Proceedings of the 30th International Symposium on Power Semiconductor Devices & ICs
May 13-17, 2018, Chicago, USA

Enhancement of Punch-through Voltage in GaN with Buried P-type Layer Utilizing Polarization-induced Doping

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***Abstract*—The effect of polarization induced (PI)-doping in GaN buried p-type layer on reverse blocking is studied for the first time. Forward and reverse I-V characteristics is measured on n-p-n diodes. With PI-doping in the buried p-type layer, the reverse punch-through voltage increases from 30 V to 240 V, even with hydrogen passivating the Mg acceptors, indicating the unique advantage of PI-doping on reverse blocking. The enhanced punch-through voltage is attributed to the polarization fixed charge in the p-layer, which is extracted to be ~1.3×10^{17} cm^{-3} and closely matched with the expected value of 1.4×10^{17} cm^{-3}. Vertical trench-MOSFETs with a breakdown voltage of 225 V are also demonstrated on the same sample.**

Keywords—GaN; polarization-induced doping; buried p-GaN; punch-through; MOCVD; vertical transistors

I. INTRODUCTION

With the availability of high quality GaN bulk substrate, GaN vertical transistors have seen rapid development in recent years, demonstrating high breakdown voltage and low on-resistance in several device designs [1-9]. GaN vertical power transistors possess unique advantages over the lateral HEMTs including higher power density, better reliability and thermal management. Buried p-type body region is prevalent in GaN vertical power transistors, providing important capabilities including reverse blocking, avalanche and RESURF (reduced surface field). It is well-known that p-GaN gets passivated due to the hydrogen present during epitaxial growth by metal-organic chemical vapor deposition (MOCVD), and requires an post-growth activation process to activate the Mg acceptors. The activation process can be realized at an elevated temperature over 700°C [10], where the Mg-H bonds is broken and H is driven out of the p-GaN surface by diffusion process. The activation of p-GaN is well-established with exposed p-GaN surface, however, it is extremely difficult for buried p-GaN [11], since the hydrogen atoms cannot go through the n-type layers above the buried p-GaN due to much lower diffusivity in n-GaN than in p-GaN. To achieve activation, the surface of the buried p-GaN needs to be exposed during the activation, which posts challenges in the design and fabrication of the vertical GaN transistors.

Polarization-induced (PI) doping is a unique doping scheme in GaN material system, offering advantages such as fully activated dopants independent of temperature [12] and increased breakdown field with the introduction of Al. Different from the p-type doping technique using Mg impurities, PI-doping technique introduces fixed polarization charge to induce mobile holes, thus immune to hydrogen passivation. PI-doped p-type layer in GaN material system has been demonstrated previously in the p-n diode platform using both molecular beam epitaxy (MBE) [12-14] and MOCVD [15] with decent reverse blocking capability. To our knowledge, no study on PI-doping in buried p-type structure has been reported. The utilization of PI-doped p-AlGaN buried body in vertical power transistors was proposed by our group [16] taking advantage of the higher critical field in AlGaN, but the advantage of the PI-doping regarding hydrogen passivation in MOCVD growth was not highlighted. In this work, we conduct the first study on the effect of PI-doping in buried p-type layer on reverse blocking. Much higher punch-though voltage is achieved with PI-doped buried p-type layer compared with the impurity-doped counterpart.

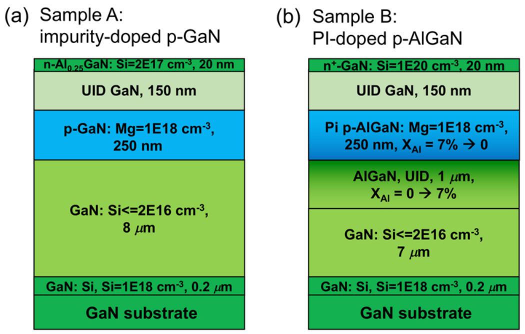

Fig. 1: Epitaxial structures of the buried p-GaN samples grown by MOCVD on bulk GaN substrate. (a) sample A: impurity-doped p-GaN (b) sample B: graded p-AlGaN with polarization-induced (PI) doping.

II. EXPERIMENTS

Two similar structures are designed without or with PI-doping in the buried p-type layer, as shown in Fig. 1. The epitaxial layers are grown by MOCVD at about 1050°C on two-inch Ga-polar bulk n-GaN substrates. On the impurity-doped sample A, the epitaxial structure has an 8 μm GaN: Si (Si: 1-2×10^{16} cm^{-3}) drift layer, followed by a 250 nm p-type GaN: Mg (Mg: 1×10^{18} cm^{-3}) layer, and then topped by a 150 nm unintentionally-doped GaN layer with a thin n-type cap. In the PI-doped sample B, the buried p-type AlGaN layer has a linearly graded Al content from 7% to 0% and the same Mg concentration as the impurity-doped sample. In order to avoid the formation of a heterojunction, the Al content is first graded linearly from 0% to 7% in the top 1 μm of the drift layer. The rest of the layers are the same as sample A. After growth, secondary ion mass spectroscopy (SIMS) is performed on sample A, as shown in Fig. 2. Low background impurity level is observed alongside with a high H concentration in the buried p-GaN layer, which suggests the passivation of the Mg dopants.

To access the voltage blocking capabilities of the buried p-type layer electrically, vertical n-p-n diodes are fabricated on both samples. The schematic cross-section of the diodes and the fabrication process flow is shown in Fig. 4. The fabrication process starts with mesa isolation by dry etch, followed by anode ohmic contact formation on the thin n-type capping layer and cathode ohmic contact formation on the back side of the substrate. Trench MOSFETs are also fabricated on sample B to further test the reverse blocking capability of the buried PI-doped p-type layer, as shown in Fig. 8.

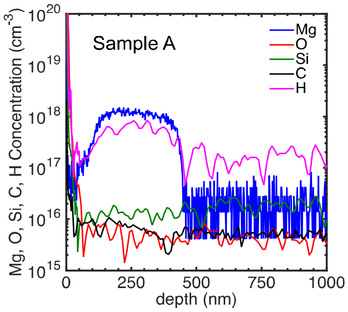

Fig. 2: SIMS profile of the various types of impurities in sample A. High level of H is present in the p-GaN layer, indicative of the passivation of Mg dopants.

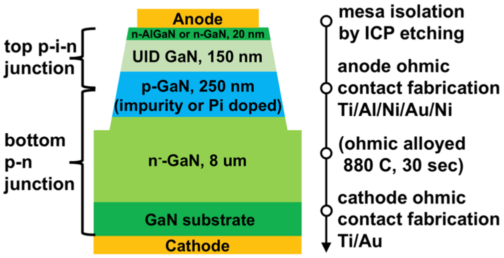

Fig. 3: Schematic cross-section of n-p-n diodes fabricated on both sample A and sample B. The process flow is indicated on the right.

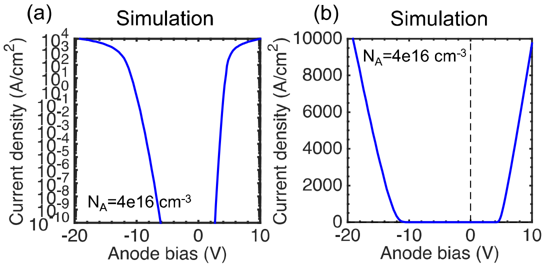

Fig. 4: Simulated I-V characteristics of the n-p-n diode using TCAD Sentaurus. The active N$_A$ in the p-type layer is set to be 4×10^{16} cm^{-3}. Punch-through behavior under forward and backward bias is clearly observed.

III. RESULTS AND DISCUSSION

To better understand the I-V characteristics of the n-p-n diodes at punch-through, the I-V characteristics is first simulated in TCAD Sentaurus as shown in Fig. 4, where the active acceptor concentration (N$_A$) in the buried p-GaN is set to be 4×10^{16} cm^{-3}. Since the i-GaN thickness is much thinner in the top p-i-n junction than the n-GaN thickness in the bottom p-n junction, the forward and reverse punch-through behavior of the diode is different. At the beginning of punch-through, the current increase exponentially, as can be seen in Fig. 4a. After punch-through, the I-V characteristics is linear, indicating a resistive behavior of the device, as shown in Fig. 4b. The punch-through voltage can be extracted at the onset of the resistive behavior, where the buried p-GaN is fully depleted.

The measured forward and reverse I-V characteristics of the n-p-n diodes on sample A and sample B is shown in Fig. 5 and Fig. 6, respectively. On each plot, the I-V curves of three typical devices are shown. The reverse punch-through voltages of the diodes on sample B are around 240 V, which is much higher than that of the sample A (~30 V), suggesting the effect of the PI-doping in boosting the punch-through voltage. The low punch-through voltages in the sample A indicate that the buried p-GaN is largely passivated. The reverse leakage current of the diodes on sample B does not show a tight distribution, likely due to the leakage through dislocation and process non-uniformity.

To understand the punch-through characteristics of the two samples, the extracted punch-through voltages at forward and

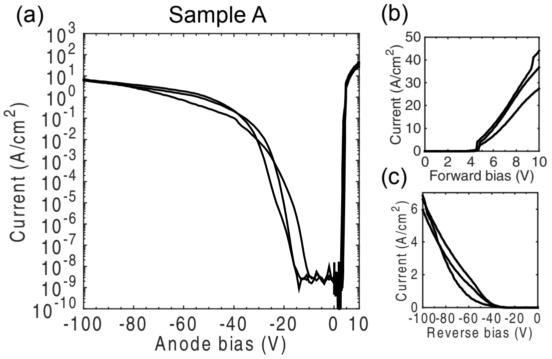

Fig. 5: Measured I-V characteristics of sample A. I-V curves of three typical devices are shown.

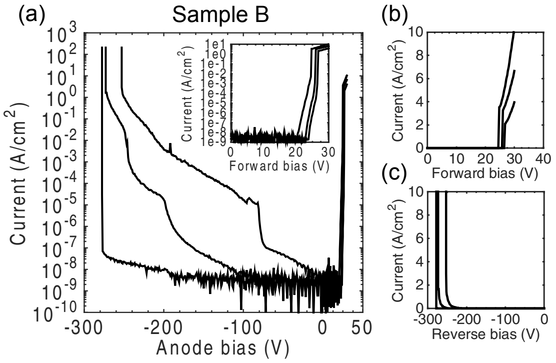

Fig. 6: Measured I-V characteristics of sample B. I-V curves of three typical devices are shown.

reverse bias are extracted on multiple devices and plotted on Fig. 7, alongside the data from simulation. The forward and reverse punch-through voltages are also calculated analytically, based on the electric field distribution when the p-type layer is fully depleted. As shown in Fig. 7, excellent agreement between the analytical calculation and the simulation is observed, validating the analytical calculation. The effective acceptor concentration, i.e. the total negative charge in the p-type layer at punch-through, is extracted for both samples by overlaying the extracted punch-through voltage on the analytical calculation. For the impurity-doped sample A, the active acceptor concentration is extracted to be ~6×10^{16} cm^{-3}. Since the total Mg concentration is 10^{18} cm^{-3} as determined from SIMS, most of the Mg dopants (~94%) is inactive, indicating strong hydrogen passivation in the buried p-GaN layer grown by MOCVD. In comparison, the total negative charge in the PI-doped sample B is extracted to be ~1.9×10^{17} cm^{-3}, which is ~1.3×10^{17} cm^{-3} higher than the sample A. According to the theoretical calculation [12], the polarization charge density in the buried graded p-AlGaN layer in sample is ~1.4×10^{17} cm^{-3}. This number is very close with the extracted net negative charge difference (~1.3×10^{17} cm^{-3}) between the two samples. Thus, it is reasonable to attribute the extra negative charge in the PI-doped sample to be the polarization fixed charge, assuming that similar percentage of the Mg dopants in the PI-doped sample B are passivated by hydrogen as in sample A (~94%). This is the first time the polarization charge is extracted from punch-through measurements in GaN.

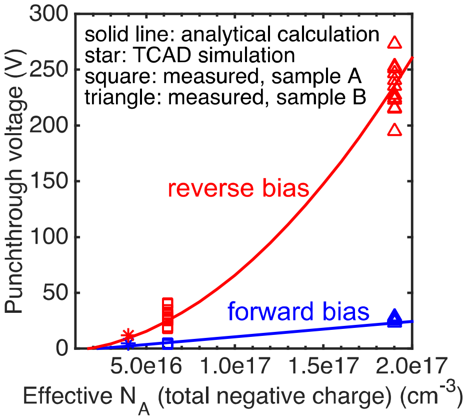

Fig. 7: Measured forward and reverse punch-through voltage of the n-p-n diodes. Solid lines are analytical calculation of the punch-through voltage. Stars shows the extraction from TCAD simulation under $N_A=4\times10^{16}$ cm^{-3}. Multiple devices on sample A and B are measured. Extracted N_A in sample A: 6×10^{16} cm^{-3}. Extracted total negative charge in sample B: 1.9×10^{17} cm^{-3}.

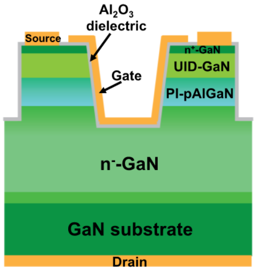

Fig. 8: Schematic cross-section of the vertical trench-MOSFETs fabricated on sample B.

On the other hand, the vertical trench-MOSFETs fabricated on sample B exhibit decent transistor behavior in the on-state, as shown in the transfer and output characteristics in Fig. 9 and Fig. 10, respectively. The 3-terminal reverse breakdown characteristics at V_{gs}=0 V is shown in Fig. 11. The transistor shows a breakdown voltage (BV) of 225 V, similar with the reverse bias punch-through voltage measured on the n-p-n diodes, indicating that the breakdown mechanism is due to the

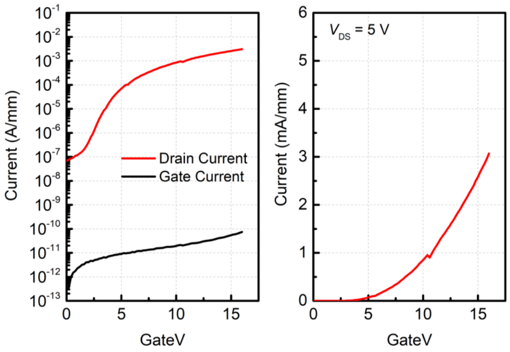

Fig. 9: Transfer characteristics of the trench-MOSFETs on sample B.

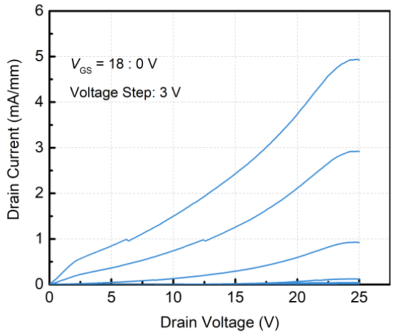

Fig. 10: Output characteristics of the trench-MOSFETs on sample B.

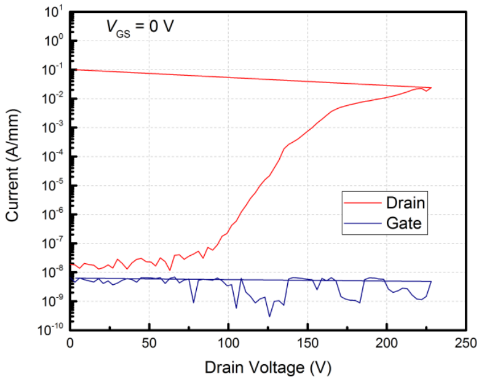

Fig. 11: 3-terminal breakdown characteristics of the trench-MOSFETs measured at V_{gs}=0 V. Measured BV=225 V.

punch-through of the buried PI-doped p-type layer. Although the BV is not very high, it highlights the unique advantage and potential offered by the PI-doping in enhancing the breakdown voltage in buried p-type structure, especially when the passivation of Mg dopants is present.

IV. CONCLUSIONS

The effect of polarization induced (PI)-doping in GaN buried p-type layer on reverse blocking is studied. N-p-n diodes are fabricated on MOCVD-grown buried p-type epitaxial structures with or without PI-doping in the p-type layer. The n-p-n diodes with only impurity doping in the buried p-GaN have a reverse punch-through voltage of ~30 V, correspond to only ~6% active Mg acceptors due to hydrogen passivation. In comparison, the n-p-n diodes with PI-doping have a much higher reverse punch-through voltage of 240 V. Aided by simulation and analytical calculation, an extra negative charge density of ~1.3×10^{17} cm^{-3} is extracted in the PI-doped p-type layer, which is attributed to the polarization fixed charge. Vertical trench-MOSFETs with a breakdown voltage of 225 V are also demonstrated on the PI-doped sample. The results indicate the unique advantage of utilizing PI-doping technique in GaN buried p-type layer: respectable enhancement in punch-through voltage can be achieved irrespective of Mg passivation due to hydrogen, which could benefit the design of a wide variety of GaN vertical power devices.

ACKNOWLEDGMENT

This work was supported in part by the ARPA-E SWITCHES program (DE-AR0000454) monitored by Tim Heidel and Isik Kizilyalli and carried out at the Cornell Nanoscale Science and Technology Facilities (CNF) sponsored by the NSF NNCI program (ECCS-15420819) and New York State.

REFERENCES

[1] S. Chowdhury, M. H. Wong, B. L. Swenson, and U. K. Mishra, “CAVET on bulk GaN substrates achieved with MBE-regrown AlGaN/GaN layers to suppress dispersion”, IEEE Electron Device Letters, vol. 33, no. 1, pp. 41-43, 2012.

[2] 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 Letters, vol. 35, no. 9, pp. 939-941, 2014.

[3] T. Oka, T. Ina, Y. Ueno, and J. Nishii, “1.8 mΩ·cm^2 vertical GaN-based trench metal–oxide–semiconductor field-effect transistors on a free-standing GaN substrate for 1.2-kV-class operation”, Applied Physics Express, vol. 8, no. 5, p. 054101, 2015.

[4] R. Li, Y. Cao, M. Chen, and R. Chu, “600 V/1.7 Ω Normally-Off GaN Vertical Trench Metal–Oxide–Semiconductor Field-Effect Transistor”, IEEE Electron Device Letters, vol. 37, no. 11, pp. 1466-1469, 2016.

[5] D. Shibata, R. Kajitani, M. Ogawa, K. Tanaka, S. Tamura, T. Hatsuda, M. Ishida, and T. Ueda, 2016, December. “1.7 kV/1.0 mΩ·cm^2 normally-off vertical GaN transistor on GaN substrate with regrown p-GaN/AlGaN/GaN semipolar gate structure”, in IEEE International Electron Devices Meeting (IEDM), pp. 10-1, December 2016.

[6] W. Li, K. Nomoto, K. Lee, S. M. Islam, Z. Hu, M. Zhu, X. Gao, M. Pilla, D. Jena, and H. G. Xing, “600 V GaN vertical V-trench MOSFET with MBE regrown channel”, in Device Research Conference (DRC), 2017 75th Annual. IEEE, pp. 1-2, June 2017.

[7] Z. Hu, W. Li, K. Nomoto, M. Zhu, X. Gao, M. Pilla, D. Jena, and H. G. Xing, “GaN vertical nanowire and fin power MISFETs”, in Device Research Conference (DRC), 2017 75th Annual. IEEE, pp. 1-2, June 2017.

[8] M. Sun, Y. Zhang, X. Gao, and T. Palacios, “High-performance GaN vertical fin power transistors on bulk GaN substrates”, IEEE Electron Device Letters, vol. 38, no. 4, pp. 509-512, 2017.

[9] C. Gupta, C. Lund, S. H. Chan, A. Agarwal, J. Liu, Y. Enatsu, S. Keller, and U. K. Mishra, “In situ oxide, GaN interlayer-based vertical trench MOSFET (OG-FET) on bulk GaN substrates”, IEEE Electron Device Letters, vol. 38, no. 3, pp. 353-355, 2017.

[10] S. Nakamura, T. Mukai, M. Senoh, and N. Iwasa, “Thermal annealing effects on p-type Mg-doped GaN films”, Japanese Journal of Applied Physics, vol. 31, no. 2B, p. L139, 1992.

[11] W. Li, K. Nomoto, K. Lee, S. M. Islam, Z. Hu, M. Zhu, X. Gao, A. Xie, M. Pilla, D. Jena, and H. G. Xing, “Activation of buried p-GaN in MOCVD-regrown vertical structures”, unpublished.

[12] J. Simon, V. Protasenko, C. Lian, H. Xing, and D. Jena, “Polarization-induced hole doping in wide–band-gap uniaxial semiconductor heterostructures”, Science, vol. 327, no. 5961, pp.60-64, 2010.

[13] S. Li, M. Ware, J. Wu, P. Minor, Z. Wang, Z. Wu, Y. Jiang, and G. J. Salamo, “Polarization induced pn-junction without dopant in graded AlGaN coherently strained on GaN”, Applied Physics Letters, vol. 101, no. 12, p. 122103, 2012.

[14] S. Li, T. Zhang, J. Wu, Y. Yang, Z. Wang, Z. Wu, Z. Chen, and Y. Jiang, 2013. “Polarization induced hole doping in graded $Al_xGa_{1-x}N$ (x=0.7~1) layer grown by molecular beam epitaxy”, Applied Physics Letters, vol. 102, no. 6, p. 062108, 2013.

[15] Y. Enatsu, C. Gupta, S. Keller, S. Nakamura, and U. K. Mishra, “P–n junction diodes with polarization induced p-type graded $In_xGa_{1-x}N$ layer”, Semiconductor Science and Technology, vol. 32, no. 10, p. 105013, 2017.

[16] H. G. Xing, B. Song, M. Zhu, Z. Hu, M. Qi, K. Nomoto, and D. Jena, “Unique opportunity to harness polarization in GaN to override the conventional power electronics figure-of-merits”, in Device Research Conference (DRC), 2015 73rd Annual. IEEE, pp. 51-52, June 2015.