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A High Voltage Vertical GaN-on-GaN Schottky Barrier Diode with High-Energy Fluorine Ion Implanted Guard Rings

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Abstract

In this work, we propose a vertical GaN-on-GaN Schottky barrier diode (SBD) terminated with high-energy fluorine ion implanted guard rings. The implantation process brings about damages to the terminated region forming a high-resistive region with high density of acceptor traps. Under reverse bias, the electrons are injected in the implanted guard rings, which are captured by the acceptor traps. These negative space charges in the fluorine ion implanted guard rings could deplete the free carriers in the drift region, which effectively spread the electric field laterally near the metal edges. The cyclical implanted-region/depleted-region grids could block the leakage current path along the surface which damaged by the high-energy and high-dose ions. The fabricated SBD is featured with a high breakdown voltage of 1.2 kV at the leakage criteria of 1 A/cm^2 and a low leakage current density of 50 μA/cm^2 at a reverse bias of 300V.

1. Introduction

With high critical electric field and high mobility, GaN vertical structure devices are promising candidate for high power devices. Compared with lateral structure devices, the electric field distribution is more uniform in the vertical structure devices, which would make full use of the superior properties of GaN. Among these devices, the vertical GaN-on-GaN Schottky barrier diode (SBD) has been under extensively research because of its advantages on speed and turn-on voltage. The electric field crowding at the metal edges hinders the application of such devices. A suitable edge termination structure should be adopted to reduce the electric field near the edge of junction. In Si and SiC SBDs, junction termination extension and guard rings are used to shield the high electric field from the anode metal and improve the breakdown voltage (*BV*). However, due to the p-type selective area doping difficulties in GaN, such edge termination techniques are immature to be adopted for GaN vertical structure SBDs. Ion implantation is alternatively used for termination structure of GaN SBDs [1-3]. The implanted ions damage the lattice of GaN and form a high-resistive terminated region. It is found that the leakage current of these devices is quiet high which leads to high loss under reverse bias [1].

In this work, SBDs with two guard rings based on the high-energy fluorine ion implantation are fabricated. The leakage current path is effectively blocked by these two guard rings. Compared with devices without termination, the SBD with 2 guard rings presents 2 order lower reverse leakage current at reverse bias of 300 V and ×3 improvement of breakdown voltage.

2. Device Structure and Fabrication Process

The 13 μm thick n$^-$-GaN drift layer and 1 μm thick n$^+$-GaN layer were grown by MOCVD on a 2-inch GaN substrate with a threading dislocation density in the range of 10^6 cm^{-2} which is revealed by CL measurement results in Fig.1 (a). The net doping density in the n$^-$ drift layer is calculated to be 2.5×10^{15} cm^{-3} from *CV* measurement at 10 kHz with mercury probe as shown in Fig. 1 (b). After surface cleaning with HCl and HF solution, the wafer was deposited with 3 μm thick PECVD grown SiO_2. Muti-energy F ion implantation was conducted after photolithography and SiO_2 RIE etching to form the edge termination. The ion implantation process was designed by the aid of TRIM software as shown in Fig. 2 (b). The distribution of fluorine was got from the SIMS measurement. The difference between TRIM simulation and SIMS measurement results is mainly due to the channeling effect. The SiO_2 hard mask were then fully removed by buffered oxide etching (BOE) solution. Pt/Au circular Schottky contacts were formed by photolithography, electron beam evaporation and following lift-off. The Schottky contact had an overlap of 2 μm (L_T) on the edge termination region. Ti/Al/Ni/Au ohmic contacts were formed on the back surface of the wafer by electron beam evaporation. The structure of SBD with two guard rings are shown in Fig. 2 (a). The implanted guard rings can be clearly seen in the image of device surface. For comparison, the SBD without termination(unterminated-SBD), SBD terminated with infinite high-energy fluorine ion implanted region (HEFIT-SBD) and SBD with one or two ion implanted guard tings are fabricated on the same wafer.

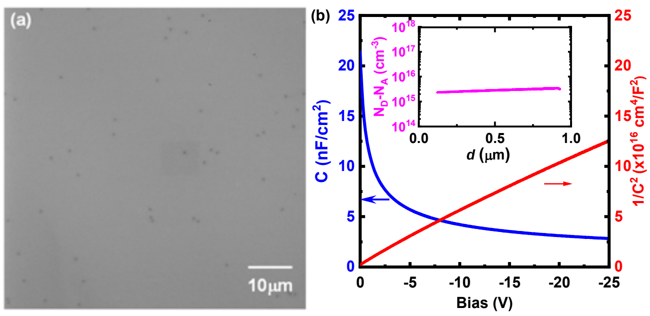

Fig. 1. (a) Cathodoluminescence image of the GaN drift layer and the threading dislocation density is calculated to be 7.4×10^5 cm^{-2}. (b) *C-V* curve of the GaN-on-GaN wafer measured with mercury probe at 10 kHz and inset of (b) extracted depth dependent net doping concentration in the n$^-$-GaN drift region.

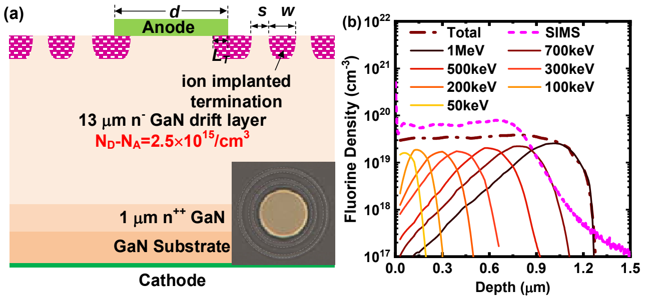

Fig. 2. (a) The schematic cross section view and surface image of the vertical GaN SBD with ion implanted two guard rings. (b) The distribution of F ions from TRIM simulation and the SIMS measurement.

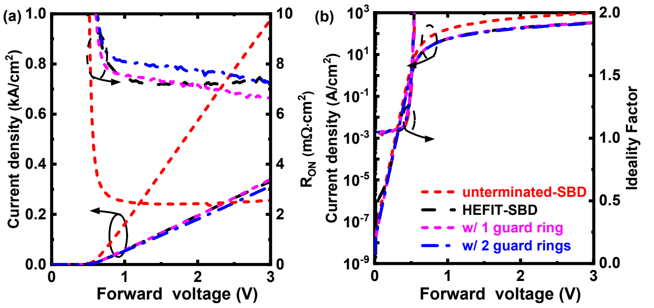

Fig. 3 IV curves of various SBDs with d=48 μm in (a) linear scale and (b) semi-log scale. The specific on-resistance and ideality factor of SBDs are also shown in the figure.

3. Results and Discussion

Fig. 3 (a) and (b) compare the *IV* curves of the SBD of various structure. The specific differential on-resistance ($R_{on,sp}$) of the SBD with two guard rings and unterminated-SBD are 7.3 and 2.4 mΩ·cm^2, respectively, for d =48 μm. For the unterminated-SBDs, the current spreading effect results in a higher current density and a lower on-resistance. The current spreading path is partially blocked by the implanted high-resistive region in the HEFIT-SBD and SBDs with guard rings. Besides, the lateral extension effect of F leads to a reduced active area, resulting in a higher $R_{on,sp}$. The SBDs with guard rings present almost the same forward IV characteristics as the HEFIT-SBD. The forward current of the SBD with guard rings obey the thermal emission model, while the IV curve of HEFIT-SBD below 0.3 V deviates from the thermal emission model (Fig. 3(b)) because of the leakage from the implanted region. The ideality factors of all the devices are close to unity, suggesting the high quality of Schottky contact. The 3 μm thick PECVD grown SiO_2 hard mask is effective to prevent the high-energy fluorine ions getting into the active region.

As shown in Fig. 4 (a), the reverse leakage current of HEFIT-SBD at low reverse voltage is high, which hinders the application of such devices. In order to reduce the leakage current through the termination region, the SBD guarded with two separated implanted regions (GR-SBD) is fabricated on the same wafer. The GR-SBD presents reduced reverse leakage current at low reverse bias compared with the HEFIT-SBD as shown in Fig. 4 (a), while maintaining almost the same forward characteristics. The reverse leakage current of GR-SBD with two guard rings is 2 orders of magnitude lower

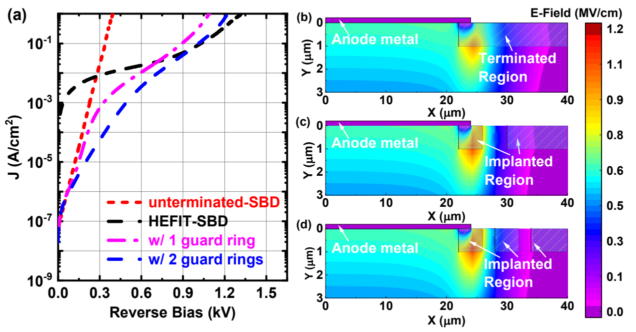

Fig. 4 (a) Reverse characteristics of SBDs. Simulated electric field distribution of the (b) HEFIT-SBD, SBD with (c) one guard ring and (d) two guard rings at -400 V.

than that of HEFIT-SBD and unterminated-SBD at a reverse bias of 300 V. The *BV* of GR-SBD is improved from 400 V to 1200 V, compared with the unterminated-SBD. The reduced leakage current is helpful to decrease the static loss at reverse bias and improve the power system efficiency. Fig. 4 (b)-(d) show the field distribution of HEFIT-SBD, GR-SBD with one guard ring and GR-SBD with two guard rings at a reverse bias of 400 V, respectively. The accumulated space charges near the metal edges deplete the free carriers of unterminated-region between two separated implanted regions as shown in Fig. 4 (d). The leaky path through the implanted region is partially blocked by the depleted unterminated-region, which reduces the reverse leakage current at low bias. Under reverse bias, the cyclical implanted-region/depleted-region grids could effectively smoothen the electric field along the surface and reduce the leakage current. Therefore, the GR-SBD with 2 guard rings presents a lower leakage current and an improved breakdown voltage than the GR-SBD with 1 guard ring.

4. Conclusion

A guard ring termination structure based on high-energy fluorine ion implantation is implemented on vertical Ga-on-GaN SBD. Guarded with 2 guard rings, the SBD presents nearly ideal forward current characteristics and a breakdown voltage of 1200 V. The space charges in the fluorine ion implanted guard rings could deplete regions between the implanted guard rings under reverse bias. The implanted-region/depleted-region grids effective block the reverse current, presenting lower leakage current compared with the infinite ion implantation terminated device.

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