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ABSTRACT
This paper reports on a high-voltage vertical GaN Schottky barrier diode (SBD) using fluorine (F) ion implantation treatment. Compared with the GaN SBD without F implantation, this SBD effectively enhanced the breakdown voltage from 155V to 775V and significantly reduced the reverse leakage current by $10^5$ times. These results indicate that the F-implanted SBD showed improved reverse capability. In addition, a high $I_{on}/I_{off}$ ratio of $10^8$ and high Schottky barrier height of 0.92 eV were also achieved for this diode with F implantation. The influence of F ion implantation in this SBD was also discussed in detail. It was found that F ion implantation to GaN could not only create a high-resistant region as effective edge termination but be employed for adjusting the carrier density of the surface of GaN, which were both helpful to achieve high breakdown voltage and suppress reverse leakage current. This work shows the potential for fabricating high-voltage and low-leakage SBDs using F ion implantation treatment.

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Gallium Nitride (GaN) power devices have attracted worldwide attention due to the huge potential for high voltage and high power application.1 Recently, due to the breakthrough of bulk GaN growth, there has been a chance for GaN power devices to be grown homoepitaxially, which accelerates the progress of vertical GaN devices.2 Compared to lateral devices, achievements can be realized easier in vertical devices including high power in small size, superior thermal management and high reliability.3

With the merits of low turn-on voltage and high-speed switching, vertical GaN Schottky barrier diodes (SBDs) are highly desired for various high power application in electronic circuits. However, vertical GaN SBDs always suffer from high reverse leakage current and premature breakdown voltage. To solve the above challenges, one solution is to lower the doping concentration of drift layer.4–6 It has been known that reducing the doping concentration of the top drift layer could reduce the peak electric field at the junction and thus enhance the breakdown voltage. Although controlling the doping concentration of GaN epilayer has been realized to a certain extent by metalorganic chemical vapor deposition (MOCVD), the ultra-low doping concentration (about $10^{15}$ cm$^{-3}$ or below) is still hardly obtained restricted by growth condition.7–9 Another solution is to design effective edge termination.10–12 It has been found that electric field crowding occurs at the edge of Schottky contact, and edge termination technique could distribute electric field to achieve high breakdown voltage. In particular, ion implantation technique is a way to form guard rings or create high-resistance region to enhance reverse capability, and various groups have investigated implantation of different species.
(e.g. Mg, Ar, N and H) to be employed for GaN diodes. Compared with conventional SBD, Mg-implanted GaN rectifiers can obtain lower leakage current with breakdown voltage of 500-600V, while the efficiency of Mg activation is very low. The breakdown voltage for vertical GaN device can be effectively increased by Argon implant edge termination, while argon ions would also contribute to reverse leakage current. Meanwhile, fluorine (F) ion implantation technique has attracted great interests in AlGaN/GaN HEMT because F ion can deplete the 2DEG to form enhanced-mode AlGaN/GaN HEMT and improve the off-state breakdown voltage in AlGaN/GaN HEMT. This technique is also employed for active device isolation. In addition, the underlying physics and stability related with F ion implantation in GaN were also investigated by various groups. In this work, a vertical GaN SBD using F ion implantation treatment was fabricated. Compared with the GaN SBD without F ion implantation, this SBD showed significantly improved reverse capability. The SBD not only lowered the reverse current by about 5 orders of magnitude at high bias but also boosted the breakdown voltage from 155V to 775V. In addition, this SBD using F ion implantation treatment obtained a high $I_{on}/I_{off}$ ratio of $10^8$ and high Schottky barrier height of 0.92 eV.

Before device fabrication, an n'-GaN epilayer was grown on an n+ -GaN bulk substrate material ([Ge] = $10^{18}$ cm$^{-3}$) by hydride vapor phase epitaxy (HVPE) from Nanowin. Compared with Si-doped bulk GaN, Ge atoms is a shallow donor and would cause less lattice distortion. Ge-doped GaN substrate material is beneficial to further grow a smoother, fewer defects and lower stress epilayer. The GaN epilayer was analyzed by a series of characterization experiments, and the results were presented in Fig. 1. The doping concentrations of GaN epilayer were analyzed by secondary ion mass spectroscopy (SIMS) measurement shown in Fig. 1(a). The concentration of Si was about $10^{17}$ cm$^{-3}$, and the concentrations of C and O impurities were close to the detection limit. The surface morphology of the GaN epilayer was characterized by atomic force microscopy (AFM) shown in Fig. 1(b). The surface presented a typical step-flow morphology and the root-mean-square (RMS) roughness of a 10×10 µm$^2$ scanning area of the epilayer was 0.38 nm. The dislocation density of the GaN epilayer was 1.04×10$^6$ cm$^{-2}$, which was estimated by planar-sectional panchromatic cathodoluminescence (CL) images as shown in Fig. 1(c). The crystal quality was characterized by high-resolution X-ray diffraction (HRXRD). The rocking curves (RCs) of the (002) and the (102) plane of the GaN are represented in Fig. 1(d). The full width at the half maximum (FWHM) of the RCs were 39.2 and 52.6 arcsec for the (002) and the (102) plane, respectively. The thickness of the n'-GaN epilayer was about 8.4 µm checked by cross-sectional CL images as shown in Fig. 1(e), taking advantage of the image contrast caused by different carrier density. These characterization results indicate the homoepitaxial GaN layer grown by HVPE was high-quality and smooth with well-controlled impurities.

The devices fabrications started with a 1-µm-deep mesa isolation etch by inductively coupled plasma (ICP). Fig. 2(a) and (b) shows the schematic structure of the SBD without F ion...
implantation as a reference (diode A) and the SBD using F ion implantation treatment (diode B). Diode B used AZ5214 photoresist (∼1.4 µm) as a mask to define the implanted region. The F ions was implanted by three energies successively (40 keV, 80 keV and 140 keV), and the F profile as a function of depth was estimated by Srim software based on Monte Carlo simulation as shown in Fig. 2(c). The simulation result indicated F implantation would create a 350nm-deep box-like profile with a total ion concentration of \(10^{18} \sim 10^{19}\) cm\(^{-3}\). After implantation and photoresist removal, a 100-nm-thick SiO\(_2\) film was deposited on both diodes by plasma enhanced chemical vapor deposition (PECVD). Schottky barrier diodes with a diameter of 100 µm were defined by opening circle window after standard photolithography and BOE wet etching. Prior to metallization, the samples were dipped in HCl solution for 1 minute to remove the oxide film. Pt (40nm)/Au (250nm) Schottky contacts were deposited by e-beam evaporation and patterned by lift-off. Afterward, rapid thermal annealing at 400 °C in N\(_2\) atmosphere for 10 minutes was carried out for improving Schottky contacts cohesion and recovering the damage caused by ion implantation. Finally, Ti (50nm)/Pt (100nm)/Au (50nm) Ohmic contacts were deposited by e-beam evaporation at the backside of GaN bulk substrates treated by inductively coupled plasma (ICP) etching. For diode B, the actual F concentration as a function of depth without mask was also measured by SIMS after SiO\(_2\) film removal by HF solution as shown in Fig. 2(c). The actual F ion concentration was \(2 \times 10^{18} \sim 10^{19}\) cm\(^{-3}\) underneath the surface 300-nm depth in accordance with the simulation result, but the actual F concentration profile formed a long tail into n-GaN. The difference between simulation and SIMS result was mainly due to the channeling effect or diffusion by annealing. The roughness of GaN surface after F ion implantation was checked by AFM. The surface still kept a step-flow morphology as as-grown GaN shown in Fig. 1(b), and the roughness was almost identical (RMS=0.46 nm), indicating negligible surface damage by F ion implantation.

C-V measurements of two diodes were carried out at a frequency of 1 MHz shown in Fig. 3(a). The net doping concentration...
(N_D - N_A) of diode drift layers can be estimated from the following equations:

$$1/C^2 = \frac{2}{A^2 \varepsilon_0 \varepsilon_r (N_D - N_A)} (V_{fb} - V - kT/q)$$  \hspace{1cm} (1)

$$N_D - N_A = \frac{2}{A^2 \varepsilon_0 \varepsilon_r} \left[ -\frac{1}{d(1/C^2)/dV} \right]$$  \hspace{1cm} (2)

where \(\varepsilon_0\) is the permittivity of the vacuum \((8.854 \times 10^{-12} F/m)\), \(\varepsilon_r\) is the relative permittivity of GaN \((9.5)\), and \(A\) is the effective area of the diode. The net doping concentration as a function of junction depth can be plotted as shown in the inset of Fig. 3(a). For diode A, the net doping concentration of drift layer always maintained around the level of \(10^{15} \text{ cm}^{-3}\) at the whole range, which agreed reasonably with the Si doping concentration analyzed by the above SIMS result of epilayer. However, for diode B, the net doping concentration near the junction decreased significantly and returned the normal value beyond the depth of 500 nm. To investigate the surprising phenomenon of C-V measurement of diode B, the region beneath the Schottky contact of diode B was checked by SIMS measurement as shown in Fig. 3(b) after removal of the Au cap layer. Compared with Si concentration, relatively low concentration of F ion \((5\times10^{15} \text{ cm}^{-3} - 1\times10^{15} \text{ cm}^{-3})\) was detected within 500-nm depth to GaN surface. Thus, the surprising phenomenon of C-V measurement of diode B probably resulted from F ion introducing. Due to the strongest electronegativity, F ions would capture free electrons to form fixed negative charges in active area. In addition, F ions implantation would induce extra deep level acceptor-type defects decreasing carrier density further.\(^{19}\)

The forward characteristics for diode A and diode B are shown in Fig. 4. Compared with diode A, the forward current of diode B was lower as shown in Fig. 4(a). The turn-on voltages \((V_{on})\), extracted from I-V curves by linear extrapolation) of diode A and diode B were \(-0.51\text{V}\) and \(-0.64\text{V}\). The on-resistance \((R_{on})\) of diode A and diode B were \(0.20 \Omega \text{cm}²\) and \(0.27 \Omega \text{cm}²\), respectively. Besides, according to the thermionic emission model,

$$J = A^* T^2 \exp \left( \frac{-q\phi_{bi}}{kT} \right) \exp \left( \frac{qV}{\eta kT} \right)$$  \hspace{1cm} (3)

where \(A^*\) is the Richardson constant \((26.4\text{A cm}^{-2} \text{K}^{-2})\) for n-GaN), \(\eta\) is the ideality factor and \(\phi_{bi}\) is Schottky barrier height \((\text{SBH})\).\(^{26}\) \(\eta\) and \(\phi_{bi}\) of diode A and diode B were 1.22, 0.70eV and 1.07, 0.92eV by drawing lnJ-V curves as shown in the inset of Fig. 4(a). Besides, high \(I_{on}/I_{off}\) ratio of electronic devices is key for future high voltage and high power application.\(^{12,27-29}\) As shown in Fig. 4(b), diode B had a high \(I_{on}/I_{off}\) ratio in the order of \(10^4\), while the ratio of diode A was \(10^3\). Table I summarizes the device parameters of forward characteristics for diodes. These results indicate that diode B using F ion implantation treatment obtained a higher \(I_{on}/I_{off}\) ratio and SBH but increased on-resistance slightly.

Fig. 5 presents the reverse characteristics of diode A and diode B. The breakdown voltage of diode B was 775V, while diode A broke down at 155V. Diode B had lower reverse leakage current by about \(10^5\) times than diode A at the reverse bias of 150V. The rate of the reverse current rise of diode B was also slower than diode A, which indicated that more leakage paths may exist in diode A. These results showed diode B performed better reverse capability. Besides, for a given doping concentration \((N_D)\), the breakdown voltage \((\text{BV})\) of vertical GaN SBD could be estimated with this power

### Table I. Summary of device parameters of forward characteristics for diodes.

| Sample | \(I_{on}/I_{off}\) | \(\eta\) | SBH (eV) | \(V_{on}\) (Volts) | \(R_{on}\) (\(\Omega\text{cm}^2\)) |
|--------|----------------|-------|--------|--------------|----------------|
| Diode A | \(10^4\) | 1.22 | 0.70 | 0.51 | 0.20 |
| Diode B | \(10^8\) | 1.07 | 0.92 | 0.64 | 0.27 |

![FIG. 4. Forward characteristics of diode A and diode B (a) on a linear scale; (b) on a semi-log scale.](image1)

![FIG. 5. Reverse characteristics of diode A and diode B.](image2)
law by solving the ionization integral\(^6\): \[ BV_{pp} = 2.51 \times 10^{15} \left( \frac{1}{N_D} \right) \]

By substituting the \( N_D \) with \( 10^{17} \text{ cm}^{-3} \), the ideal breakdown voltage of 446.3V was calculated. The measured breakdown voltage of diode B was higher than the ideal breakdown voltage with drift layer of uniform doping concentration of \( 10^{17} \text{ cm}^{-3} \). It indicates the carrier density in the surface of GaN was decreased in accordance with the above C-V results. In particular, the catastrophic damages of both diodes occurred at the edge of Schottky contacts due to edge electric field crowding, as shown in the optical microscopy image in the inset of Fig. 5. Thus, the maximal electric field should be occurred at the edge of Schottky contacts for both diodes and edge termination is critical for GaN SBDs.

The electric field distributions of two diodes were also simulated by using Silvaco TCAD software as shown in Fig. 6(a) and (b). For diode A, a uniform doping concentration of \( 10^{17} \text{ cm}^{-3} \) for drift layer was set. For diode B, the carrier density in the region of 600 nm-depth beneath SiO\(_2\) film was assumed to be fully compensated forming a high-resistance region, where the concentration of F was higher than Si according to SIMS result in Figure 2(c). The net doping concentration in the active area as a function of depth used the data calculated by C-V measurement. The bias voltages were set to the measured breakdown voltage, which were -155V for diode A and -775V for diode B. By plotting the electric field near the surface of GaN drift layers in diode A and diode B shown in Fig. 6(c) and (d), the electric field crowding both happened at the edge of Schottky contacts for two diodes, which agreed with the above optical image in Fig. 5. The maximal electric field were 2.97 MV/cm for diode A and 3.73 MV/cm for diode B respectively when they broke down, which both close to the previous report (3.75MV/cm).\(^7\) Besides, the significantly reduced leakage current of diode B could be attributed to the high-resistance region at the edge of Schottky contact and the elevated Schottky barrier height.

In summary, a vertical GaN Schottky barrier diode (SBD) using F ion implantation treatment was fabricated, and the device performance was analyzed by comparing with the SBD without F ion implantation. This SBD using F ion implantation treatment not only boosted breakdown voltage significant from 155V to 775V but also lowered reverse leakage current by \( 10^5 \) times. Thus, F ion implanted SBD showed significantly improved reverse capability but increased on-resistance from 0.20 \( \Omega \cdot \text{cm}^2 \) to 0.27 \( \Omega \cdot \text{cm}^2 \). In addition, this SBD had higher \( I_{on}/I_{off} \) ratio and Schottky barrier height. This work shows the potential for obtaining high-voltage and low-leakage GaN SBDs using F ion implantation treatment.

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