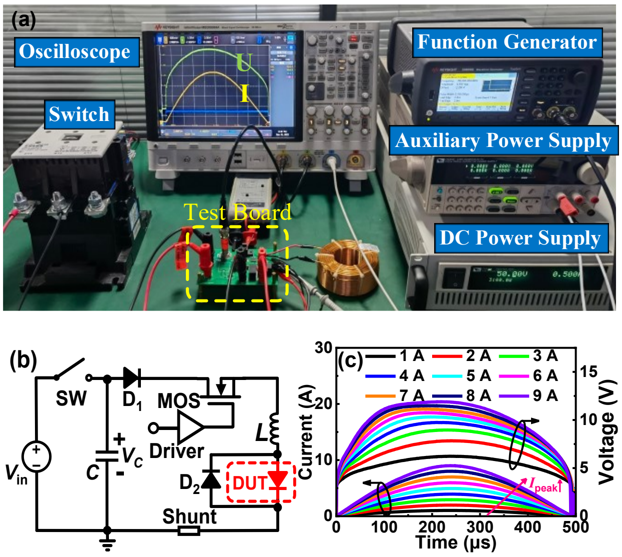

Fig. 3: (a) Characterization platform for surge current ruggedness evaluation. (b) Schematic of the PCB test board. (c) Surge current and voltage waveforms of the vertical GaN-on-GaN PiN diode.

resistance ($R_{p\text{-}GaN}$), drift layer resistance (R_{Drift}), substrate resistance (R_{Sub}) and contact resistance to substrate (R_{C_Sub}), is 2.2 mΩ·cm^2, in which the calculated R_{Drift} of ~1.3 mΩ·cm^2 occupies a relatively large portion. It is noteworthy that the measured $R_{ON,sp}$ (~0.45 mΩ·cm^2 at 4 A) is significantly lower than the calculated value, and continuously decreases with higher current, suggesting the desirable conductivity modulation in direct-bandgap GaN vertical PiN diode.

III. Surge Current Ruggedness

Fig. 3(a) and Fig. 3(b) show the platform and schematic circuit diagram for the surge current characterizations, respectively. The test board is based on *LC* resonance, mainly including a DC power supply, switch (SW), charge capacitor (C), MOSFET, driver circuit, load inductor (L), device under test (DUT) and coaxial current shunt. Firstly, the switch is on and MOSFET is off, whereby C is charged to the power supply voltage (V_{in}). When the MOSFET is turned on while the switch is off, the resonance can generate a half-sinusoidal surge current that flows into the DUT. The current and voltage waveforms of the DUT can be captured by current shunt and voltage probe, respectively. In order to investigate the evolvement and mechanisms of surge current capability in the vertical GaN PiN diode, t_{surge} is varying within 5 μs~10 ms whereas I_{peak} is increased up to 10 kA/cm^2, by adjusting *C*, *L* and capacitor voltage (V_C) according to Eqs. (1) and (2)

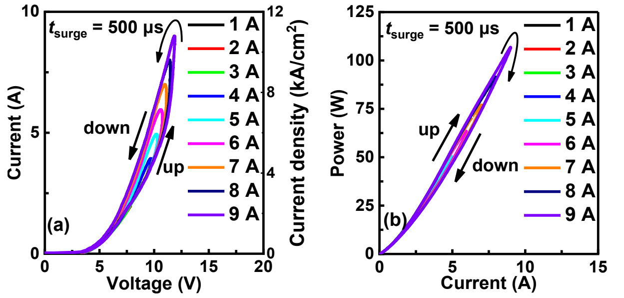

Fig. 4: (a) Double-sweep *I-V* and (b) *P-I* characteristics extracted from surge current tests with varying I_{peak} up to 9 A and t_{surge} of 500 μs.

$$t_{surge} = \pi \times \sqrt{C \times L} \tag{1}$$

$$I_{peak} = V_C \times \sqrt{\frac{C}{L}} \tag{2}$$

Fig. 3(c) shows the representative surge current and voltage waveforms, from which the corresponding forward *I-V* characteristics (Fig. 4(a)) with varying I_{peak} from 1 A up to 9 A (or 10 kA/cm^2) at a certain t_{surge} can be extracted. With t_{surge} of 500 μs, all the double-sweep *I-V* curves with I_{peak} varying from 1 A up to 9 A exhibit anti-clockwise hysteresis, which is a unique feature of the vertical GaN-on-GaN PiN diode and is distinct from that of Si and SiC devices [8]. Moreover, the down-sweep *I-V* continuously shifts toward the negative direction with higher I_{peak}, suggesting enhanced forward conduction with increased I_{peak}. Such enhanced forward conduction, yielding reduced forward voltage drop at a certain current in the down sweep than that in the up sweep, also leads to clockwise hysteresis in the double-sweep *P-I* characteristics (Fig. 4(b)). Such enhanced forward conduction capability with increased I_{peak} is correlated with the conductivity modulation in Fig. 2(a), which is desirable for enhanced surge current capability in vertical GaN power devices.

Fig. 5 shows the double-sweep *I-V* curves extracted from surge current tests with t_{surge} varying from 5 μs to 10 ms at a certain I_{peak} of 4 A, which can be primarily classified into two regimes according to the t_{surge}-dependent hysteresis evolvement: (I) With t_{surge} increasing from 5 μs to 100 μs, the initial anti-clockwise hysteresis gradually decreases and diminishes as the up-sweep *I-V* curves continuously shift towards the negative direction, possibly resulting from accumulated hole injection at longer t_{surge}, photon reabsorption/recycling and photon-enhanced conductivity

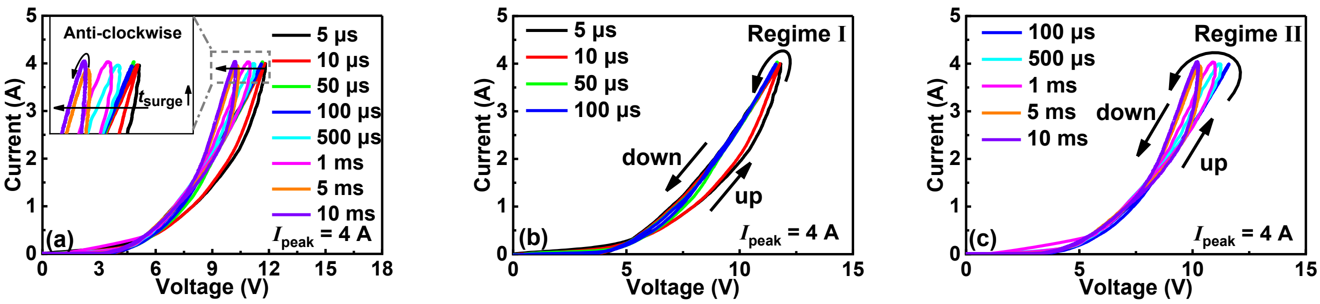

Fig. 5. *I-V* waveforms of surge current test with I_{peak} of 4 A and t_{surge} varying (a) from 5 μs to 10 ms, which is primarily classified into 2 regimes according to t_{surge}-dependent hysteresis evolvement: (b) t_{surge} from 5 μs to 100 μs, (c) t_{surge} from 100 μs to 10 ms.

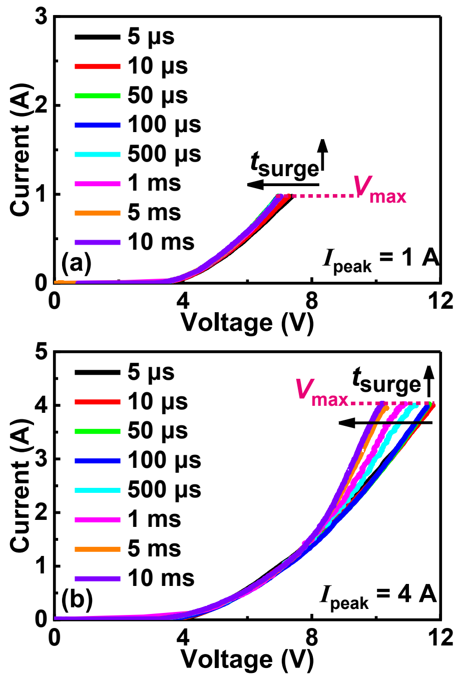

Fig. 6. Corresponding down-sweep *I-V* curves of surge current test with t_{surge} varying from 5 μs to 10 ms and I_{peak} of (a) 1 A and (b) 4 A.

modulation [3, 14]. (II) With t_{surge} increasing from 100 μs to 10 ms, the anti-clockwise hysteresis re-occurs as there is significant negative shift particularly in the down-sweep *I-V* curves, possibly stemming from modest self-heating at higher surge current and thermally-enhanced conductivity modulation thanks to the higher p-GaN activation that will be discussed in Section IV. In addition, the enhanced forward conduction capability with t_{surge} leads to a decrease in the required maximum voltage (V_{max}) at a certain I_{peak}, as the down-sweep *I-V* curves continuously shifting towards the negative direction particularly at longer t_{surge} in regime (II) (Fig. 5(c)) and higher current level (Fig. 6).

The surge current and voltage waveforms with a typical t_{surge} of 10 ms are shown in Fig. 7. Owing to the desirable conductivity modulation, a surge energy density of 282 J/cm^2 can be realized in the vertical GaN-on-GaN PiN diode with t_{surge} of 10 ms. The device failure possibly results from severe thermal accumulation at high current level [9, 10].

IV. Conductivity Modulation

Two possible mechanisms of photon-enhanced conductivity modulation in the vertical GaN-on-GaN PiN diode are illustrated in Fig. 8, which feature reabsorption of photons generated by the radiative recombination in the direct-bandgap GaN [14]. In agreement with the I_{peak}/t_{surge}-dependent surge current capability abovementioned, the higher intensity of hole injection at increased I_{peak} or hole accumulation with longer t_{surge}, leads to the photon-enhanced conductivity modulation.

On the other hand, self-heating during surge current characterizations and the impact of elevated junction temperature on the forward conduction of vertical GaN PiN diode, should also be considered. In general, the forward conduction capability of the unipolar diode would deteriorate at higher temperature due to phonon scattering and the reduced carrier mobility [10, 11, 15, 16]. By contrast, the vertical GaN-on-GaN PiN diode exhibits enhanced forward

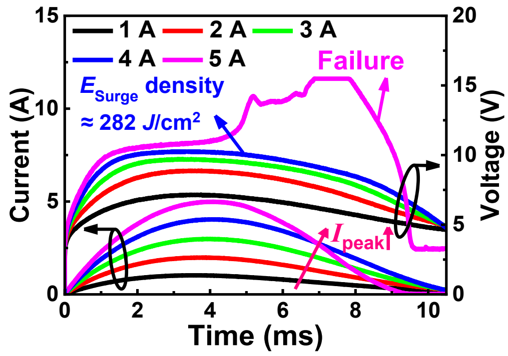

Fig. 7: Surge current and voltage waveforms of the vertical GaN-on-GaN PiN diode with t_{surge} of 10 ms and I_{peak} varying from 1 A and 5 A.

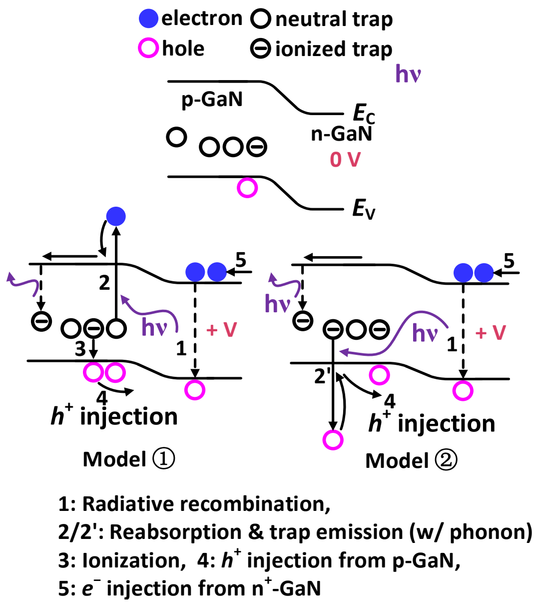

Fig. 8: Energy-band diagrams illustrating two possible photon-enhanced conduction mechanisms (reabsorption of the radiative recombination by the initially neutral or ionized traps in p-GaN) in GaN PiN diode.

conduction performance with higher I_{peak} and t_{surge} prior to device failure in this work, suggesting thermally-enhanced conductivity modulation. In fact, the sheet resistance (R_{Sh}) of p-GaN is reduced and the effective acceptor doping concentration (N_A-N_D) is increased with temperature rising from 25 °C to 150 °C (Fig. 9), verifying thermally-enhanced p-GaN activation that would facilitate hole injection and conductivity modulation. The thermally-enhanced p-GaN

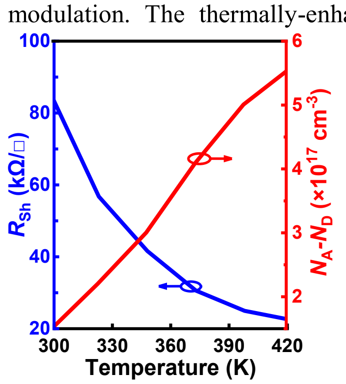

Fig. 9: Extracted sheet resistance (R_{Sh}) and effective acceptor concentration (N_A-N_D) in p-GaN as a function of temperature.

activation and hole injection is particularly correlated with the enhanced forward conduction performance at higher I_{peak} (Fig. 6(b)) or with longer t_{surge} (Fig. 5(c)). Owing to the desirable photon- and thermally-enhanced conductivity modulation, vertical GaN-on-GaN PiN diode can deliver superior surge current capability.

V. Conclusion

In this work, the evolvement of surge current capability in vertical GaN-on-GaN PiN diode with varying t_{surge} (5 μs~10 ms) and I_{peak} up to 10 kA/cm^2 has been systematically investigated, in which the role of conductivity modulation in direct-bandgap GaN is also analyzed and discussed. With longer t_{surge} and higher I_{peak}, vertical GaN-on-GaN PiN diode features anti-clockwise hysteresis in the double-sweep dynamic *I-V* characteristics extracted from surge current measurements. Thanks to the desirable photon- and thermally- enhanced conductivity modulation, the superior surge current ruggedness in direct-bandgap GaN vertical PiN diode show great potential in high power electronic applications.

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References

[1] H. Ohta, K. Hayashi, F. Horikiri, M. Yoshino, T. Nakamura, and T. Mishima, "5.0 kV Breakdown-Voltage Vertical GaN p–n Junction Diodes," *Jpn. J. of Appl. Phys.,* vol. 57, no. 4S, p. 04FG09, Feb. 2018.

[2] I. C. Kizilyalli, A. P. Edwards, H. Nie, P. Bui-Quang, D. Disney, and D. Bour, "400-A (Pulsed) Vertical GaN p-n Diode With Breakdown Voltage of 700 V," *IEEE Electron Device Lett.,* vol. 35, no. 6, pp. 654-656, Jun. 2014.

[3] S. Han, S. Yang, and K. Sheng, "Conductivity Modulation in Vertical GaN PiN Diode: Evidence and Impact," *IEEE Electron Device Lett.,* vol. 42, no. 3, pp. 300-303, Mar. 2021.

[4] S. Han, S. Yang, R. Li, X. Wu, and K. Sheng, "Current-Collapse-Free and Fast Reverse Recovery Performance in Vertical GaN-on-GaN Schottky Barrier Diode," *IEEE Trans. Power Electron.,* vol. 34, no. 6, pp. 5012-5018, Jun. 2019.

[5] R. J. Kaplar, B. P. Gunning, A. A. Allerman, M. H. Crawford, J. D. Flicker, A. M. Armstrong, L. Yates, A. T. Binder, J. R. Dickerson, G. Pickrell, P. Sharps, T. Anderson, J. Gallagher, A. Jacobs, A. Koehler, M. Tadjer, K.Hobart, M. Ebrish, M. Porter, R. Martinez, K. Zeng, D. Ji, S. Chowdhury, O. Aktas, and J. Cooper, "Development of High-Voltage Vertical GaN PN Diodes," in *IEDM Tech. Dig.,* Dec. 2020, pp. 5.1.1-5.1.4.

[6] A. Cuevas and D. Macdonald, "Measuring and Interpreting the Lifetime of Silicon Wafers," *Sol. Energy,* vol. 76, no. 1-3, pp. 255-262, Jul.2004.

[7] A. Salemi, H. Elahipanah, B. Buono, A. Hallén, J. U Hassan, P. Bergman, G. Malm, C. Zetterling, and M. Östling, "Conductivity Modulated On-axis 4H-SiC 10+ kV PiN Diodes," in *Proc. 27th Int. Symp. Power Semiconductor Devices ICs (ISPSD),* May/Jun. 2015, pp. 269-272.

[8] J. Wu, N. Ren, H. Wang, and K. Sheng, "1.2-kV 4H-SiC Merged PiN Schottky Diode With Improved Surge Current Capability," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 3, pp. 1496-1504, Sep. 2019.

[9] J. Liu, R. Zhang, M. Xiao, S. Pidaparthi, H. Cui, A. Edwards, L. Baubutr, C. Drowley, and Y. Zhang, "Surge Current and Avalanche Ruggedness of 1.2-kV Vertical GaN p-n Diodes," *IEEE Trans. Power Electron.,* vol. 36, no. 10, pp. 10959-10964, Oct. 2021.

[10] F. Zhou, W. Xu, F. Ren, D. Zhou, D. Chen, R. Zhang, Y. Zheng, T. Zhu, and H. Lu, "Demonstration of Avalanche and Surge Current Robustness in GaN Junction Barrier Schottky Diode With 600-V/10-A Switching Capability," *IEEE Trans. Power Electron.,* vol. 36, no. 11, pp. 12163-12167, Nov. 2021.

[11] S. Han, S. Yang, Y. Li, Y. Liu, and K. Sheng, "Photon-Enhanced Conductivity Modulation and Surge Current Capability in Vertical GaN Power Rectifiers," in *Proc. 31st Int. Symp. Power Semiconductor Devices ICs (ISPSD),* May/Jun. 2019, pp. 63-66.

[12] Q. Wei, F. Zhou, W. Xu, F. Ren, D. Zhou, D. Chen, R. Zhang, Y. Zheng, and H. Lu, "Demonstration of Vertical GaN Schottky Barrier Diode With Robust Electrothermal Ruggedness and Fast Switching Capability by Eutectic Bonding and Laser Lift-Off Techniques," *IEEE J. Electron Devices Society,* vol. 10, pp. 1003-1008, Nov. 2022.

[13] 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 pn Diodes with Avalanche Breakdown," *Appl. Phys. Lett.,* vol. 107, no. 24, p. 243501, Dec. 2015.

[14] K. Mochizuki, "Vertical GaN Bipolar Devices: Gaining Competitive Advantage From Photon Recycling," *Phys. Status Solidi A,* vol. 214, no. 3, p. 1600489, Sep. 2017.

[15] B. Heinze, J. Lutz, M. Neumeister, R. Rupp, and M. Holz, "Surge Current Ruggedness of Silicon Carbide Schottky- and Merged-PiN-Schottky Diodes," in *Proc. 20th Int. Symp. Power Semiconductor Devices ICs (ISPSD),* May/Jun. 2008, pp. 245-248.

[16] M. Xiao, B. Wang, J. Liu, R. Zhang, Z. Zhang, C. Ding, S. Lu, K. Sasaki, G. Lu, C. Buttay, and Y. Zhang, "Packaged Ga_2O_3 Schottky Rectifiers With Over 60-A Surge Current Capability," *IEEE Trans. Power Electron.,* vol. 36, no. 8, pp. 8565-8569, Aug. 2021.