High Voltage Vertical GaN p–n Diode With N_2O Sidewall Treatment on Free-standing GaN Wafer

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ABSTRACT

In this study, a vertical GaN PN diodes on free-standing (FS) GaN wafer was fabricated with N_2O plasma treatment at the anode interface, and it was compared with a conventional GaN p–n diode. The N_2O plasma provided N atoms to produce a native oxide-free interface. The fabricated diode demonstrated a reverse breakdown voltage of 2.3 kV and specific on-resistance of 3.13 mΩ.cm^2. The figure of merit of this diode was 1.76MW/cm^2. These results were superior to those of the conventional GaN p–n diode. The reverse recovery time of the N_2O-treated vertical GaN p–n diode was 17.6 ns. Moreover, the Ron,D/Ron,S ratio decreased to 20.1 relative to that of the conventional diode, suggesting that the N_2O plasma treatment improved the surface states of N-vacancies.

INTRODUCTION

Gallium nitride (GaN)-based power diodes, such as Schottky barrier diodes and p–n diodes, are attractive because of their high power and high voltage performance. Conventional GaN power devices have been grown on various substrates such as Si and SiC substrates. However, the high defect density of these materials considerably limits the device performance [1]. Recently, vertical GaN p–n power diodes grown on bulk GaN substrates with a low defect density of $<10^6$ cm^{-2} have been demonstrated to have high breakdown voltage and low on-resistance levels [2]–[4].In this study, a high-performance vertical GaN p–n diode was fabricated with the surface subjected to N_2O plasma treatment to reduce the N-vacancy surface states. This diode was compared with a conventional diode in terms of performance. Experimental results revealed that the N_2O-treated diode exhibited better reverse breakdown voltage, specific on-resistance, and figure of merit (FOM) compared with the conventional GaN p–n diode.

DEVICE FABRICATION

The epi structure of the GaN p–n diode is shown in Fig. 1. The top layer comprised a 30-nm p++ GaN (Mg: 2×10^{20} cm^{-3}) contact layer, a 400-nm p-GaN (Mg: 1×10^{18} cm^{-3}) layer, a 13-μm N^- GaN drift region with a target Si doping concentration of 1.2×10^{16} cm^{-3}, and a 2-μm N^+ GaN buffer layer (Si: 2×10^{18} cm^{-3}) on a bulk GaN substrate, all grown by metalorganic vapor phase epitaxy. The p-type GaN layer had a hole concentration of 6.32×10^{16} cm^{-3} with a mobility of 29.2 cm^2/V·s at 25 °C, as determined by Hall effect measurements. The schematic cross sections of the fabricated GaN diode with a field plate (FP) are illustrated in Fig. 1. The FP was formed by extending a metal layer over the entire mesa of the diode covered by SiO_2 and spin-on-glass (SOG) to reduce the reverse leakage current and thereby improve the breakdown voltage.

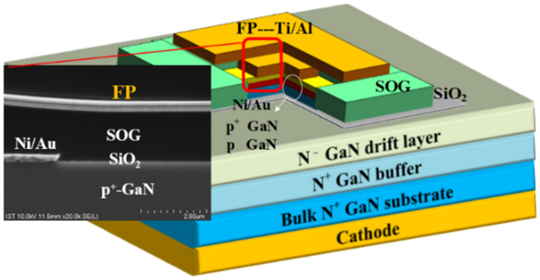

Fig. 1. GaN p–n diode structure and device cross section.

In the fabrication process, $BCl_3 + Cl_2$ and Ar plasma dry etching was first performed at a reactive-ion etching power of 300 W, and a pressure of 100 mTorr was used to define the mesa. After the mesa isolation process, the surface of sample B was treated using N_2O plasma. The device size of the diode mesa was 500 μm×500 μm. The Ni/Au (30/130 nm) contact was alloyed through rapid thermal annealing at 600 °C forming square anodes on the p++ GaN layer. Subsequently, a 200-nm SiO_2 and a 1.5-μm SOG film were coated and cured at 400 °C for 30 min. Contact holes were wet etched and followed by a Ti/Al stack to form the FP structure. Finally, a Ti/Al/Ni/Au (40/150/30/130 nm) electrode was evaporated on the back surface of the GaN substrate as a back-side cathode contact.

DEVICE RESULTS AND DISCUSSION

X-ray photoelectron spectroscopy (XPS) was performed to determine the origin of interface traps after the fabrication of a recess structure on the separate samples. The interface of the vertical GaN p–n diode was determine to verify whether the N_2O treatment could produce a native oxide-free interface. Fig. 2 shows the XPS energy spectrum for the conventional GaN p–n diode. The Ga2p3 signal was split into two peaks representing Ga–N and Ga–O bonds. For the conventional device, peaks were observed at 1118 and 1116.8 eV, corresponding to the Ga–N and Ga–O bonds, respectively [5]. For the N_2O-treated device, peaks were located at 1117.9 and 1116.8 eV, corresponding to Ga–N and Ga–O bonds, respectively [5]. Moreover, the difference in binding energy between the Ga–O and Ga–N bonds was 1.1 eV, which is in good agreement with that in a previous study [6]. The peak intensity of the Ga–N bond increased in the N_2O-treated sample, demonstrating that N atoms produce a native oxide-free interface.

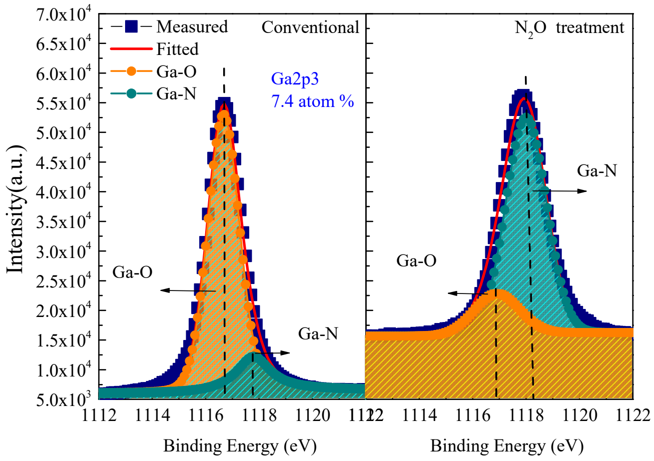

Fig. 2. XPS spectra of the interface of the two diodes.

Fig. 3 shows the forward-bias I–V characteristics of the two devices at 300 and 500 K. The size of the anode was 1600 μm^2. Fig.3(a) shows the turn-on voltages of the GaN p–n diode at 300 K were approximately 3.6V and 4.1 V, as expected because of the diffusion potential of the GaN p–n junction. When the temperature was increased to 500 K, the turn-on voltage of the GaN p–n diode was the same as that at 300 K. However, the forward current of the two devices were decreased due to the thermal issue. The forward current decreased about 5% and 14% for the N_2O treatment and conventional GaN p–n diode,respectively. This indicates that the N_2O treatment improved the thermal stability of the GaN p–n diode. Fig.3 (b) shows the the Ron values at forward voltage 5V were 3.13 for the N_2O-treated p–n diode and 5.7 mΩ·cm^2 conventional p–n diode.

The reverse breakdown voltage characteristics of the vertical p–n diodeswith N_2O treatment and conventional untreated are shown in Fig. 4. The two samples were measured at room temperature on-wafer by using an Agilent B1505.

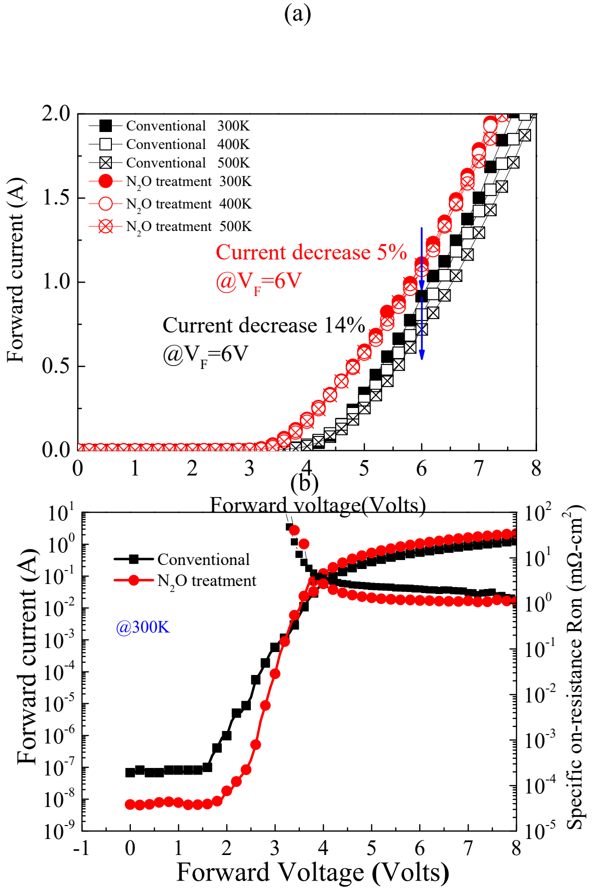

Fig. 3. (a)Forward-bias I–V characteristics and (b)specific on-resistance of the two GaN p–n diodes from 300K to 500 K.

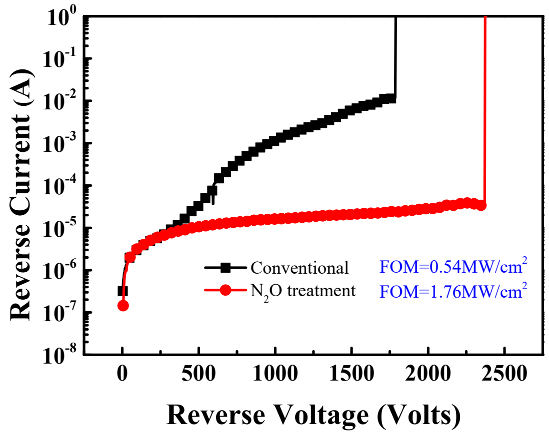

Fig. 4. Reverse I–V characteristics of GaN p–n diode.

The N_2O treatment resulted in a marked improvement in the reverse leakage and a breakdown voltage exceeding 1.7 kV in the vertical GaN p–n diode. To our knowledge；this is the highest breakdown voltage achieved in vertical GaN p-n diodes. Furthermore, using N_2O treatment for suface and also effecting edge termination resulted in a breakdown voltage approaching 2.3 kV. A slightly higher leakage was observed at a higher reverse bias (>500 V), and this was most likely engendered by the leakage path induced by the N_2O treatment. For the N_2O-treated diode, combining a *BV* of 2.3 kV and *Ron* of 3.13 mΩ·cm^2 resulted in a higher FOM (VB^2/Ron) of approximately 1.76MW/cm^2. For the conventional p–n diode, combining a *BV* of 1.7 kV and Ron of 5.7 mΩ·cm^2 resulted in an FOM (VB^2/Ron) of approximately 0.54MW/cm^2. [7]. This confirms that the N_2O treatment effectively could suppress electric field crowding at the edge.

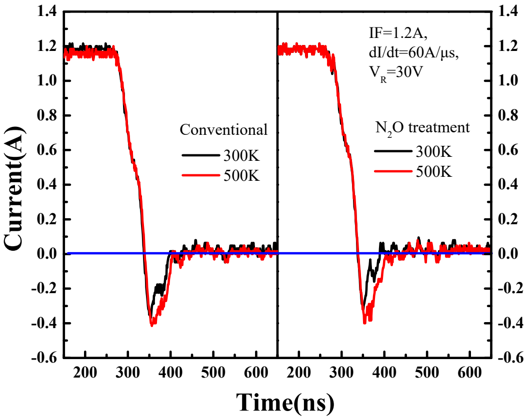

Fig. 5. Reverse recovery characteristics of both devices.

An oscilloscope plot of the diode current versus time was created. Because the reverse recovery time of a vertical GaN p–n diode is limited by capacitance rather than minority carrier storage, its performance is considerably superior to that of a high-speed silicon diode. The reverse recovery characteristics of the GaN p–n diodes were measured under the same conditions of IF = 1.2 A, di/dt = 60A/µs, and VR = 30 V (Fig. 5). The two samples were measured at 300 and 500 K. The reverse recovery process is related to the minority carrier extraction process when the diode is switched from on-state to off-state. The diffusion length of minority carrier hole (electron) in the n-region (p-region) of gallium nitride PN diodes is strongly temperature-dependent, and becomes longer with increasing the temperature, which results in increasing the diffusion capacitance of minority carrier hole (electron) in the n-region (p-region) of gallium nitride PN diodes. This explains the longer reverse recovery time (Trr) observed under high temperature, owing to the large minority carrier diffusion capacitance. The peak reverse recovery currents of the conventional p–n diode were −0.36 ,–0.45 A at 300K and 500K, respectively, N_2O-treated diode were –0.32 and −0.39 A for 300K and 500K, respectively. The reverse recovery times of the conventional p–n diode were 22.8ns and 17.6 ns, and the N_2O-treated diode were 21.2 and 23.6ns.

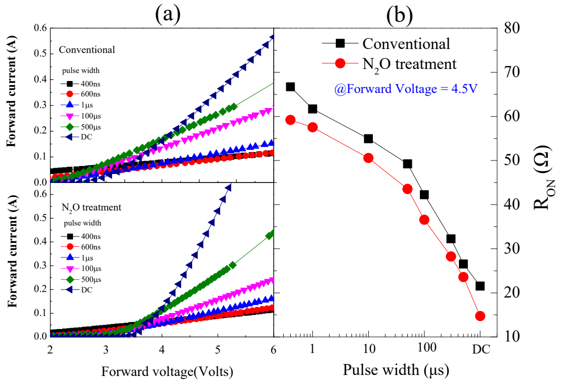

Fig. 6. Pulse current and Ron of the devices.

Fig.6 (a)shows the pulsed current-voltage of the fabricated vertical GaN p-n diode and R_{on} characteristics of the two diodes. The pulse current were measured using an AMCAD pulse measurement system. The measurement pulse width was from 400 µs to 1000 µs(DC). Fig.6 (b) shows the values of the on-resistance R_{on} for the two GaN p–n diodes. Because of the instrument's capability, R_{on} could be accurately measured after 400 ns. The N_2O plasma treatment effectively suppressed the current collapse. The R_{on} of the N_2O-treated GaN p–n diode at pulse width 400ns was 59.2Ωand the conventional p–n diode was 66.6Ω. This demonstrates reduction of surface state traps related to N-vacancies for N_2O treated samples.

CONCLUSION

A GaN p–n diode grown on a bulk GaN substrate with N_2O plasma treatment exhibited improved reverse breakdown voltage and on-resistance. Additionally, N_2O-treated vertical GaN p–n diode fabricated on bulk GaN exhibited a breakdown voltage of 2.3 kV and specific on-resistance of 3.13mΩ·cm^2. The pulse R_{on} of pulse width was 59.2Ω, suggesting that the N_2O plasma treatment improved surface states of the N-vacancies.

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ACRONYMS

FOM:figure of merit
SOG :spin-on-glass
XPS: X-ray photoelectron spectroscopy
Trr: reverse recovery time