Improved Dynamic ON-resistance of a Normally Off p-GaN Gate High-Electron-Mobility Transistor Using a Nongated-Region Oxidation Technique

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Abstract
In this study, a device structure for a high-resistivity high-electron-mobility transistor (HR-HEMT) was developed for a normally off p-GaN gate HEMT with low gate lag and high saturation current. Instead of using a traditional etching process, oxygen plasma was adopted to compensate for holes in the p-GaN gate above the two-dimensional electron gas (2DEG) channel to release electrons in the 2DEG channel and form a high-resistivity area to protect the device. Moreover, a comparison of the traditional etching process and oxygen plasma treatment revealed that the HR-HEMT exhibited higher performance than a traditional device, with a saturation current of 111 mA/mm at VGS = 6 V and a lower dynamic ON-resistance of 1.25 times at a gate bias stress of −15 V.

INTRODUCTION

GaN-based power devices are emerging as promising candidates for next-generation power switching applications due to their high mobility and wide band gap. A traditional AlGaN/GaN high-electron-mobility transistor is a normally-on device, featuring high mobility and high-density two-dimensional electron gas (2DEG) [1]. These transistors feature a quantum well beyond the Fermi level, which means that the device operates at a negative bias. However, normally off device operate at a positive bias, which are desirable for power switching devices because of simplified gate-drive topology and failsafe operation [2]. Many approaches exist for making a normally off device, such as fluoride plasma treatment [3], [4], a p-GaN gate [5]– [9], and a gate recess [10], [11]. These approaches have been used for obtaining a normally off HEMT. Structures with p-type gates have drawn increasing attention in the industry due to their low on-state resistance and a large threshold voltage. To improve the performance of p-GaN HEMTs, the etching depth uniformity of the nongated active region and the plasma-induced damage during the p-GaN removal process are particularly crucial. Traditional chlorine-based dry etching generally provides a rough surface that causes gate lag due to surface traps. Chiu et al. [12] demonstrated that an HEMT structure with an aluminum nitride (AIN) etching stop layer improved performance. This method can avoid over etching and protect the AlGaN barrier layer, which may improve the leakage current, drain lag, and dynamic ON-resistance (Ron). In [3], HR-GaN was obtained through hydrogen plasma treatment. The electric field distribution of a conventional p-GaN gate HEMT and a high-resistivity HEMT (HR-HEMT) in the off state were simulated. This indicated that passivation may occur in HR-GaN, and there were negative charges that appeared at the interface that can improve the off-state breakdown voltage [3]. Varying radio frequencies have also been used to treat p-GaN with inductively coupled plasma (ICP) [13]. However, bonds between magnesium and hydrogen are easily broken at high temperatures, which is a challenge in the alloying process. In this work, an HR-GaN cap layer was fabricated through oxygen plasma treatment with an AlN etching stop layer. The oxygen plasma treatment caused acceptors in p-GaN to be passivated by the formation of Mg–O and Ga–O, which offer high resistivity and stability as insulator materials.

EXPERIMENTAL PROCEDURES

The purpose of the oxygen plasma treatment for p-GaN HEMTs can be illustrated using a schematic band gap diagram created using 1D Poisson software, as shown in Fig. 1. After oxygen plasma treatment, Mg–GaN is oxidized and changed to MgO, Ga2O3, and gas N2O. This makes p-GaN lose its p-type effect, and the p–n junction becomes invalid. Subsequently, the conduction band in the channel is pulled under the Fermi level, causing 2DEG to form in the channel. In addition, after oxygen plasma treatment, the low-resistivity p-GaN becomes HR- GaN.

Fig.1 Band gap diagram of p-GaN/AlGaN/GaN with HR-GaN.
Fig. 2 presents diagrams of epistructures used in this study. The p-GaN/AlGaN/GaN HEMT was grown on 6-inch Si (111) substrates through metal organic chemical vapor deposition. A 300-nm-thick undoped GaN channel was grown on top of a 4-μm-thick undoped AlGaN/GaN buffer transition layer. Then, a 12-nm-thick Al$_{0.17}$Ga$_{0.83}$N layer, 2-nm-thick AlN layer, and 70-nm-thick p-type GaN top layer were composited. The Mg concentration was 3 × 10$^{19}$ cm$^{-3}$, which was thermally annealed through MOCVD at 720°C for 10 min in N$_2$ ambient, and the activation of Mg concentration was 1 × 10$^{18}$ cm$^{-3}$ according to the Hall measurement.

For the HEMT device fabrication, the mesa region was etched with a combination of Cl$_2$, BCl$_3$, and Ar gases through reactive ion etching (RIE). Subsequently, the p-GaN nongated regions were etched using different methods. As shown in Fig. 2, device A, a standard HEMT (ST-HEMT), was etched through RIE with Cl$_2$/BCl$_3$/Ar. However, device B, an HR-HEMT, was fabricated through oxygen plasma treatment. High-density oxygen plasma was produced by the ICP over 18 min with an RF power of 300 W and a DC power of 100 W at room temperature. The ohmic contact region was etched by CF$_3$ and Ar, and Ti/Al/Ni/Au metal film was deposited as a source and drained by electron beam evaporation. It was then annealed at 875°C for 35 s in a N$_2$ atmosphere using an RTA system, and Ti/Au was deposited as the gate metal. Ti/Au was subsequently deposited as the pad for interconnection. Eventually, two devices were passivated with Si$_3$N$_4$ through plasma-enhanced chemical vapor deposition. The fabricated devices had a gate width of 100 μm, a gate length of 2 μm, a source-gate distance of 3 μm, and a gate–drain distance of 6 μm.

**RESULTS AND DISCUSSION**

Fig. 3(a) and (b) show the output characteristic and the transfer characteristic of the ST-HEMT (with dry etching) and HR-HEMT (oxygen plasma treatment) with L$_{GS}$/L$_G$/L$_{GD}$/W$_G$ = 3/2/6/100 μm, respectively. From Fig. 3(a), the drain leakage currents for the HR-HEMT and ST-HEMT were 4.4 × 10$^{-7}$ and 1.03 × 10$^{-6}$ mA/mm, respectively, at V$_{GS}$ = 0 V. These results indicate that O$_2$ plasma passivated p-GaN, resulting in extremely low damage to the device. By contrast, conventional etching of p-GaN with corrosion gases resulted in many dangling bonds. These bonds were traps that blocked electrons’ path from the drain to source by hopping conduction. Additionally, the threshold voltage (V$_{TH}$) value was 1.3 V in both devices. The drain ON/OFF current ratio (I$_{ON}$/I$_{OFF}$) values of the HR-HEMT and ST-HEMT were 3.9 × 10$^9$ and 1.8 × 10$^7$, respectively, and the subthreshold swing was improved from 118 to 104 mV/dec in the HR-HEMT. In Fig. 2(b), the I$_{DS}$–V$_{DS}$ curves of the HEMTs are shown by varying gate bias. The maximum output current density was 88 mA/mm at a gate bias of 6 V, and the ON-resistance was 31.8 Ω·mm for the ST-HEMT. By contrast, these results were respectively 159 mA/mm and 17.1 Ω·mm for the HR-GaN HEMT. The greater output current performance of the HR-HEMT may be increased due to Al$_2$O$_3$ stop layer which can protect AlGaN barrier layer. This may have had the same effect as an etching stop layer that was shown previously [12]. In the present study, Al$_2$O$_3$ was formed through an etching process and could protect the AlGaN barrier layer. However, the O$_2$ plasma treatment passivated p-GaN, which raised the performance of the device. Compared with a conventional etching process, the HR-HEMT had a favorable current density and low leakage current.
To analyze the surface trapping/detrapping from dry etching and oxygen plasma treatment in the p-GaN HEMT, low frequency noise spectra were taken five conditions at 100 Hz in different bias. The $1/f$ noise measurement system was performed using an HP-4142 power supply, a 35670A dynamic signal, and an Agilent E3611a control unit. In this work, the frequency range was measured from 10 to 1000 Hz. If the slope of $S_{ID}/ID^2$ is close to $-2$, the spectral fluctuation will be dominated by surface traps [14]. The slopes for HR-GaN and ST-GaN were $-1.52$ and $-1.73$, respectively. Moreover, the noise of HR-HEMT was lower than that for ST-HEMT by approximately one order of magnitude.

Proof of the off-state breakdown voltage through simulation of HRCL-HEMT and conventional p-GaN HEMT has been published previously [15]. Hao et al. demonstrated that negative charges appear at the interface of HR-GaN/AlN/AlGaN because of negative polarization [16]. This effect may disperse the electric field and thereby improve the off-state breakdown voltage. Surface traps are considered to be causes of gate lag, and buffer traps are considered to be causes of drain lag [17]. As shown in Fig. 6, by comparison, the dynamic $R_{on}$ ratio of the HR-HEMT was only 1.46 times at a gate bias stress of $-15$ V, much lower than the dynamic $R_{on}$ of the ST-HEMT, which was 2.52 times. Therefore, using oxygen plasma treatment for p-GaN can more effectively reduce surface traps than dry etching.

**CONCLUSIONS**

In this study, an HR-HEMT was fabricated through oxygen plasma treatment. The HR-HEMT exhibited low drain leakage current of $4.4 \times 10^{-7}$ and a higher output current (159 mA/mm) than an ST-HEMT (88 mA/mm). Furthermore, the off-state breakdown voltage rose to 530 V at $V_{GS} = 0$ V in the HR-HEMT. The dynamic $R_{on}$ ratios were measured, which were 1.46 times for the HR-HEMT and 2.52 times for the ST-HEMT, meaning that the HR-HEMT caused lower
gate lag. These characteristics of the HR-HEMT were a result of the oxygen plasma treatment causing very low damage to the surface, effectively reducing surface traps. However, controlling the oxidation depth of oxygen plasma treatment for p-GaN remains a challenge because of the edge effect.

REFERENCES


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ACRONYMS

GaN: Gallium nitride
AlN: Aluminum Nitride
HR-HEMT: High Resistivity High Electron Mobility Transistor
2DEG: Two Dimensional Electron Gas
ICP: Inductively Coupled Plasma
ST-HEMT: Standard High Electron Mobility Transistor
RIE: Reactive Ion Etching