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Influence of high Al fraction on reactive ion etching of AlGaN/GaN heterostructures

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In this study, the results of reactive ion etching (RIE) process of diversified Al content $Al_xGa_{1-x}N$/AlN/GaN/sapphire heterostructures were presented. The Al fractions of 22, 25, 31 and 36% were examined. An impact of Al content in the heterostructures on the etch rates and surface morphology was investigated. The influence of used $Cl_2/BCl_3/Ar$ gas mixture with varying of BCl_3 flow on the etch rate of $Al_{0.2}Ga_{0.8}N$/GaN/sapphire, surface morphology and angle of mesa slope, was discussed.

Keywords: reactive ione etching, HEMT, AlGaN/GaN heterostructure.

1. Introduction

Gallium nitride (GaN) and aluminum gallium nitride (AlGaN) are the materials currently investigated by numerous research groups because of many potential advantages such as wide band gap, high saturation velocity and high electron mobility [1]. These materials would allow to fabricate advanced (opto)electronic devices such as lasers, UV detectors and high power/frequency transistors, which could work in harsh environment. Commonly used processes of fabrication of electronic devices have to include the stages of active region definition in the device: photolithography and wet or dry etching of the semiconductive structure. In order to fabricate high electron mobility transistors (HEMTs) or other GaN based devices, highly controllable mesa etching process has to be performed. The etch depth in such structures must be larger than AlGaN layer thickness. In this case more than 25 nm of heterostructure have to be etched. Very high resistivity of GaN and AlGaN to wet etching chemicals results in insufficient etch rates. The process of reactive ion etching is a viable technique, which enables to create a desired shape of mesa profile in a reasonable time regime. The AlGaN layer with a high bond energy (11.52 eV/atom) is much more resistant to dry etching compared with the GaN with the bond energy of 8.9 eV/atom [2]. An easy solution in obtaining high etch rates relies on increasing RF power during the reactive ion etching (RIE) process. However, the experience in doing this will make the process of etching very fast with relatively high surface damage caused by a high energy of ion bombardment. By choosing adequate gas mixture [3], a sufficiently high etch rate combined with relatively low surface damage can be achieved.

2. Experiment

The test structures are the heterostructures of $Al_xGa_{1-x}N$/GaN/sapphire and $Al_xGa_{1-x}N$/AlN/GaN/sapphire with the following thicknesses: 20 nm ($Al_xGa_{1-x}N$), 1–2 nm (AlN), 2040–2125 nm (GaN). The experiment consists of two parts. In order to examine the influence of BCl_3 flow rate on surface roughness, heterostructures with 20% of Al were etched using $Cl_2/BCl_3/Ar$ gas mixture with the diversified gas flows: 10 sccm (Cl_2), 5 sccm (Ar), 2, 5 and 10 sccm (BCl_3). Then, the heterostructures with similar and higher Al content were etched using adequate gas mixture in order to evaluate surface roughness and the etch rates. All the processes were conducted in Plasmalab 80+ RIE system with asymmetric electrodes. The process parameters were set as follows: pressure $p = 20$ mTorr (2.66 Pa), RF power $P_{RF} = 150$ W, self DC bias $U_{DC} = 110$ V and temperature $T = 7$ °C. The system software enabled us to maintain constant U_{DC} during the processes. The surface morphology as well as the etch depths of etched heterostructures were examined using AFM (atomic force microscope) technique and the surface topography with the angle of mesa slope was evaluated using Hitachi SU-6600 SEM (scanning electron microscope).

3. Results and discussion

The $Al_{0.2}Ga_{0.8}N$/GaN/sapphire heterostructures were etched with three different gas flows: 2, 5 and 10 sccm which equals to 11, 25 and 40% of BCl_3 in the total $Cl_2/BCl_3/Ar$ gas mixture. The surface morphology of etched $Al_{0.2}Ga_{0.8}N$/GaN/sapphire test structures is presented in Fig. 1. The lowest amount of BCl_3 resulted in reduced roughness average parameters and very low etch rate of $Al_{0.2}Ga_{0.8}N$ equal to 4 nm/min. With increasing the BCl_3 amount in the gas mixture, the values of roughness average (R_a) and root mean square (RMS) evaluated from AFM pictures were constantly increasing indicating rough surface. It is possible to use this effect to improve adhesion of metal contact to etched mesa structures created in the heterostructures. The AFM pictures were collected from etched GaN which is lying underneath $Al_{0.2}Ga_{0.8}N$ layer. In all the cases the surface investigation was performed at a comparable etch depth (50–70 nm). The average etch rates of $Al_{0.2}Ga_{0.8}N$/GaN/sapphire heterostructures in the gas mixtures employing 5 and 10 sccm of BCl_3 were 20 and 36 nm/min, respectively. It is well known that BCl_3 enhances the etching by effective removal of oxygen during the process [4]. Oxygen present in the native oxide on the surface as well as in the chamber may reduce the etch rate significantly. Considering the fact that native oxide causes a micro masking effect, it is crucial to

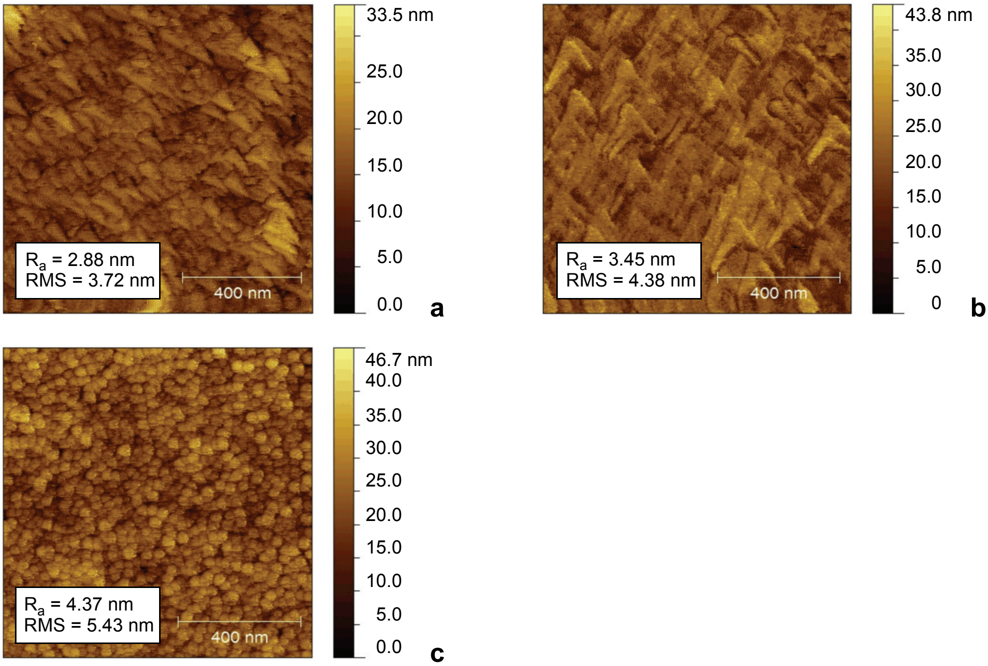

Fig. 1. A surface morphology of etched $Al_{0.2}Ga_{0.8}N/GaN$ using gas $Cl_2/BCl_3/Ar$ gas mixture containing BCl_3 amount equal to 2 sccm (**a**), 5 sccm (**b**) and 10 sccm (**c**).

remove it at the beginning of the process. The combination of $Cl_2/BCl_3/Ar$ was chosen, because of high reactivity of chlorine. The main reason why it is the appropriate gas mixture was carefully described in our previous work [3]. The BCl_3–Cl_2 plasmas show encouraging results in etching, because of improved sputter desorption due to higher mass ions, and also reduced surface oxidation by gathering H_2O from the reaction chamber [5]. Lee *et al.* [6] pointed to the fact that the highest etch rate was obtained for 10% of BCl_3 in BCl_3–Ar plasma when the highest current density as well as the chlorine radical density are at the highest level. In this study, the combination of $Cl_2/BCl_3/Ar$ was used and addition of chlorine to each investigated mixture increased chlorine radical density and 40% of BCl_3 caused the highest observed etch rate. Plasma diagnostics results presented by Kim *et al.* [7] revealed that the main ion species are Cl_2^+ and BCl_2^+ at 20 mTorr (2.66 Pa). Those and the other species (Cl^+, BCl_x^+, B^+) present in Cl_2–BCl_3 plasma increase the etch rates, because of creation of high volatile etch products, such as $AlCl_3$ and $GaCl_3$ with relatively low boiling points: 183 and 201 °C, respectively. Kim *et al.* [8] suggested that although the temperature of a sample holder is being kept at around room temperature, the heat conduction from the plasma probably provides the temperature high enough to enable boiling of $GaCl_3$, thus increasing the etch rates. These are the main reasons why employing more BCl_3 into the $Cl_2/BCl_3/Ar$ gas mixture results in the magnified etch depths in examined samples. The investigation of surface topography, using SEM technique, revealed a lower angle

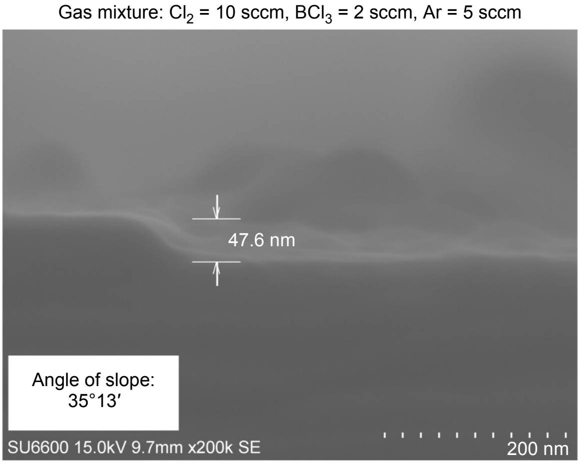

Fig. 2. An example of mesa-slope angle obtained for the Cl_2/BCl_3/Ar gas mixture containing 2 sccm of BCl_3.

of slope of about 35° for less amount of BCl_3 (11%) compared to an angle of about 35° obtained for both 25% and 40% of BCl_3 amount. An example of SEM picture obtained for the heterostructure etched with the Cl_2/BCl_3/Ar gas mixture containing 2 sccm of BCl_3 is presented in Fig. 2.

The second part of the study focuses on etching of high Al content heterostructures with an additional 1–2 nm thick AlN spacer. The above results let us conduct the processes of etching with 40% of BCl_3 in the gas mixture. The test structures with the etch rate vs. Al fraction dependence are presented in Tab. 1 and Fig. 3**a**. Increasing Al content in the heterostructures leads to decreasing the etch rates. In the light of the fact that there are much more Al–N and Al–O bonds whose binding energies are harder to break, the result is sensible. The main etch product of Al etching is $AlCl_3$ with its bonding energy equal to 183 °C. However, more Al–O binds at the surface are preventing the AlGaN to be etched quickly. KIM *et al.* [7] demonstrated that the etch rate of AlGaN appeared to be strongly related to the removal of AlO_x on the etched AlGaN surface rather than the abundance of the specific radicals and ions in the plasma.

Table. 1. The Al_xGa_{1-x}/AlN/GaN/sapphire test structures.

Sample	Al content [%]	Thickness [nm]			Depth on which R_a, RMS and median values were measured [nm]
		$Al_xGa_{1-x}N$	AlN	GaN	
60	22	20	1.66	2355	76±3
62	25	20	1.66	2355	67±3
64	31	20	1.66	2265	53±2
66	36	20	1.66	2315	79±4

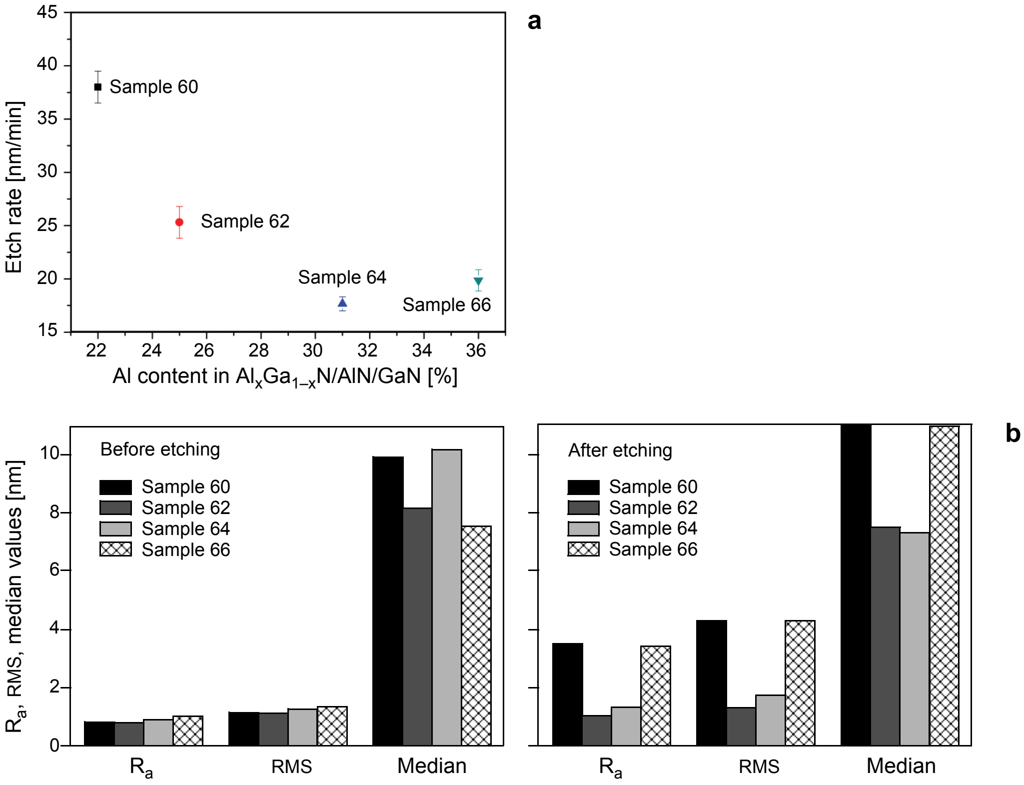

Fig. 3. The etch rate vs. Al fraction dependence (**a**) along with roughness parameters comparison of investigated surfaces (**b**).

In the context of dry etching, there is a phenomenon called dead-time which is a time lag between the start of plasma discharge and the start of etching [9]. More Al–O bonds at the surface have a strong influence on the etch depths, which results in a decreased etch rate for an increasing Al content in the heterostructures. In accordance with Smith's study [10], $AlCl_x$ – a main etch product of Al has a lower volatility compared to $GaCl_x$. This explains the time-lag and a much slower AlGaN layer etch rate as compared to that achieved for GaN layer. The heterostructures with 36% of Al were etched with a slightly increased etch rate compared to that obtained for 31%. This result can be explained by smooth and uniform "as grown" heterostructure surface, as evidenced from the lowest noted median value.

On the grounds that the etch rate of heterostructure with and without the AlN spacer was comparable, employing the AlN spacer did not influence the etch depths significantly.

The surface roughness parameters collected in Fig. 3**b** revealed that the surface of etched GaN, compared to "as grown" surface of the investigated heterostructures containing layers with Al content equal to 25% and 31%, has very similar roughness parameters. Lower median values, in case of etched heterostructures, indicate a very low impact of ion bombardment on surface roughness deterioration. On the etched samples with Al content equal to 22% and 36%, the influence of ion impact is more evident, what can be related to bigger etch depth.

4. Conclusions

The reactive ion etching processes with different gas mixtures were successfully conducted on heterostructures with 20% of Al content. An increased amount of BCl_3 in gas mixture of $Cl_2/BCl_3/Ar$ leads to intensified surface roughness and increased etch rates. Also more BCl_x radicals present in the plasma resulted in a higher value of a mesa slope angle. By applying different gas mixtures, the surface morphology can be modified as required. This includes improving metallization adhesion at the metal–AlGaN interface and changing overall properties of GaN surface.

An increased amount of Al fraction in the $Al_xGa_{1-x}N$ layers resulted in a decreased value of an etch rate which is strongly related to AlO_x removal from the chamber and the total amount of Al–O bonds created on the surface. More Al–O bonds cause formation of native surface oxide, that can be dislodged with BCl_3 treatment. In the light of the fact that $AlCl_x$ is less volatile than $GaCl_x$, the overall etch rates of AlGaN layers are significantly lower, as compared with those obtained for GaN. In some cases the etch dead-time occurs, however in this study it was not observed.

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