# Switching Characterization of Vertical GaN PiN Diodes

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***Abstract*— The switching characteristics of vertical Gallium Nitride (v-GaN) diodes grown on GaN substrates are reported. v-GaN diodes were tested in a Double-Pulse Test Circuit (DPTC) and compared to test results for SiC Schottky Barrier Diodes (SBDs) and Si PiN diodes. The reported switching characteristics show that GaN diodes, like SiC SBDs, exhibit nearly negligible reverse recovery current compared to traditional Si PiN diodes. The reverse recovery for the v-GaN PiN diodes is limited by parasitics in the DPTC, precluding extraction of a meaningful recovery time. These results are very encouraging for power electronics based on v-GaN and demonstrate the potential for very fast, low-loss switching for these devices.**

***Keywords—Gallium Nitride; power diode; switching characterization; v-GaN; wide bandgap; reverse recovery***

## I. Introduction

The desire for size, weight, and power (SWaP) improvements in power conversion systems (PCS) has driven the use of wide bandgap (WBG) devices as a replacement for silicon (Si). Gallium nitride (GaN) and silicon carbide (SiC) devices have emerged as the most heavily utilized WBG power devices, and been developed and instituted to improve performance metrics in a variety of PCS applications. The relative immaturity of native GaN substrates has historically driven the development of GaN-on-Si and GaN-on-SiC solutions for power switching and RF devices, respectively. While this heteroepitaxial growth uses lower cost substrates than does GaN-on-GaN, these devices have suffered from high defect densities and have been limited to lateral device topologies (e.g. HEMTs). Difficulties in electric field management in lateral structures have limited GaN power devices to applications under approximately 600V, allowing SiC devices to be dominant in WBG power electronics high voltage applications [1, 2].

With the advent of higher quality, lower cost GaN substrates, new vertical device structures such as GaN diodes grown on GaN substrates form the basis of a compelling argument for high voltage GaN devices in power electronics. These new devices have been demonstrated to hold off 1200 V or more and have current carrying capability of 100 A [2], allowing for the possibility of their incorporation in high power applications. However, the performance and reliability of these devices is relatively unknown, with little reported in the literature on the metrics necessary for incorporation into PCS. In this paper, we report on the switching characteristics of v-GaN diodes in a realistic loaded switching environment and compare those results with a SiC SBD and a conventional Si diode.

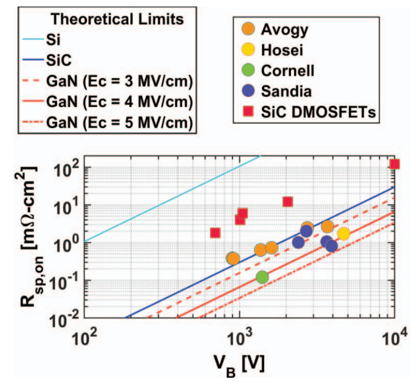


**Fig. 1. Unipolar FOM for different materials systems.**

### *A. Advantages of Vertical GaN*

As a material, GaN has favorable properties compared to Si and SiC, offering a better unipolar figure-of-merit (FOM), shown in Fig. 1 [3-6]. The higher bandgap of GaN means that GaN diodes can achieve higher breakdown voltage at lower on-resistance [3, 6]. This theoretical limit in device performance has been elusive in traditional lateral GaN devices, due partly to the necessary growth on non-native substrates such as sapphire, Si, and SiC. To improve power device performance, v-GaN device structures have emerged as competitors to both lateral GaN and SiC devices [9-11]. The v-GaN structure, which can be seen in Fig. 2, allows for higher breakdown voltage through the use of a thick, low-doped drift region coupled with appropriate edge termination to reduce field crowding. An additional advantage of v-GaN over lateral GaN is the robustness introduced by avalanche breakdown capability [8, 11].

### *B. Importance of Switching Characteristics*

In Si diodes, switching is the dominant loss mechanism, which has prompted numerous investigations dating back many decades into the reasons for these large switching losses [13, 14]. It is well-known that Si diodes experience a reverse recovery effect when switching from a conducting state to a blocking state. The reverse recovery period is typically defined as the time during which the diode current falls below 0 A before returning to 0 A [15]. In a minority-carrier device such as a PiN diode, the reverse recovery effect can be explained by

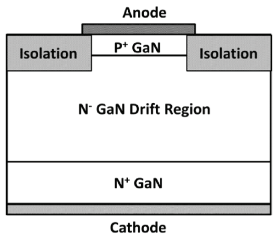


**Fig. 2. Schematic of v-GaN diode on native GaN substrate**

the minority carriers injected across the junction. When conducting current, the diode is flooded with minority carriers, which causes current to flow across the junction. When switching from conducting to blocking, the minority carriers present in the depletion region must be swept out via recombination, which is manifested as a reverse current [3, 16]. Although junction capacitance also contributes, for Si devices this minority-carrier recombination limits the reverse recovery time.

Shorter carrier lifetime decreases the reverse recovery effect significantly, so a GaN diode with very short minority-carrier lifetime could achieve significantly faster switching, and consequently would have much smaller switching loss [16, 17]. A similar effect can be realized by removing the p-n junction entirely, as is done in SBDs, which are majority-carrier devices [18, 19]. In majority-carrier devices, the reverse recovery period is dictated only by the capacitance of the Schottky junction.

Significantly, v-GaN PiN diodes are expected to be able to match a SiC SBD's switching capabilities, with the added benefits of having a better FOM, and being projected as cheaper to produce (on a per Amp basis) in the near future.

### *C. Avogy Vertical GaN Diodes*

Avogy Inc. has fabricated high-quality v-GaN diodes (AVD05120 series) that offer a true vertical structure, being grown on conducting GaN substrates. These PiN diodes consist of an $n^+$ region, an $n^-$ drift region, and a $p^+$ as well as the required edge termination structures, as shown in Fig. 2 [3, 11, 17]. The diodes are rated for 1200 V (reverse) and 100 A (forward, pulsed).

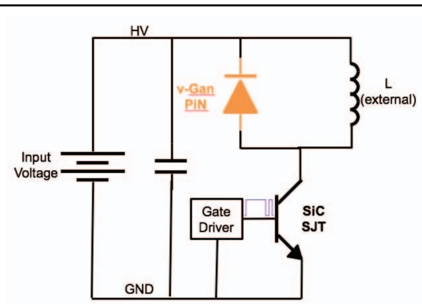


**Fig. 3. DPTC used to evaluate the switching characteristics of v-GaN diode as well as SiC SBD and conventional Si diode under loaded switching conditions**

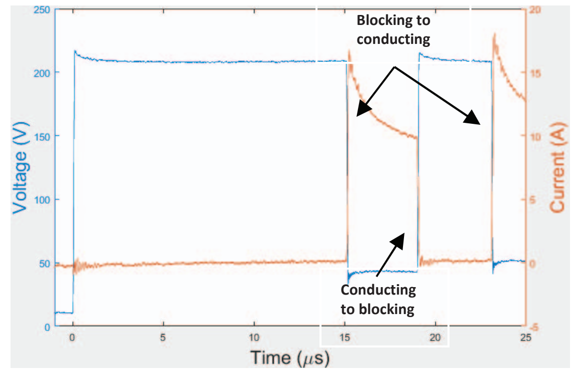


**Fig. 4. Diode voltage (blue trace) and current (red trace) measured during a DPTC switching event.**

## II. Experimental Setup & Results

The GaN diodes were evaluated using the DPTC shown in Fig. 3. This circuit is most often used to test transistors, but uses a diode to do so. Thus, switching the device under test from the transistor to the diode is a simple matter of measuring different signals within the circuit. In this case, four signals were measured - the input voltage, $V_{in}$; the transistor voltage, $V_{DS}$; the transistor current, $I_{DS}$; and the diode current, $I_D$. From these measured quantities, the diode voltage, inductor current, diode power, and transistor power signals were calculated. The diode voltage and inductor current waveforms were found using a simple application of Kirchoff's voltage and current laws, respectively.

The DPTC was driven by a long pulse of 15 µs followed by a short pulse of 4 µs. The two pulses were separated by a pause of 4 µs. The described pulse sequence is mirrored by the diode voltage shown in Fig. 4 (blue trace). This input allowed for the measurement of one conducting-to-blocking transition and two blocking-to-conducting transitions in the diode. The

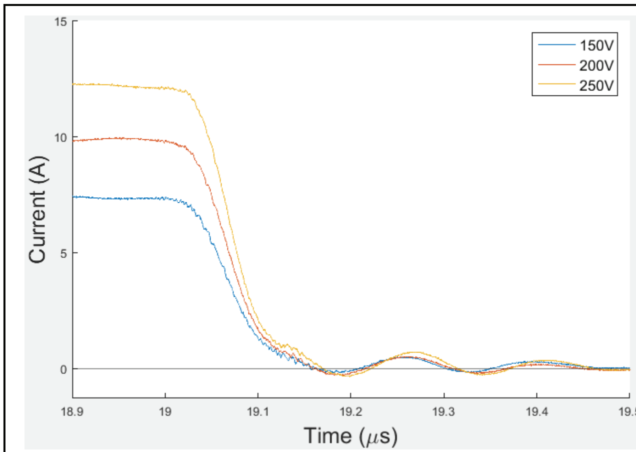


**Fig. 5. GaN PiN diode conducting-to-blocking transition during DPTC test at various $V_{in}$ values. The current traces show a distinct lack of reverse recovery. Additionally, the switching transition is independent of $V_{in}$.**

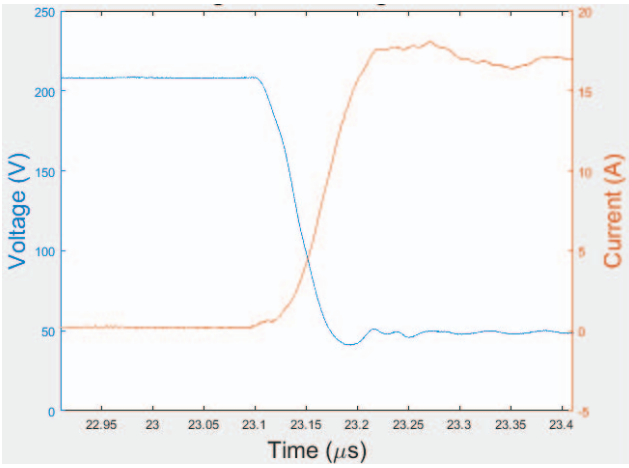


**Fig. 6. GaN PiN diode blocking-to-conducting transition voltage and current traces, at $V_{in}$ = 200 V.**

conducting-to-blocking transition is of primary interest here because it is the transition that is dictated by the reverse-recovery process. Fig. 5 shows the diode current waveform zoomed into on the region where the reverse recovery period is expected. However, the waveform displays no evidence of a reverse recovery effect; instead, there is just a transient ripple in the current after it falls. This apparent absence of a reverse-recovery effect in the v-GaN diode is similar to the behavior of SiC SBDs. Further examination of this conducting-to-blocking transition (Fig. 5) reveals a consistent switching time of around 70 ns, and the same inspection of blocking-to-conducting transitions (Fig. 6) reveals switching times of around 100 ns, although this is limited by circuit parasitics as opposed to the intrinsic properties of the device, since GaN devices are expected to have carrier lifetimes on the order of single nanoseconds [20]). The lack of an apparent reverse-recovery period was investigated further by testing the diodes at different input voltages. The results of these tests can also be seen in Fig. 5 and indicate that the input voltage of the DPTC does not significantly affect the reverse recovery in v-GaN PiN diodes.

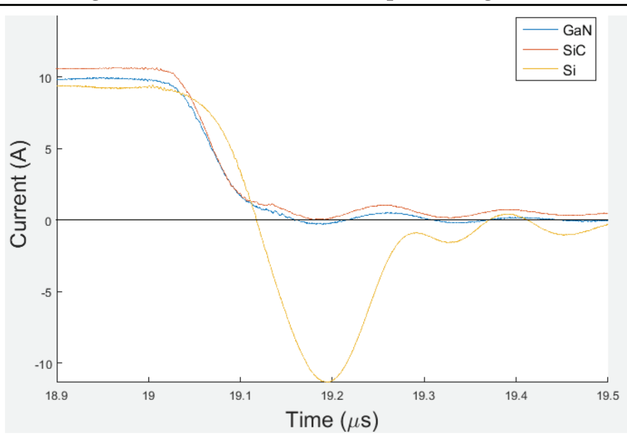


**Fig. 7. Conducting-to-blocking for v-GaN PiN diodes, SiC Schottky SBDs, and Si diodes. The SBD and v-GaN diodes show negligible reverse recovery while the Si diode shows a distinct reverse recovery region.**

Once the effect of varying input voltage on the GaN diode behavior was fully investigated, the diode behavior was compared to that of Si diodes and SiC SBDs, which were subjected to the same tests as the GaN diode. The reverse recovery characteristic of each diode is shown in Fig. 7, with Si having an obvious reverse recovery effect, and the SiC SBD and the v-GaN PiN both showing negligible reverse recovery.

## III. Conclusion

As shown by the data in Fig. 7, the reverse recovery period is dominated by circuit parasitics for both the v-GaN diode and the SiC SBD. The SiC and GaN diodes also shared very consistent switching times between different input voltage levels. These similarities, combined with v-GaN's insensitivity to changes in input voltage (Fig. 5) indicate that this new type of GaN diode has potential for use in high voltage switching applications.

It is extremely important to realize that the results presented herein are largely qualitative, and show primarily that v-GaN switching time is comparable to SiC SBD switching time. The exact numbers for v-GaN's switching characteristics cannot be determined using a basic test circuit like the DPTC, because the intrinsic switching time of the device is masked by circuit parasitics. Nevertheless, the results indicate that GaN has a future in high voltage applications and can provide fast, low-loss switching in power electronics.

## IV. Future Work

To further evaluate the potential for v-GaN devices in high-voltage switching applications, additional work must be done. First, it is critical to identify the causes for the RC transients in the DPTC (evident in Fig. 4), and find a way to reduce these parasitics so that the reverse recovery characteristics can be better observed and quantified. It is also important to adapt the DPTC to handle higher voltages, so that switching characterization can be done at the voltages for which the v-GaN devices are rated. The DPTC is a natural testing circuit for transistors, so similar characterization may in the future be applicable to vertical GaN transistors, which are in development but which are less mature than the diodes.

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## References


[1] R. Mitova, R. Ghosh, U. Mhaskar, D. Klikic, M. X. Wang, and A. Dentella, "Investigations of 600-V GaN HEMT and GaN Diode for Power Converter Applications," IEEE Transactions on Power Electronics, vol. 29, pp. 2441-2452, 2014.

[2] S. Coffa, M. Saggio, and A. Patti, "SiC- and GaN-based power devices: Technologies, products and applications," in 2015 IEEE International Electron Devices Meeting (IEDM), 2015, pp. 16.8.1-16.8.5.

[3] I. C. Kizilyalli, A. P. Edwards, O. Aktas, T. Prunty, and D. Bour, "Vertical Power p-n Diodes Based on Bulk GaN," IEEE Transactions on Electron Devices, vol. 62, pp. 414-422, 2015.

[4] H. Ohta, N. Kaneda, F. Horikiri, Y. Narita, T. Yoshida, T. Mishima, *et al.*, "Vertical GaN p-n Junction Diodes With High Breakdown Voltages Over 4 kV," *IEEE Electron Device Letters,* vol. 36, pp. 1180-1182, 2015.

[5] Z. Hu, K. Nomoto, B. Song, M. Zhu, M. Qi, M. Pan, *et al.*, "Near unity ideality factor and Shockley-Read-Hall lifetime in GaN-on-GaN p-n diodes with avalanche breakdown," *Applied Physics Letters,* vol. 107, p. 243501, 2015.

[6] 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 Letters, vol. 35, pp. 247-249, 2014.

[7] A. M. Armstrong, A. A. Allerman, A. J. Fischer, M. P. King, M. S. v. Heukelom, M. W. Moseley, *et al.*, "High voltage and high current density vertical GaN power diodes," *Electronics Letters,* vol. 52, pp. 1170-1171, 2016.

[8] I. C. Kizilyalli, P. Bui-Quang, D. Disney, H. Bhatia, and O. Aktas, "Reliability studies of vertical GaN devices based on bulk GaN substrates," Microelectronics Reliability, vol. 55, pp. 1654-1661, 2015.

[9] M. Meneghini, G. Meneghesso, I. Rossetto, J. Bartholomeus, F. Rampazzo, C. D. Santi, *et al.*, "Field-dependent degradation mechanisms in GaN-based HEMTs," in *2016 IEEE 23rd International Symposium on the Physical and Failure Analysis of Integrated Circuits (IPFA)*, 2016, pp. 77-80.

[10] D. Disney, H. Nie, A. Edwards, D. Bour, H. Shah, and I. C. Kizilyalli, "Vertical power diodes in bulk GaN," in *2013 25th International Symposium on Power Semiconductor Devices & IC's (ISPSD)*, 2013, pp. 59-62.

[11] H. Nie, Q. Diduck, B. Alvarez, A. P. Edwards, B. M. Kayes, M. Zhang, et al., "1.5-kV and 2.2-mΩ-cm$^2$ Vertical GaN Transistors on Bulk-GaN Substrates," IEEE Electron Device Letters, vol. 35, pp. 939-941, 2014.

[12] O. Aktas and I. C. Kizilyalli, "Avalanche Capability of Vertical GaN p-n Junctions on Bulk GaN Substrates," IEEE Electron Device Letters, vol. 36, pp. 890-892, 2015.

[13] W. Wei, F. Luo, C. Zhang, and Q. Shen, "Detection of reverse recovery characteristics of power diodes," IET Power Electronics, vol. 9, pp. 476-481, 2016.

[14] S. Jahdi, O. Alatise, L. Ran, and P. Mawby, "Accurate Analytical Modeling for Switching Energy of PiN Diodes Reverse Recovery," IEEE Transactions on Industrial Electronics, vol. 62, pp. 1461-1470, 2015.

[15] Vishay General Semiconductor, "Rectifiers: Application Note," Available: http://www.vishay.com/docs/84064/anphyexp.pdf.

[16] H. Benda and E. Spenke, "Reverse recovery processes in silicon power rectifiers," Proceedings of the IEEE, vol. 55, pp. 1331-1354, 1967.

[17] I. C. Kizilyalli, A. P. Edwards, H. Nie, D. Disney, and D. Bour, "High Voltage Vertical GaN p-n Diodes With Avalanche Capability," IEEE Transactions on Electron Devices, vol. 60, pp. 3067-3070, 2013.

[18] L. Efthymiou, G. Camuso, G. Longobardi, F. Udrea, E. Lin, T. Chien, et al., "Zero reverse recovery in SiC and GaN Schottky diodes: A comparison," in 2016 28th International Symposium on Power Semiconductor Devices and ICs (ISPSD), 2016, pp. 71-74.

[19] V. P. Galigekere and M. K. Kazimierczuk, "Effect of SiC schottky and Si junction diode reverse recovery on boost converter," in 2007 Electrical Insulation Conference and Electrical Manufacturing Expo, 2007, pp. 294-298.

[20] Daniel L. Mauch, Fred J Zutavern, Jarod J. Delhotal, Michael P. King, Jason C. Neely, Isik C. Kizilyalli, et al., "Ultra-Fast Reverse Recovery Measurement for Wide-Bandgap Diodes," 2016 (Submitted IEEE Transactions on Power Electronics).