Boron trichloride plasma treatment effect on ohmic contact resistance formed on GaN-based epitaxial structure

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Abstract. A BCl_3 plasma treatment effect on GaN surface and reduction of ohmic contact resistance in GaN/AlGaN epitaxial structure with a GaN cap layer has been studied. The BCl_3 plasma treatment was carried out by an inductively coupled plasma reactive ion etching (ICP RIE) system under conditions of low discharge power with zero external bias controlling power to prevent any recess etching of the GaN cap layer. The measured average contact resistances with and without plasma treatment were 1.8×10^{-5} and 1.05×10^{-5} $\Omega \cdot cm^2$, respectively. To study the BCl_3 plasma treatment effect on GaN surface and explain the increasing of contact resistance, the elemental composition of GaN surface was measured using x-ray photoelectron spectroscopy. It was found that a B_x–Cl_y layer covered the GaN surface after the BCl_3 plasma treatment. This can indicate that ion bombardment from plasma is inefficient to prevent deposition of BCl_x radicals on the GaN cap layer surface and subsequent formation of the B_x–Cl_y layer which is responsible for increase of ohmic contact resistance after the BCl_3 plasma treatment.

1. Introduction

The GaN-based high electron mobility transistors (HEMT) are promised to play a key role in the next-generation electronic devices such as mobile communication systems and pulsed radars. High breakdown fields, high saturation velocities and high thermal conductivities of GaN/AlGaN HEMTs result in its successful application at high powers, high frequencies and high temperatures [1]. To achieve excellent performance of these devices, it is important to obtain low-resistance ohmic contacts. Plasma enhanced etching processes in chlorine environments have been established to lower the contact resistance in GaN-based HEMT [2, 3]. However, the implementation of uniform ohmic contact is still difficult in case of large diameter wafers using this technology because of difficulty with provision of plasma enhanced etching uniformity.

Recently, Fujishima and co-authors [4] have reported a BCl_3 plasma treatment technique without any recess etching of the substrate implemented for low-resistance ohmic contact formation on GaN/AlGaN HEMTs with GaN cap layer using an Inductively Coupled Plasma Reactive Ion Etching (ICP-RIE) system. According to x-ray photoelectron spectroscopy and positron annihilation spectroscopy measurements they established that a surface oxide layer was efficiently removed from GaN cap layer and the vacancy-type defects were generated during the plasma treatment resulting in

reduction of contact resistance [4]. Earlier other studies were also dedicated to the mechanism of GaN surface donor density increasing during the ion irradiation from plasma [5, 6].

In the present study BCl_3 plasma treatment of GaN cap layer without any recess etching have been performed using ICP-RIE system to obtain a lower contact resistance. To study its effect on GaN surface and subsequent ohmic contact resistance, the elemental composition of GaN surface after BCl_3 plasma treatment was measured using x-ray photoelectron spectroscopy (XPS).

2. Experimental setup

AlGaN/GaN structure with 2 nm GaN cap layer was deposited on SiC substrate using Molecular Beam Epitaxy (MBE) method. Photolithography was performed to pattern the ohmic contacts. Then, O_2 plasma ashing was performed to remove photoresist residuals, followed by a dip in pre-metallization solution of deluted HCl. After that one half of the wafer was exposed to BCl_3 plasma treatment in ICP-RIE system (Corial 210D) at power of 200 W under pressure of 10 mTorr and gas flow rate of 10 sccm for 1 minute of plasma treatment. External bias controlling power was set to zero because increasing of DC bias increases ion bombardment from plasma which results in recess etching of the sample. During the plasma treatment another half of the wafer was masked with a piece of quartz wafer and was not exposed to plasma. Then, ohmic contacts metallization Ti/Al/Ni/Au was performed followed by Rapid Thermal Anneal (RTA) at 830°C. Mesa isolation was formed by dry etching in BCl_3/Ar mixture in ICP-RIE system. Finally, contact resistance was measured by the Transmission Line Method (TLM). The width and length of the contacts were both 100 μm. The distance between contacts was of 5, 10, 20, 40, 200 μm as it is shown in figure 1.
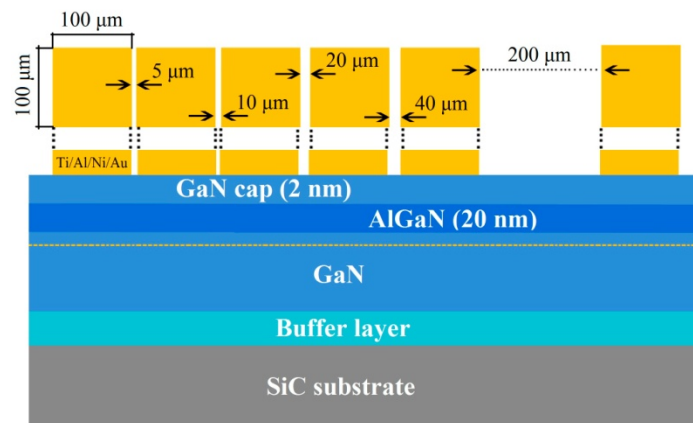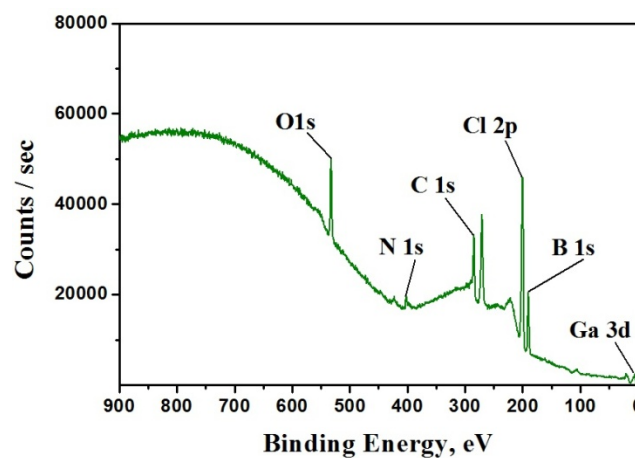

Figure 1. Schematic TLM structure of AlGaN/GaN epitaxial structure with 2 nm GaN cap layer and ohmic contact metallization.
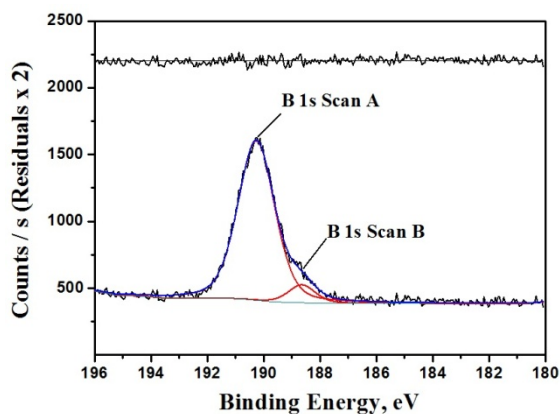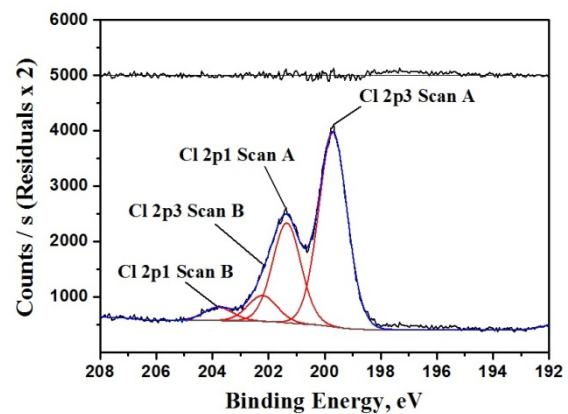
3. Results and discussion

In the case of substrate exposed to BCl_3 plasma treatment for 1 minute the measured average ohmic contact resistance was 1.8×10^{-5} $\Omega \cdot cm^2$ which is 1.7 times higher than for the untreated one (1.05×10^{-5} $\Omega \cdot cm^2$). To study the BCl_3 plasma treatment effect on surface of GaN cap layer and increase of ohmic contact resistance, XPS analysis of GaN cap layer was carried out using a VG Escalab technique. The surface chemical composition of the substrate after plasma treatment step was characterized by monitoring the B 1s, C 1s, Cl 2p, Ga 3d, N 1s and O 1s peaks. The high atomic percentages of boron (29.7%), chlorine (35%) and carbon (20.6%) elements were observed at the surface after exposure to BCl_3 plasma. Summarized information on measured atomic percentage is presented in the table 1. Very low XPS signal coming from GaN substrate (gallium and nitrogen atomic elements) was obtained as it is shown from the measured survey spectrum in figure 2. High percentage of carbon at GaN surface is explained by exposure to ambient atmosphere and difficulties with its removal during the measurements.

Table 1. Atomic composition of GaN cap layer surface after BCl_3 plasma treatment obtained from XPS measurements.

Element peak	Binding energy peak (eV)	Atomic percentage (%)
Cl 2p	200.31	34.97
B 1s	190.39	29.67
C 1s	284.85	20.59
O 1s	532.71	8.71
Ga 3d	19.19	3.11
N 1s	402.58	1.74

Figure 2. XPS survey spectrum measured after BCl_3 plasma treatment of GaN cap layer.

Two high peaks characterizing a B–Cl bond obtained from the analysis of GaN surface after exposure to BCl_3 plasma are also reported. The B 1s peak located at 190.2 eV is attributed to B bonded to Cl and Cl 2p one located at 199.7 eV is attributed to Cl bonded to B. Therefore, we can assume an existence of B_x–Cl_y layer on the GaN surface after BCl_3 plasma treatment step. The corresponding high-resolution spectra in the energy range of the B 1s and Cl 2p signal are shown in figure 3 and figure 4, respectively.

Figure 3. High-resolution B 1s spectrum obtained from XPS measurements of GaN surface after plasma treatment.

Figure 4. High-resolution Cl 2p spectrum obtained from XPS measurements of GaN surface after plasma treatment.

Another chlorine binding state was observed at binding energy of 201.4 eV and could be attributed to Cl–O bond because of possible oxygen incorporation from the quartz walls of the reactor during the plasma treatment [7].

It is known that exposure to BCl_3 plasma is a good recipe to remove Ga_xO_y layer formed after O_2 ashing step and exposure to ambient atmosphere [4, 8]. During the plasma processing BCl_x radicals generated by electron impact dissociation increase oxide layer etching by forming volatile B_xOCl_y and B_xO_y surface by-products which are removed from substrate by ion bombardment from plasma. On the other hand, if ion bombardment is weak due to low ions energy and flux, removal of the volatile by-products from the surface covered by thin oxide layer will be inefficient and the deposition of BCl_x radicals can lead to formation of B_x–Cl_y layer during the plasma processing. The analogous mechanism describing an impact of ion bombardment on a transition process from the deposition regime to the recess etching in case of HfO_2 and SiO_2 etching by BCl_3 plasma was reported by Sungauer and co-authors [7]. Therefore, in our case it is necessary to increase ion energy and flux by application of external bias controlling power to remove B_x–Cl_y layer and induce nitrogen vacancies during the BCl_3 plasma treatment step without any recess etching of the GaN cap layer. The measured average contact resistance in case of increased ion energy was 6.79×10^{-6} $\Omega\cdot cm^2$ which is 1.54 times lower than for the untreated one (1.05×10^{-5} $\Omega\cdot cm^2$).

4. Conclusion

In present work BCl_3 plasma treatment effect on surface of GaN cap layer of AlGaN/GaN epitaxial structure has been studied. Plasma treatment was performed in ICP-RIE system at low ICP power and zero external bias controlling power. It was found that exposure to BCl_3 plasma treatment resulted in increase of the ohmic contact resistance, in contrast to the results from the [4]. The measured average ohmic contact resistances after plasma treatment and without it were 1.8×10^{-5} and 1.05×10^{-5} $\Omega\cdot cm^2$, respectively. In order to study the BCl_3 plasma treatment effect on GaN cap layer surface and subsequent increase of contact resistance, the chemical composition of the GaN surface was characterized by monitoring the B 1s, C 1s, Cl 2p, Ga 3d, N 1s and O 1s peaks using XPS. The measurements have shown the high atomic percentage of boron (29.7%), chlorine (35%) and carbon (20.6%) elements and small signal from GaN substrate elements (Ga and N). C 1s peak characterizes the carbon contamination from ambient atmosphere. The obtained B 1s and Cl 2p peaks characterize the B–Cl bonds. This indicates that the B_x–Cl_y layer covers the GaN surface because of inefficient removal of the volatile by-products and subsequent deposition of BCl_x radicals on the GaN surface covered by thin oxide layer. The analogous mechanism was described previously for HfO_2 and SiO_2 etching in BCl_3 plasma [7]. The increase of ion energy during the BCl_3 plasma treatment by applying additional bias controlling power resulted in 1.54 times decrease of contact resistance which can be explained by removal of B_x–Cl_y layer and subsequent reduction of ohmic contact resistance.

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