Plasma-assisted surface treatment for low-temperature annealed ohmic contact on AlGaN/GaN heterostructure field-effect transistors

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In this study, a low-temperature annealed ohmic contact process was proposed on AlGaN/GaN heterostructure field effect transistors (HFETs) with the assistance of inductively coupled plasma (ICP) surface treatment. The effect of ICP treatment process on the 2DEG channel as well as the formation mechanism of the low annealing temperature ohmic contact was investigated. An appropriate residual AlGaN thickness and a plasma-induced damage are considered to contribute to the low-temperature annealed ohmic contact. By using a single Al layer to replace the conventional Ti/Al stacks, ohmic contact with a contact resistance of 0.35 Ω·mm was obtained when annealed at 575 °C for 3 min. Good ohmic contact was also obtained by annealing at 500 °C for 20 min.

Keywords: AlGaN/GaN HFET, low-temperature ohmic contact, inductively coupled plasma (ICP), surface treatment

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1. Introduction

AlGaN/GaN heterostructure field-effect transistors (HFETs) have advantages to develop high-frequency and high-power devices owing to the high electron mobility, high saturation velocity and high electron density of the two-dimensional electron gas (2DEG) channel.[1–6] To improve the performances of AlGaN/GaN HFETs, a self-aligned-gate (SAG) structure was proposed to decrease the access resistance.[7] In the SAG structure, T-shaped Schottky gate is fabricated firstly as a mask directly for the ohmic metal evaporation. After that, it is necessary to anneal the Schottky gate and the ohmic electrodes simultaneously in order to obtain a good ohmic contact. To avoid degradation of the Schottky contact after annealing at high temperature (commonly above 800 °C for the AlGaN/GaN HFETs), one way is to find a gate material which can withstand the high-temperature annealing.[8] Another way is to reduce the ohmic contact annealing temperature[9] or even develop a non-annealing ohmic process.[10] Furthermore, dielectrics such as Al_2O_3[11] and HfO_2[12] layers are also necessary in high-frequency and high-power devices to reduce the leakage current and/or noise. The present of dielectrics requires an annealing temperature to be lower than 600 °C because of the low poly-crystallization temperature of the dielectrics.[13]

In our previous work, with the assistance of inductively coupled plasma (ICP) treatment on the surface of ohmic contact area, good ohmic behavior between the metal stack and the semiconductor could be realized at a relatively low annealing temperature of 575 °C and short annealing time of 1 min. It was found that the ohmic contact resistance showed a strong relationship with the ICP treatment conditions.[14] However, the effect of the ICP treatment on the treated surface was not evaluated in detail. The formation mechanism of the low-temperature ohmic contact was not clear, especially on the point of which factor, the lattice damage caused by the ICP treatment or the thinning of the AlGaN layer, takes more important role to the formation of the low-temperature ohmic contact.

Herein, the ICP plasma-assisted low annealing temperature ohmic contact on the AlGaN/GaN heterostructure was investigated to verify the formation mechanism. Samples with entirely-treated surface were fabricated to evaluate the effect of the ICP treatment process on the 2DEG channel. By using a low melting point metal Al to replace the conventional Ti/Al stack, an optimized ohmic contact was achieved with an annealing temperature as low as 500 °C.

2. ICP surface treatment and device fabrication

The epitaxial wafers of the AlGaN/GaN HFETs used in this experiment were grown by metal organic chemical vapor deposition (MOCVD) on a high resistance silicon substrate. It consists of a buffer layer, a 1 μm i-GaN, a 25 nm i-AlGaN, and a 2 nm i-GaN from the bottom to the top. The Al mole fraction of the AlGaN layer is approximately 25%.

To evaluate the effect of ICP treatment on the surface and to verify the formation mechanism of low-temperature ohmic

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process for AlGaN/GaN heterostructure, two groups of samples with the transmission line model (TLM) patterns were prepared by plasma-assisted treatment using an ICP system (Fig. 1). The residual AlGaN thickness after treatment was measured using atomic force microscope (AFM). After cleaning, the surface of one group of samples were entirely treated with a residual AlGaN layer thickness of approximately 25.0 (without treatment), 20.0, 17.7, 13.1, 10.8, and 8.2 nm, under both ICP and bias power of 100 W. The surface of another group of samples were treated with ICP power of 100 W and bias power of 20, 60, and 100 W, respectively, by keeping the residual AlGaN thickness at the same level of approximately 10.8 nm. Then, mesa with a depth of 100 nm was formed by the same ICP system to serve as the device isolation. The mass flow of the $SiCl_4$ etching gas was 4 sccm and the pressure of the chamber was 0.3 Pa for all the dry process. After the treatment process, all the samples were dipped into a solution of BHF/HNO_3 (1:1) to remove the possible Si contamination induced by the ICP process. After that, a standard lithography process was used to define the TLM patterns. The ohmic electrodes for all the samples were formed by magnetron sputtering of Al films with a thickness of 200 nm. Lastly, these two groups of samples were annealing at 575 °C for 3 min to form ohmic contact. A Ni/Au (70/30 nm) bi-layer was then formed by sputtering as the gate electrode.

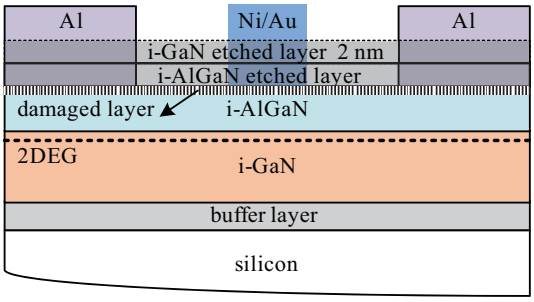


Fig. 1. (color online) Cross sectional view of the devices fabricated on an entirely-treated surface.

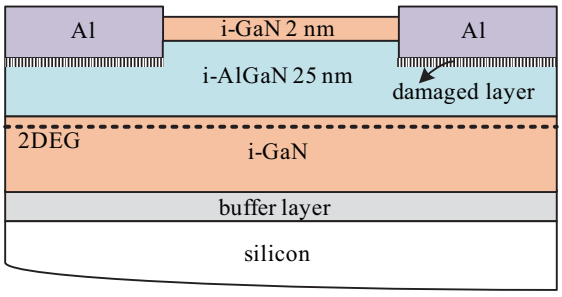


Fig. 2. (color online) Cross sectional view of the evaluation structure fabricated on a partially-treated surface.

Samples used to evaluate the ohmic contact at low annealing temperature were also prepared. After sample cleaning, the surface of the samples were treated partially on the ohmic contact area after mesa isolation (Fig. 2). The etching conditions were the same as the entirely-treated samples with the residual AlGaN thickness of approximately 10.8 nm for all these samples. After the surface treatment process and the BHF/HNO_3 (1:1) dipping, a 200 nm Al electrode was deposited using magnetron sputtering. Finally, the samples were annealed at 500 °C for 5, 10, 15, 20, 25, and 30 min.

3. Results and discussion

We firstly evaluated the ohmic contact on the entirely-treated (treating power/bias power were fixed at 100/100 W) AlGaN/GaN surface with different residual AlGaN thickness. The surface roughness for all samples after ICP treatment are comparable as confirmed by AFM (approximately 0.6 nm in 5×5 μm^2, not shown). Figure 3 shows the current-voltage (I–V) characteristics recorded on the TLM patterns with an interval of 5 μm and a width of 150 μm. After annealed at 575 °C for 3 min, all samples present linear curves suggest that good ohmic contact behavior are formed between metal and semiconductor. The corresponding ohmic contact resistance and sheet resistance at different residual AlGaN thickness were obtained as shown in Fig. 4. It is found that the sheet resistance increases and the contact resistance decreases with the increasing treatment time. Minimum contact resistance of 0.35 Ω·mm and a contact resistivity of 1.10×10^{-6} Ω·cm^2 are obtained at the residual AlGaN thickness of 10.8 nm. However, when the residual thickness of AlGaN layer decreases to 8.2 nm, both the contact resistance and sheet resistance increase suddenly implying that the 2DEG channel nearly disappeared.[15]

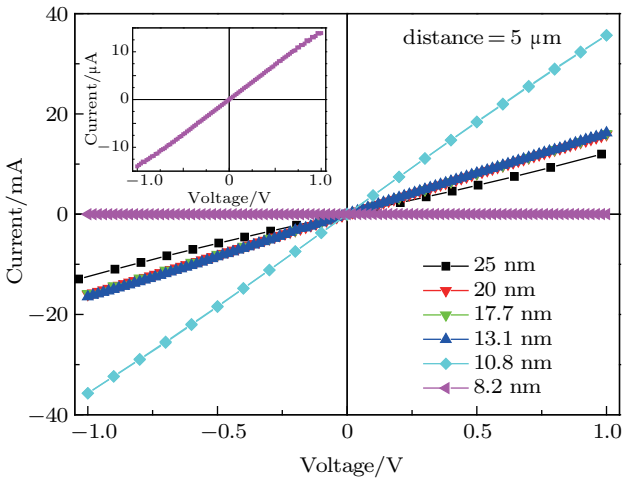


Fig. 3. (color online) Current–voltage (I–V) characteristics recorded on the TLM patterns with an interval of 5 μm. Inset: residual AlGaN thickness is 8.2 nm.

The sudden increase of the sheet resistance at the residual AlGaN layer of less than 8.2 nm is possibly due to the weakened piezoelectric effect. By using a transconductance-capacitance method on an FATFET, the electron mobility and electron sheet density of the entirely-treated AlGaN/GaN

HFETs were measured and shown in Fig. 5. To calculate the electron sheet density, the sheet resistance data shown in Fig. 4 were used. From Fig. 5, we can see that the 2DEG mobility and sheet density decrease mildly with the increasing treating depth and kept almost constant until the residual AlGaN thickness to approximate 10.8 nm with a mobility of approximately 961 cm^2/V s and a sheet density of approximately 5.95×10^{12} cm^{-2}. Finally, both of the mobility and density decrease drastically when the residual AlGaN thickness became 8.2 nm, implying that the residual AlGaN thickness is lower than the critical thickness. The transfer characteristics (inset of Fig. 5) were recorded for transistors fabricated on the entirely-treated surface. The threshold voltage shifts positively with the decreasing residual AlGaN thickness. This also confirms the weakened piezoelectric effect (lower 2DEG concentration). From these results, the residual AlGaN thickness is a key parameter to obtain a good ohmic contact at a low annealing temperature. A critical AlGaN thickness exists to keep certain electron mobility and sheet carrier density of the 2DEG channel.

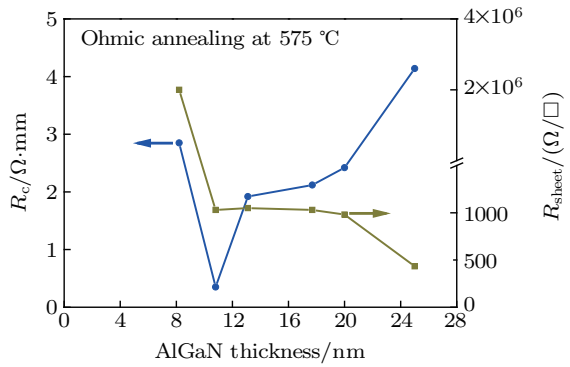


Fig. 4. (color online) Ohmic contact resistance (R_c) and sheet resistance (R_{sheet}) of the samples with different residual AlGaN thickness.

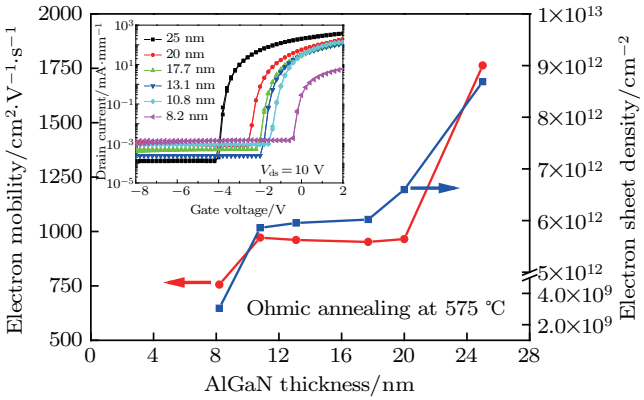


Fig. 5. (color online) The dependency of mobility and sheet density on residual AlGaN barrier thickness. Inset is the corresponding transfer characteristics of transistors fabricated on the recessed surface.

The ICP damage was also reported to introduce n-type doping (N-vacancies),[7] which will upshift the Fermi level at the surface of the AlGaN. Fermi level close to the conduction band edge can decrease the effective Schottky barrier height (SBH) for electron transport (Fig. 6). To verify the role of the damage on the contact resistance of the AlGaN layer, we fabricated samples treated with ICP power of 100 W and bias power of 20, 60, and 100 W, respectively, but keeping the same AlGaN thickness of approximately 10.8 nm. As shown in Fig. 7, the ohmic contact resistance decreases with the increasing ICP bias power, while the sheet resistance increased with the increasing bias power. High bias power can cause more N vacancies, leading to the electron mobility and density decreasing. Additionally, the reduced AlGaN thickness by the ICP treatment will reduce the thickness of the Schottky barrier (Fig. 6). If the ICP-treated AlGaN is thin enough, combining the damage-induced n-type layer, the electron can tunnel through the barrier layer to form a good ohmic contact.

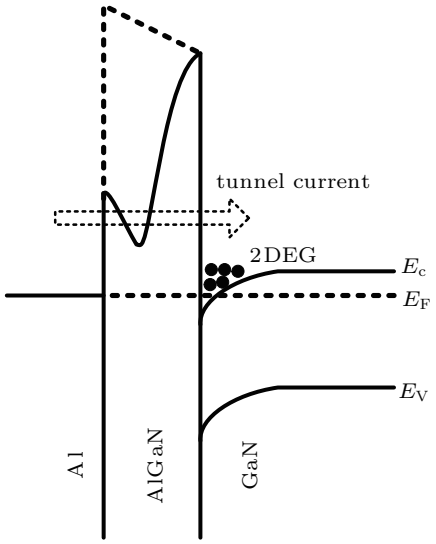


Fig. 6. Band diagram of the surface-treated AlGaN/GaN heterostructure with Al electrode.

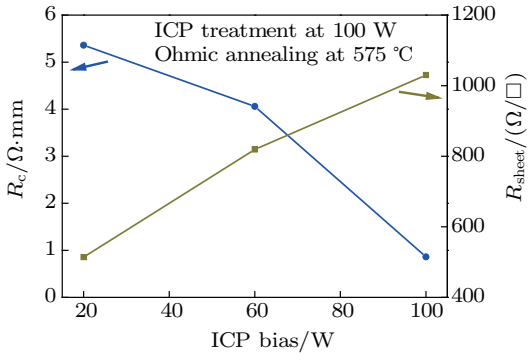


Fig. 7. (color online) ICP bias dependence of the ohmic contact resistance (R_c) and the sheet resistance (R_{sheet}).

It should be mentioned that good ohmic contact could not be obtained using this low-temperature process if the conventional Ti/Al-based metal stack was utilized. Compared with the Al electrode, the TLM result of the Ti/Al/Ti/Au electrode confirms that the existence of Ti would hindrance the contact

between Al and the AlGaN, deteriorating the ohmic contact. A possible reason is related to the formation mechanism on AlGaN/GaN heterostructure. The formation of the N vacancy caused by plasma treatment brings merit for the ohmic contact formation, which agrees well with some literatures using the conventional Ti/Al/Ti/Au or Ti/Al/Ni/Au stacks.[16–19] However, the annealing temperatures in their works were still around 800 °C. For the conventional Ti/Al-based metal stack, Ti will react with AlGaN layer under high temperature annealing to generate N vacancy in the AlGaN.[20] N vacancy then create a highly-doped n-type region in the proximity of the interface and decrease the contact resistance between Al and AlGaN. However, in the low-temperature (below 600 °C) annealed ohmic contact process, Ti will nearly not react with AlGaN because of the extremely high melt point (approximately 1678 °C). Therefore, for the plasma-assisted surface treatment, the damage-induced n-type doping layer (N-vacancies) can fill up the function of Ti and Al single layer is much suitable to obtain a low-temperature annealed ohmic contact.

To verify the ohmic contact at a lower annealing temperature of 500 °C, we used samples with ICP-treatment only in the ohmic area for evaluation. The remained AlGaN thickness was approximately 10.8 nm with both ICP and bias power of 100 W. After annealed at 500 °C for 5–30 min (Fig. 8), *R*c decreases from approximately 2.96 Ω·mm (5 min) to approximately 0.70 Ω·mm (15 min) and 0.69 Ω·mm (beyond 20 min). Further increasing the time, the R_c value kept at approximately 0.69 Ω·mm and 1.18×10^{-5} Ω·cm^2. These results confirm that good ohmic contact performance can be realized at a relatively low annealing temperature with long time on the ICP-treated AlGaN/GaN heterostructure.

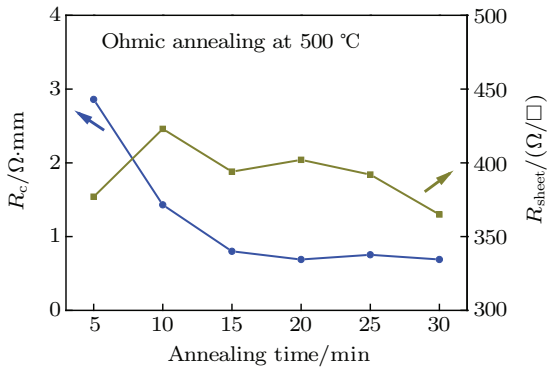


Fig. 8. (color online) Dependence of the ohmic contact resistance (R_c) and the wafer sheet resistance (R_{sheet}) on the annealing time when annealed at 500 °C.

4. Conclusions

In conclusion, the mechanism of a low-temperature annealed ohmic contact on AlGaN/GaN HFETs with the plasma-assisted surface treatment was verified. Both the N vacancies caused by the ICP damage and the reducing of AlGaN thickness during the ICP treatment are beneficial for obtaining a low-temperature annealed ohmic contact. A low ohmic contact can be achieved by using a single Al layer to replace the conventional Ti/Al stacks. With the assistance of the ICP treatment, an ohmic contact with a contact resistance of 0.35 Ω·mm and a contact resistivity of 1.10×10^{-6} Ω·cm^2 were obtained at the residual AlGaN thickness of 10.8 nm when annealing at 573 °C for 3 min. Even at a lower annealing temperature of 500 °C, an ohmic contact with a contact resistance of 0.69 Ω·mm and a contact resistivity of 1.18×10^{-5} Ω·cm^2 was obtained. This low-temperature annealed ohmic contact process is helpful for the self-aligned-gate structure AlGaN/GaN HFETs and some fabrication process where high temperature should be avoided.

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