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Normally-off Operation GaN HEMT Devices with Nano-pattern Structure

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Abstract

This paper presents a novel process by introducing nano-imprint technique into AlGaN/GaN high-electron-mobility-transistor (HEMT) device. This process consists of nano-imprint to form the nano-pattern hard mask and then transfers to the electron supply AlGaN layer of the two-dimensional electron gas (2DEG) device, followed by SF6 irradiation and capping with p-NiO layer encapsulation. This device with the novel gate structure exhibits normally-off characteristic. The threshold voltage of this nano-pattern device is higher than 2 V and the breakdown voltage is higher than 1800V. The use of P-NiO layer can effectively prevent the off-state leakage current, leading to high ON/OFF current ratio of ~10^8 in the proposed devices. At room temperature, SS as low as 84 mV/dec. was observed.

1. Introduction

The High-Electron-Mobility Transistor (HEMT) device based on AlGaN/GaN hetero structure has low resistance characteristic by taking advantage of two-dimensional electron gas (2DEG) induced by piezoelectric polarization mechanism, so this device has been attracting considerable attention and intensively studied as for the next-generation power electronic devices applications. However, the conventional HEMT device typically has a negative threshold voltage because of the inherent existence of the 2DEG channel, and thus it becomes a normally-on device. This is rather inconvenient of use for some safety-concerned applications. Several techniques to achieve the normally-off property of the AlGaN/GaN devices have been reported, such as the fluoride-based plasma treatment method [1, 2], the use of p-type layers underneath the gate region [3-5] to lift up the conduction band, or thin down the electron supply AlGaN layer to form a recessed gate structure [6, 7]. This recess would weaken the electric field contributed by a lower piezoelectric polarization, and generate a lower carrier concentraion in the 2DEG layer for Vt improvement. However, this approach is difficult to control the remaining AlGaN thickness and therefore exhibits poor device uniformity. Although many papers adopted various methods to achieve normally-off property, it sacrificed device turn-on performance in some cases. The purpose of this study is to develop a normally-off device with minimum impact on the drain current by proposing a novel imprint method to form the nano-porous or nano-rod gate structures.

2. General Instructions

Contents

A nano-porous hard mask was formed by nano-imprint around the gate region, followed by partially AlGaN etching and then implanting F-ion by SF6 plasma irradiation. And then the P-type NiO is selectively deposited on the AlGaN to help to raise the potential of the 2DEG channel region. This device combines all the benefits of F-ion implantation, p-NiO gate and recessed gate devices to exhibit the normally-off property. Owing to the AlGaN layer under the gate is not fully removed, the piezoelectric polarization can still be high enough so that the drain current can be almost comparable to the conventional HEMT device.

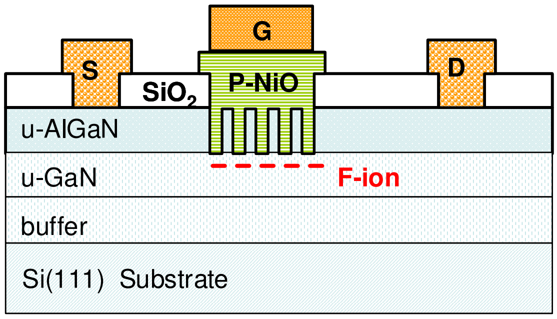

Fig. 1 illustrates the schematic structure of the proposed device structure.

Figure 2 shows the tilt SEM view of nano-porous structure on whole wafer surface. The area ratio occupied by these nano-porous is about 30% . The threshold voltage and the output characteristic of this device can be adjusted by designing different area ratio of the nano-pattern structure. We believe the partially etched AlGaN layer, i.e. nano-porous structure, can has better tradeoff characteristic as compared to the fully etched AlGaN layer, i.e. gate-recessed structure. The nano pattern on whole wafer surface was making by nano-imprinting technology [8, 9]. The mold diameter of hole and period was175nm and 350 nm, respectively.

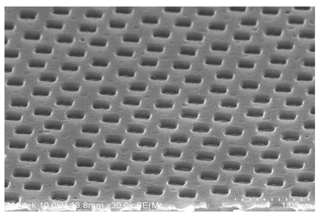

Fig. 2 SEM view of nano-porous structure.

The NiO films with 100 nm thickness were deposited on Corning 1737F glass substrates by sputtering NiO targets using radio frequency (rf) magnetron sputtering in a pure O_2 (16 sccm) atmosphere at room temperature. The carrier concentration , resistivity and carrier mobility of NiO films were measured with the Hall system using Van der Pauw's method. Its electrical resistivity, carrier concentration and mobility were 0.11 Ω-cm, 7.06×10^{19} cm−3 and 0.76 cm^2/Vs, respectively. And the polarity of the NiO was P-type.

Figure 3 (a) shows the comparison of the DC transfer characteristics on different HEMT devices. The nano-porous device exhibits a peak drain current Id of 266 mA/mm at gate to source voltage Vgs of 9V. This value does not degrade too much as compared to peak Id of 418 mA/mm at Vgs of 4V from the standard HEMT device. The percentage of drain current drops is about 36%. The threshold voltage Vth can be extracted from the linear extrapolation of the Id-Vgs plot in Fig. 3(a). A positive Vth value of 2.3V (normally-off property) was achieved from the nano-porous with P-NiO cap HEMT device, while a negative value of -2V was presented from the standard AlGaN/GaN HEMT device. Figure 3 (b) shows the log plotted transfer characteristics of he nano-porous with P-NiO cap HEMT device. The subthreshold swing of ~84 mV/dec was obtained. The off-state leakage current decreases from 10^{-5} (Standard AlGaN/GaN HEMT device) to 10^{-9} mA/mm, leading to a high I_{on}/I_{off} ratio of ~10^8. The reverse blocking characteristic of the proposed nano-porous with P-NiO cap HEMT device. The breakdown voltage of this device is higher than 1800V.

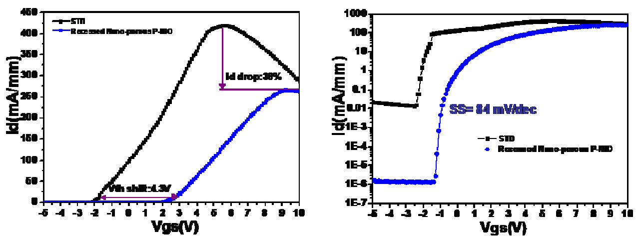

Fig. 3 (a) Comparison of DC transfer characteristics on different GaN-on-Si HEMT devices. (b) show in log scale

3. Conclusions

In conclusion, we have demonstrated a nano-porous AlGaN/GaN HEMT device with normally-off, high on-state current and high breakdown voltage performances. The positive threshold voltage and high drain current performance is attributed to the nano-porous structure underneath the gate region because of the discontinued 2DEG layers formed so that the high current maintained and the threshold voltage can be modulated by F- implanted and adopt P-NiO cap layer. This device also exhibits high breakdown voltage and low leakage current. The nano-porous AlGaN/GaN device is very promising for the high current and high voltage power device applications.

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