Optimization of Oxygen Plasma Treatment on Ohmic Contact for AlGaN/GaN HEMTs on High-Resistivity Si Substrate

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Abstract: The oxygen plasma surface treatment prior to ohmic metal deposition was developed to reduce the ohmic contact resistance ($R_C$) for AlGaN/GaN high electron mobility transistors (HEMTs) on a high-resistive Si substrate. The oxygen plasma, which was produced by an inductively coupled plasma (ICP) etching system, has been optimized by varying the combination of radio frequency (RF) and ICP power. By using the transmission line method (TLM) measurement, an ohmic contact resistance of 0.34 $\Omega \cdot \text{mm}$ and a specific contact resistivity ($\rho_C$) of $3.29 \times 10^{-6} \Omega \cdot \text{cm}^2$ was obtained with the optimized oxygen plasma conditions (ICP power of 250 W, RF power of 75 W, 0.8 Pa, $\text{O}_2$ flow of 30 cm$^3$/min, 5 min), which was about 74% lower than that of the reference sample. Atomic force microscopy (AFM), energy dispersive X-ray spectroscopy (EDX), and photoluminescence (PL) measurements revealed that a large nitrogen vacancy, which was induced near the surface by the oxygen plasma treatment, was the primary factor in the formation of low ohmic contact. Finally, this plasma treatment has been integrated into the HEMTs process, with a maximum drain saturation current of 0.77 A/mm obtained using gate bias at 2 V on AlGaN/GaN HEMTs. Oxygen plasma treatment is a simple and efficient approach, without the requirement of an additional mask or etch process, and shows promise to improve the Direct Current (DC) and RF performance for AlGaN/GaN HEMTs.

Keywords: AlGaN/GaN HEMTs; ohmic contact; oxygen plasma; nitrogen vacancy; inductively coupled plasma (ICP) etching

1. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) have shown significant advantages over silicon devices in high-frequency, high-voltage and high-power applications, benefitted from high-density and high-mobility two-dimensional electron gas (2D$\text{E}_G$) [1–4]. Significant progress in recent years has been made. However, some key aspects of the technology still need to be understood and improved. High ohmic contact resistance ($R_C$) is one of these issues, it can cause additional increased static power and worsen the device reliability etc.

Several approaches on AlGaN/GaN heterostructure have been demonstrated to achieve low $R_C$, such as, optimization of the ohmic metal multilayer [5–8], AlGaN barrier recess [9–11], annealing optimization [12–14], insertion of a layer beneath the ohmic metal [15,16], n-type doping [17], regrown technology [18], plasma surface treatment [19–21] etc. At present, oxygen plasma treatment prior to ohmic metal deposition has not been investigated on the AlGaN/GaN heterostructure and on AlGaN/GaN HEMTs. Several commonly used surface treatment approaches have been reported in the literature to achieve low $R_C$. One is based on recess prior to the metallization of the ohmic contacts to
get a lower AlGaN barrier layer [9]. The downside of this technology is that etching ohmic recess needs precise etching rate control, which increases the complexity of this process. Another method is to deposit the passivation layers under the ohmic metals [15], but the appropriate thickness and a high annealing temperature are required. The surface treatment of donors such as Si has been studied previously by Yu et al. [17]. While \( R_C = 0.4 \Omega \cdot \text{mm} \) has been achieved using ion implantation technology, the dopant activation needs a very high temperature (>1500 °C), which could create secondary defects and degrade the device performance. Some researchers have proved that oxygen may be doped as a donor in GaN, which can lead to a thin barrier and enhance the tunneling effect [22]. An ohmic contact with \( R_C = 0.24 \Omega \cdot \text{mm} \), fabricated by combination with oxygen plasma treatment, HCl cleaning, and the etching process, has been reported by Song et al., which suggests that oxygen plasma treatment helps to remove the impurities and change the surface morphology. However, oxygen plasma treatment prior to ohmic metal deposition has not yet been deeply investigated on AlGaN/GaN heterostructure and AlGaN/GaN HEMTs, and high-performance ohmic contacts have not been fabricated through the oxygen plasma treatment process. The oxygen plasma treatment impacts the ohmic contacts, and the formation mechanism needs to be explained in depth.

This work proposes a simple and efficient oxygen plasma treatment to reduce the \( R_C \) of HEMTs. Oxygen plasma produced by the inductively coupled plasma (ICP) (Sentech, SI500) etching system is used for surface treatment prior to the ohmic metal deposition. Meanwhile, we will carry out an in-depth study of the ohmic formation mechanism and treatment conditions by oxygen plasma surface treatment in this work.

2. Materials and Methods

The epitaxial layers were grown by metal-organic chemical vapor deposition (MOCVD) on High-Resistivity (HR) Si substrate, consisting of a 2 µm GaN buffer layer, a 500 nm undoped GaN channel layer, a 1 nm AlN spacer layer between the GaN channel and the barrier in all the wafers, a 20 nm AlGaN barrier layer, and a 2 nm GaN cap layer on top of the structure. The Hall measurements exhibited a sheet carrier density of \( 1.23 \times 10^{13} \text{ cm}^2 \), an electron mobility of 1663 cm²/Vs, and a sheet resistance of 305 Ω. Firstly, the samples surface was cleaned with acetone and ethanol for 5 min, followed by rinsing with deionized water and blowing dry with nitrogen. The ohmic region was formed by using a standard photolithography process. Then, the oxygen plasma treatment on the GaN ohmic surface was realized by the ICP system. The pressure, flow and time of the oxygen plasma treatment were fixed at 0.8 Pa, 30 cm³/min and 5 min, respectively. This experiment focused on the effects of radio frequency (RF) power and ICP power on GaN ohmic contact. All the experimental conditions are shown in Table 1.

| Sample | Treatment  | RF Power (W)     | ICP Power (W) |
|--------|------------|------------------|---------------|
| A      | reference  | 0                | 0             |
| B–F    | O-plasma   | 30/60/75/90/120  | 250           |
| G–J    | O-plasma   | 75               | 150/200/300/350|

Secondly, the metal layer of Ti/Al/Ni/Au (20 nm/150 nm/45 nm/55 nm) was deposited by electron beam evaporation, followed by rapid thermal annealing (RTA) at 830 °C for 50 s in N₂ ambient to form the ohmic electrode. Next, the transmission line method (TLM) mesa isolation structure was realized by ICP dry etching. The cross-section of the ohmic contact structure is shown in Figure 1, with spacing of 6 µm. After the photoresist (PR) was stripped, the etched depth was 760 nm measured by the DektakXT, indicating the two-dimensional electron gas (2DEG) was removed completely.
3. Results and Discussion

Finally, the electrical characteristics of the TLM structure (Figure 2), with different spacings (from small to large spacings as follows: 6, 8, 10, 13, and 18 µm), were measured by the Keithley 4200 (OH, USA), and the effects of the oxygen plasma treatment on $R_C$ under different powers were studied. The contact mechanism was further analyzed by plotting the change in $R_C$ with the power, and $R_C$ was calculated from the classical formula of $R_{\text{total}} = (d/W) R_{\text{sh}} + 2R_C$. Where $R_{\text{total}}$ is the total resistance, $R_{\text{sh}}$ is the sheet resistance, $d$ is the distance between the electrodes and $W$ is the width of the electrodes.

Figure 1. Cross-section views of the sample structure.

Figure 2. Top view of the transmission line method (TLM) structure.

3.1. Material Characterization and Analysis

Firstly, the morphology of the samples treated by oxygen plasma were analyzed. The surface topography of reference sample A and sample D (measuring an area of $317 \times 317 \mu m^2$) due to the oxygen plasma that bombards the sample surface, while the surface RMS of sample A without the oxygen plasma treatment is 0.564 nm. It proved that the oxygen plasma treatment process used in this paper caused a certain degree of damage to the GaN surface and introduced defects.
Figure 3. Ohmic contact resistance ($R_C$) values of sample A and sample D. The inset shows a linear fit of total resistances of the TLM.

Table 2. Treatment conditions of all samples.

| Sample | $x_{Ga,3d}$/% | $x_{N,1s}$/% | $n$ ($x_{N,1s}/x_{Ga,3d}$) |
|--------|----------------|--------------|-----------------------------|
| A      | 48.1           | 37.6         | 0.78                        |
| D      | 47.8           | 8.6          | 0.18                        |

Lastly, the photoluminescence (PL) spectra of reference sample A and sample D were measured with a 350 nm He–Cd laser at room temperature to analyze the defect density change. It can be observed, from Figure 4, that the luminescence bands of the samples extend from 2.0 eV to 2.5 eV and the main peaks were near the center of 2.2 eV, and they
have similar characteristics to yellow luminescence (YL) [24–27]. The generation of the yellow luminescence band can be attributed to the transition from a shallow donor to a deep acceptor in the GaN. The shallow donor may be nitrogen-vacancy defects generated due to the oxygen plasma treatment [26], and the deep acceptor is confirmed to be a natural defect of Ga vacancy (V$_{\text{Ga}}$) or the complex V$_{\text{Ga}}$–O$_{\text{N}}$ [26,27]. After oxygen plasma treatment, the PL intensity of sample D was significantly increased by 37% compared with reference sample A, indicating that the defect density associated with YL increased. Combined with the N deficiency found in the EDX analysis in Table 2, the shallow donor here is most likely due to the presence of a large number of N vacancies on the surface after the oxygen plasma treatment, which causes the increase in the YL peak and the decrease in the band-edge peak [28]. The formation of ohmic contact is mainly ascribed to the production of a TiN layer at the interface after high-temperature annealing, when the N in GaN reacts with Ti to form TiN, thus introducing the nitrogen-vacancy defects in the GaN layer. The N vacancies act as shallow donors, which is equivalent to the n-type doping in GaN, thus increasing the carrier concentration and enhancing the electron tunneling through the barrier, which is conducive to the formation of ohmic contact [29]. The nitrogen-vacancy defects generated during the oxygen plasma treatment process help to improve the electron tunneling mechanism to form Ohmic contact. Therefore, oxygen plasma treatment of the surface can effectively reduce $R_C$ [30], noise sources, and power consumption, and improve device stability etc.

### Table 2. Treatment conditions of all samples.

| Sample  | xGa,3d/% | xN,1s/| E, eV | PL Intensity, a.u. |
|---------|----------|--------|------|-------------------|
| A       | 2.0      | 2.5    | 3.0  | 3.5               |
| D       | 2.0      | 2.5    | 3.0  | 3.5               |


![Figure 5. Photoluminescence (PL) spectra of sample A and sample D.](image)

**3.2. Study the Influence of RF Power and ICP Power**

The influence of RF power and ICP power on the formation of ohmic contact and its mechanism were emphatically studied. The main reason is that increasing the RF power assists in increasing the plasma energy, while increasing the ICP power can produce high-density plasma. Figure 6a shows the influence of different RF power treatments on ohmic contact at an ICP power of 250 W. The best $R_C$ was 0.34 Ω mm at an RF power of 75 W. Samples with RF power greater than 75 W (90 W and 120 W) and RF power less than 75 W (30 W and 60 W) have relatively poor ohmic performance compared to those with RF power of 75 W. When RF power was less than 75 W, the GaN surface was bombarded with lower energy, resulting in fewer Ga–N bond fractures. Therefore, the number of N vacancies decreased compared with that at 75 W, leading to a decrease in ohmic contact performance. When RF power was greater than 75 W, high-energy particles bombarded the surface of the GaN, leading to surface disorder in the crystal lattice or the formation of a large number of defects on the sample surface [31]. Moreover, defects cannot be eliminated entirely
Figure 6. Impact of radio frequency (RF) power on $R_C$. (a) $R_C$ with different RF power. (b) I–V characteristic curve of different RF power.

The ICP power can also affect the ohmic contact. Figure 7a shows the influence of different ICP power treatments on ohmic contact at an RF power of 75 W. As ICP power increases from 150 W to 250 W, $R_C$ decreases slightly. According to the literature [34], the majority of the implanted O ions were present at an interstitial site in GaN, and consequently had not contributed to the formation of the O donor level. Therefore, excluding the donor-doping effect of O$_N$ introduced by oxygen plasma treatment, and there may be other mechanisms to reduce $R_C$. The analysis shows that as the ICP power increases, the concentration of O ions increases. When high-energy particles bombarded the GaN surface, the number of Ga–N bond breaks increased, which generated more active Ga and N atoms and increased the number of N vacancies. However, the increase in N vacancies was very limited, so $R_C$ decreases by 27% as ICP power rises to 250 W. However, when ICP power exceeded 250 W, $R_C$ was not related to the change in ICP power. Because, increasing the number of O ions may not increase the concentration of oxygen atoms incorporated into the GaN, resulting in the number of Ga–N bond breaks remaining unchanged, as the solubility of oxygen was limited by the formation of Ga$_2$O$_3$ [31]. The I–V characteristics of ohmic contact with oxygen plasma treatment at different ICP power were measured on the TLM patterns with a spacing of 6 µm, as shown in Figure 7b. It can be seen from the figure that with the increase in ICP power, the slope of the I–V curve increases, but when RF power exceeds 250 W, the slope of the I–V curve remains unchanged.

3.3. AlGaN/GaN HEMTs DC Characteristics

The output and transfer characteristics of the AlGaN/GaN HEMTs fabricated using oxygen plasma treatment (ICP power of 250 W, RF power of 75 W, 0.8 Pa, O$_2$ flow of 30 cm$^3$/min, 5 min) are depicted in Figure 8a,b respectively. The device has a gate length,
Lg = 0.8 μm, and a gate-to-drain distance, Lgd = 4 μm. The gate bias was varied from +2 V to −1.5 V in steps of −0.5 V. The maximum drain current was 0.77 A/mm at Vg = +2 V, and the threshold voltage was −1.9 V (at 1 mA/mm) at Vd = 6 V. These results demonstrate that the oxygen plasma treatment method has efficiently improved the DC performance of HEMTs by optimizing the ohmic characteristics.

Figure 7. Impact of inductively coupled plasma (ICP) power on R_C. (a) R_C with different ICP power and (b) I–V characteristic curve of different ICP power.

Figure 8. (a) Output and (b) transfer characteristic curves of AlGaN/GaN high electron mobility transistors (HEMTs).

4. Conclusions

This paper studied the effects and mechanisms of oxygen plasma surface treatment on ohmic contact of AlGaN/GaN HEMTs. The experiments show that the R_C of AlGaN/GaN HEMTs, which were treated with the oxygen plasma generated by the ICP system (ICP power of 250 W, RF power of 75 W) and annealed for 50 s at 830 °C in N2 ambient, reduced by about 74% (up to 0.34 Ωmm) compared with the sample without oxygen plasma treatment. It can be inferred, from AFM, EDX and PL characterization results, that oxygen plasma treatment increases the nitrogen-vacancy defects near the surface, and nitrogen vacancy appears as a shallow donor, which reduces R_C through the tunneling
effect. Compared with other treatment methods, the oxygen plasma treatment method has a simple process and can be widely used in the industry.

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