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Reactive ion etching of GaN and AlGaN/GaN assisted by Cl_2/BCl_3

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This work reports on the latest results of etching of different $Al_xGa_{1-x}N/GaN$ heterostructures in relation to percentage composition of aluminum. The etching processes were carried out in a reactive ion etching (RIE) system using the mixture of $BCl_3/Cl_2/Ar$. The topography of the heterostructures surfaces and the slope were controlled using atomic force microsopy (AFM) technique. The photoluminescence spectra were used to determine the surface damage and to calculate the Al content in AlGaN/GaN heterostructures commonly used for high electron mobility transistors (HEMTs) fabrication.

Keywords: *plasma, RIE, reactive ion etching, Cl_2, BCl_3, HEMT*

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1. Introduction

Gallium nitride (GaN) and aluminum gallium nitride (AlGaN) are the materials of interest of numerous research groups due to their potential advantages such as wide band gap, high saturation velocity and high electron mobility [1]. These materials allow us to fabricate new advanced electronic and optoelectronic devices, such as lasers, UV detectors, high power and high frequency transistors, which are able to work in harsh environment. The processes, commonly used to fabricate electronic devices include the stage of active region definition in the device. It consists of photolithography and wet or dry etching of the semiconductive structure. In order to fabricate UV light sources, HEMTs or other GaN based devices, highly controllable mesa etching process has to be performed [2].

In order to achieve low leakage current, mesa structure of AlGaN/GaN hetereostructure has to be fabricated. Unfortunately, high resistance of GaN to chemicals, such as KOH or NaOH results in very slow etch rates. Reactive ion etching seems to be a viable technique to obtain smooth surface and controllable angle between the surface and the wall in the etched heterostructres.

The etch rates obtained using RIE technique, are incomparably higher than those reached with chemical etchants. Ion bombardment assisted by plasma discharge increases the etch rate of gallium nitride significantly to a value in a range of 50 – 100 nm/min. However, because of low ion density, the etch rate of AlGaN is much lower, due to higher bond energy (about 11.0 eV against 8.9 eV in GaN). There are numerous studies on RIE of GaN using chlorine based plasmas [3–12]. Only some of them focus on RIE using BCl_3 [3–8], not to mention the etching of $Al_xGa_{1-x}N/GaN$ heterostructures. In this work, we investigated the etching characteristics of GaN grown on Al_2O_3 substrate with a particular focus on BCl_3 flow rate and RF power, in the process assisted by BCl_3, Cl_2 and Ar gases. Surface morphology of the etched samples has been studied and discussed. In Table 1, the process parameters and the results obtained in this work in comparison with the data published in the literature in the years 1994 – 2010 are presented. The flow rate of Cl_2 and BCl_3 is expressed using sccm, which denotes standard cubic centimetres per minute.

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Table 1. The range of studied process parameters in RIE assisted by BCl_3 based mixtures.

Mixture	Flow rate (sccm)	Rf power (W)	Pressure (Pa)	Etch rate (nm/min)	Reference
BCl_3	40	200	1.33	51	[3]
BCl_3	50	150	1.33	73	[4]
BCl_3	40	100	3.33	17	[5]
BCl_3/Cl_2	40 / 5	100	2.66	67	[5]
BCl_3	9.5	200	2	104	[6]
BCl_3	5	120	3.33	45	[7]
BCl_3 / SF_6	10 / 20*	300	2.66	110	[8]
BCl_3 / SF_6	20 / 20*	150	2.66	75	[8]
BCl_3 / Cl_2	2 / 10	150	2.66	64	this work
BCl_3 / Cl_2	2* / 10	150	2.66	40	this work

* n-type GaN

2. Experiment

The unintentionally dopped GaN films were grown on sapphire substrates by metalorganic chemical vapour deposition (MOCVD). The $Al_xGa_{1-x}N$/GaN hetereostructures were deposited in the configuration depicted in Fig. 1. The RIE process was carried out in Oxford Instruments Plasmalab 80 Plus system. The lower electrode was cooled to maintain the ambient temperature of $T = 7$ °C. The RIE system was equipped with a turbomolecular pump reaching the base pressure of $p = 1\times10^{-3}$ Pa. The pressure in the reactor chamber was controlled with an automatic pressure controller (APC). In order to examine the profiles of the etched structures, lithography processes were employed. The etch depths and surface morphology were assessed using the atomic force microsope (Nanoscope V Veeco Instruments). The PL-spectra of investigated structures were measured in order to examine the surface morphology of the samples before and after etching and the level of surface damage. Plasma-resistant photoresist was used as an etching mask in each process. Unintentionally doped gallium nitride, Si-doped gallium nitride and AlGaN/GaN heterostrustures were investigated in this work. The process parameters were as follows: $p = 2.66$ Pa, Cl_2 flow rate $F_{RCl2} = 10$ sccm, BCl_3 flow rate $F_{RBCl3} = 2$ sccm, RF-power $P = 150$ W.

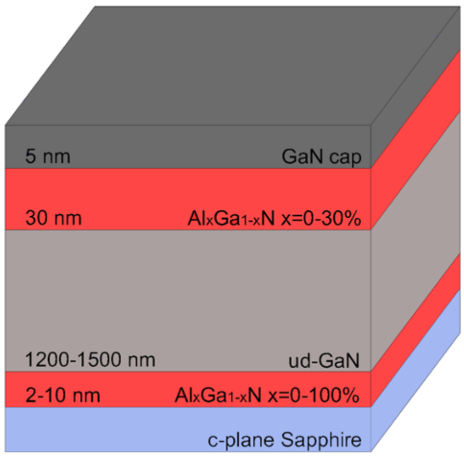

Fig. 1. Investigated structures of $Al_xGa_{1-x}N$/GaN.

3. Results and Discussion

Different BCl_3 flow rates, RF power, chamber pressure were the variables in the process of RIE optimization for GaN. Chlorine plasma and the chemical radicals, such as Ga^+, $GaCl^+$, $GaCl_2^+$, N_2^+, created during an ion bombardment, improve the material removal from the substrate. In [13] the authors claim that GaN etch rates obtained with an addition of BCl_3 are higher in comparison with etch rates obtained using Cl_2 plasmas. It has been shown that the presence of BCl_3 creates BCl_2^+ ions, which additionally increases the etch rate of

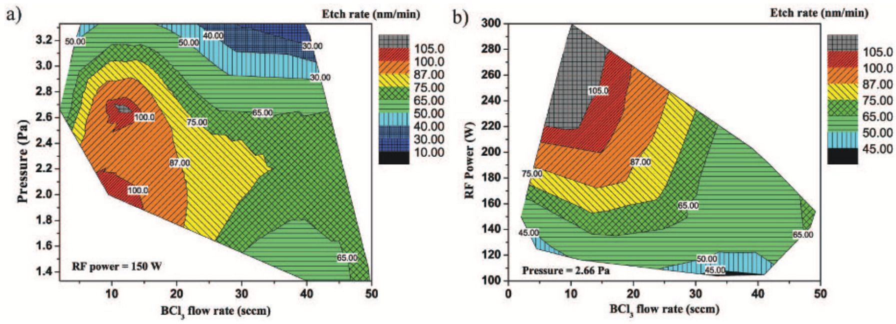

Fig. 2. Constant etch-rate contours of GaN depending on (a) chamber pressure and BCl_3 flow rate, and (b) RF power and BCl_3 flow rate.

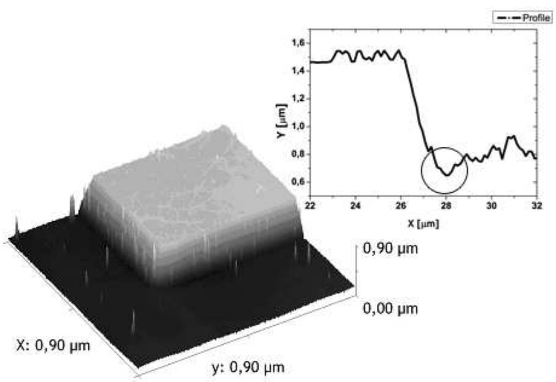

Fig. 3. The mesa profile of the etched i-GaN with characteristic under-etched region measured using AFM.

GaN. Although, BCl_2^+ is not as effective as Cl_2^+ in material removal, it slightly increases the etch rate, because of the chemical reactions from radicals combined with ion bombardment. In his work, Kim et al. [14] claimed, that $GaCl_3$ with a boiling point measured at 201 °C also increases the etch rate because the reaction product is more volatile and vaporizes from the surface faster. Although the temperature of the sample holder was kept around T = 7 °C during this experiment, the heat conduction from the plasma probably provided sufficiently high temperature to enable boiling of $GaCl_3$. The effect of BCl_3 flow rate, combined with the pressure (a) or the RF power (b) on the etch rate of GaN was depicted in Fig. 2. The maximum etch rate has been obtained for the chamber pressure in the range of $p = 2-2.66$ Pa, BCl_3 flow rate in a range of $FR = 10-15$ sccm and RF power in the range of $p = 200-300$ W. The BCl_3 flow rate at a constant pressure (i.e. p = 2 Pa) changed the etch rate of GaN. This phenomenon can be explained by superiority of the chemical process over physical removal. The higher flow rate caused an increase in the total number of particles, hence more ions were able to react with the substrate material. However, more particles in the chamber at the same pressure, could suppress the physical process of material removal. The RF-power is crucial to control the etch rate because the power directly affects the energy of ions [15] which penetrate into the surface of GaN and remove the GaN/AlGaN particles physically. The more energy provided by RF power, the more anisotropic sidewalls are being exposed during the RIE process. Thus, the mesa profile obtained in RIE at high RF power has a strong anisotropic profile. Providing too much power to the ions, leads to creation of unwanted under-etched region near the mesa profile. In order to properly control the drain current in HEMTs, the profile cant‘t be neither too abrupt, nor too plain. During the research it was observed that increasing the BCl_3 flow rate minimizes slightly the under-etch effect in $Al_xGa_{1-x}N$/GaN heterostructures used for HEMTs fabrication. Fig. 3 illustrates the mesa profile of the etched gallium nitride with characteristic under-etch effect.

Increase of the etch time did not affect the etch rate in gallium nitride. The etch rate of

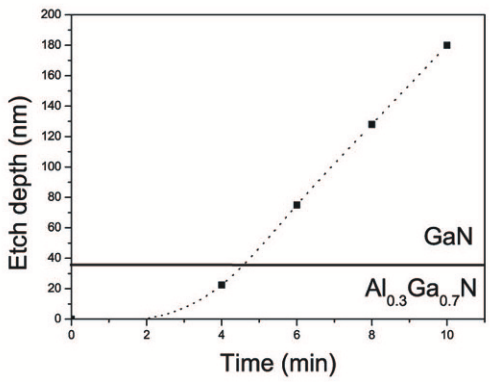

Fig. 4. Time dependence of the etch depth for $Al_{0.3}Ga_{0.7}N$/GaN heterostructure.

AlGaN layer was significantly lower due to the higher bonding energy. This layer was covered with 5 nm buffer layer of GaN to prevent oxidation of Al. Fig. 4 illustrates the time dependence of the etch depth in $Al_{0.3}Ga_{0.7}N$/GaN heterostructures. The etch depth for described process conditions was estimated from AFM scans. The etch rate of $Al_{0.3}Ga_{0.7}N$ was about $E_R = 6$ nm/min and for the i-GaN about $E_R = 25$ nm/min. The etch depths of GaN increased almost linearly with the time due to the constant etch rate of bulk GaN.

To estimate the composition of $Al_xGa_{1-x}N$ and examine the change of optical parameters (surface damage as well) photoluminescence spectra were measured. To count the energy from the wavelength, we used the following equation:

$$E[\text{eV}] = 1.238/\lambda[\mu\text{m}] \tag{1}$$

The selected samples were etched for 10 minutes in conditions as follows: BCl_3 flow rate - $F_{RBCl3} = 10$ sccm, C_2 flow rate - $F_{RC2} = 10$ sccm, Ar flow rate - $F_{RAr} = 5$ sccm, pressure $p = 2.66$ Pa, RF power $P = 150$ W, temperature $T = 7$ °C. We observed a shift of the peaks in PL bands towards longer wavelengths for both heterostructures after etching which was also reported in [16] (Fig. 5). Band broadening is visible for both heterostructures after performing the RIE process. This means that in the RIE process, surface defects were build in. It is known that dry etching causes incorporation of nitrogen vacancies (V_N) acting as shallow donors in semiconductor materials [17], thus the band moves toward longer wavelenghts. Photoluminescence intensities after plasma treatment are higher than before the treatment. However, the photoluminescence spectra measured before RIE process, come from the excitation of three layers (5 nm GaN cap, 30 nm of AlGaN, bulk GaN). The excitation energy used to collect the PL lines of the heterosturcures is used for excitation of cap, AlGaN and bulk GaN layers. That is why the overall bulk GaN photoluminescence intensity coming from the heterostructures seems to be lower. If we consider underneath bulk GaN only, the PL intensity is higher after the RIE process, but in this case, the total excitation energy, coming from UV laser is used to excite the bulk GaN because the AlGaN layer and GaN cap have been etched entirely in the RIE process. We believe that this is the reason why the PL intensity increases after plasma treatment.

In order to investigate surface roughness of the GaN, we performed AFM measurements. The surface roughness of both intrinsic and n-type GaN (Si doped: $N_d = 8\times10^{17}$ cm^{-3}), obtained at the etching conditions described above, was investigated using AFM images presented in Fig. 6. The root mean square (*RMS*) parameters, calculated for intrinsic GaN and n-type GaN, were $RMS_{GaN} = 11.2$ nm and $RMS_{n-GaN} = 58.9$ nm, respectively. Respective roughness average (R_a) were $R_{a\ GaN} = 9.1$ nm and $R_{a\ n-GaN} = 46.7$ nm. The surface of the etched intrinsic GaN contained large amount of whiskers, thus the *RMS* and R_a values, were much higher compared to the doped GaN. Both values seem to be very high compared to those presented in [6] ($RMS = 1 - 1.5$ nm). Further optimization of process parameters is necessary to reach smoother surfaces, after Cl_2/BCl_3 plasma treatment.

4. Conclusion

The RIE technique was used to fabricate HEMTs and hydrogen sensors based on $Al_xGa_{1-x}N$/GaN heterostructures. To obtain

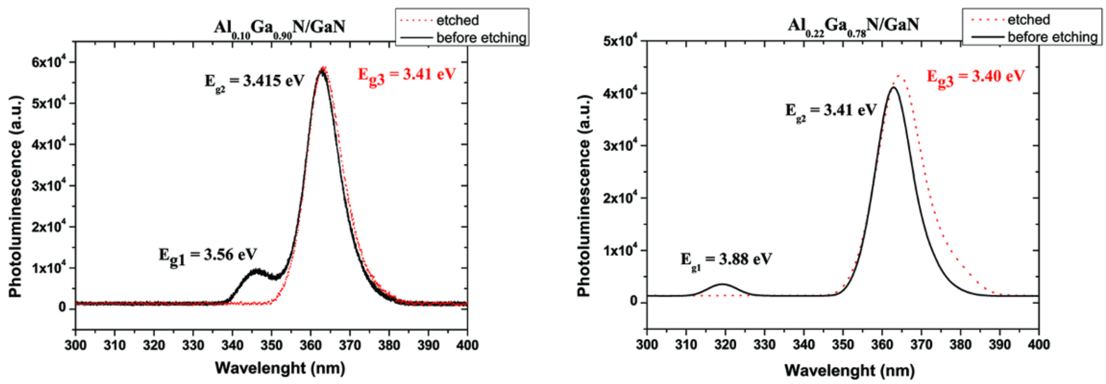

Fig. 5. PL-spectra of $Al_{0.1}Ga_{0.9}N$/GaN (a) and $Al_{0.22}Ga_{0.78}N$/GaN (b) heterostructures.

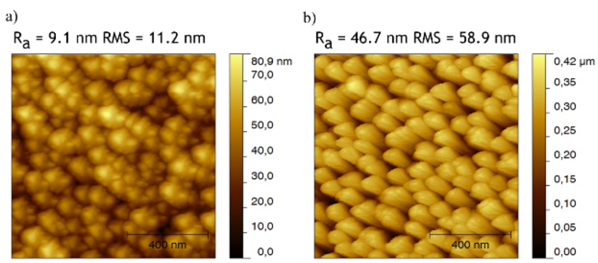

Fig. 6. AFM scans of (a) intrinsic GaN and (b) n-GaN topographies.

appropriate mesa shape, allowing continuous metallization, a mixture of Cl_2/ BCl_3/Ar plasma was applied. Although the addition of BCl_3 reduced the problem of mesa under-etch effect, the surface roughness parameters for i-GaN and n-GaN are still too high. As the result of plasma treatment, the surface and optical characteristics have been changed. Photoluminescence spectra were used to investigate induced damage to the surface. The red shift and PL peak broadening was observed in selected conditions. The PL spectra indicated higher PL intensity due to plasma treatment. We speculate that the reason of this phenomenon could be the division of excitation energy in the heterostructures. The etch rate of GaN is not time dependent. Our investigations combined with the results reported in [3–8] led to the following conclusions: maximum etch rate for gallium nitride can be obtained for the chamber pressure in a range of $p = 2-2.66$ Pa, RF power in a range of $P = 200-300$ W and BCl_3 flow in a range of $F_{RBCl3} = 5-15$ sccm. However, the high power applied in the process induced surface damage and under-etch, which did not allow the preparation of adjacent metal contacts. That is why we decided to decrease the RF power in order to obtain smooth surface and minimize the depth of the pit near the mesa sidewall.

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