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Damage-free GaN Etching by Chlorine Neutral Beam

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1. Introduction

Nitride semiconductors such as GaN have attracted much attention because of their various applications in optical and electronic devices, such as light emitting diodes, laser diodes, solar cells, and power transistors [1]. Etching is a well-known process for fabricating devices, and plasma is widely used for etching GaN. However, plasma etching can seriously damage the GaN layers. The damaged layer in GaN can be as thick as 100 nm [2], and this plasma-induced damage causes degradation in the optical and electrical performances of devices.

To solve this problem, we have developed a neutral beam (NB) source and neutral beam etching (NBE) technique [3]. It can perform damage-free etching since the NB system almost completely eliminates electric charges and UV photons from plasma and only a low-energy NB is irradiated to the surface. In the previous report, we have successfully performed damage-free GaAs etching using a chlorine NB [4].

In this study, we investigated a damage-free GaN etching process using the chlorine NB. The optical and electronic properties of etched samples were measured to demonstrate damage-free GaN etching.

2. Experiment

The GaN films used in this study were commercially available Si-doped n-type GaN templates (Lumilog Inc.). The GaN layer was approximately 3-μm thick, and the carrier concentration was in the range of $1\text{-}3\times10^{18}$ cm^{-3}. Before etching, the GaN templates were cleaned using an HCl solution.

Our developed NB source apparatus is shown in Fig. 1 [3]. The apparatus consists of two chambers: an inductive coupled plasma (ICP) chamber and an etching chamber. Plasma is generated in the ICP chamber and extracted via the bottom electrode with an aperture array into the etching chamber. Plasma particles passing through the bottom electrode are neutralized by that electrode and then reach the sample placed in the etching chamber. Meanwhile, UV photons from the plasma are filtered by the aperture array. In this system, the plasma was generated by a pulse-modulated radio frequency (rf) power of 800 W with an on/off ratio of 50 μs/50 μs. The top electrode was connected to a –100 V dc bias voltage, and the bottom electrode was connected to an rf generator (600 kHz). The substrate temperature was kept at –16 °C. When a bias rf of 16 and 10 W was applied to the bottom electrode, the neutral beam energy was about 40 and 25 eV, respectively. A pure chlorine (Cl_2) gas of 40 SCCM was used for the NB etching process, and the etching depth was fixed at 50 nm.

For comparison, plasma etching of GaN was also performed using a Samco RIE-101iPH system. A gas mixture of Cl_2, Ar, and $SiCl_4$ was introduced into the reactor at a pressure of 0.6 Pa. The input powers for the ICP and the sample bias plasma were set at 100 and 30 W, respectively. The bombardment energy of ions was considered to be about 60 eV in this condition.

Photoluminescence (PL) was measured at room temperature with a He-Cd laser (325 nm) as an excitation light source to investigate the optical properties of the GaN samples before and after the etching. The electrical properties of the GaN before and after etching were characterized with Hall-effect measurements using the van der Pauw method at room temperature.

3. Results and Discussion

Scanning electron microscope images of GaN after NB etching as a function of bias power to the bottom electrode are shown in Fig. 2. These results indicate that energy of 10 eV or more is needed to obtain a smooth surface.

The normalized PL spectra are shown in Fig. 3. An emission peak at 3.4 eV was assigned as the near-band-edge emission (BE), and a peak at 2.2 eV (yellow emission: YE) was associated with defects such as Ga vacancies in the GaN [5]. Increase of the YE peak, expressed as R = $[(YE/BE)_{etched}$ –

$(YE/BE)_{initial}]$ / $(YE/BE)_{initial}$, is shown in Fig. 4. For NBE at 10 and 16 W bias (beam energy: 25 and 40 eV), R was 0.20 and 0.36, respectively. In contrast, R was about 1.79 for plasma etching, which is much higher than that for NBE. Since the bombardment energy in plasma etching is roughly the same as that in NBE, the drastic increase of the R value in plasma etching can not be explained by the physical bombardment of ions. UV or VUV irradiation from plasma is considered to be responsible for the drastic increase of the defects. The damaged layer in GaN has been reported to be as thick as 100 nm [3]. This also suggests UV irradiation is responsible for the damage because UV photons can deeply penetrate into materials and efficiently generate defects [6].

The Hall mobility and carrier concentration before and after etching are shown in Fig. 5. ICP etching was found to degrade the electron mobility and increase the carrier density. The decrease of electron mobility is regarded to be due to carrier scattering at defects. Much less degradation was found after NBE. These results agree well with the data obtained through PL measurements. Since it is widely believed that the existence of defects in nitride semiconductors seriously affects the performances of both optical and electron devices negatively, use of the NB technique could be a promising solution for future nitride devices.

4. Conclusion

Neutral beam etching was investigated to achieve damage-free dry etching of GaN. Flat and smooth surfaces after etching were achieved by using a chlorine neutral beam and bias power of higher than 10 W. Photoluminescence and Hall-effect measurements showed that etching damage was almost eliminated by using neutral beam etching, while severe damage was caused in ICP plasma etching. UV irradiation from plasma is considered to be responsible for generating defects.

References

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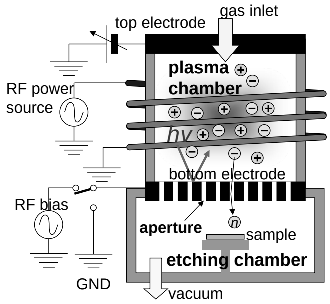

Fig. 1. Schematic diagram of our developed neutral beam source.

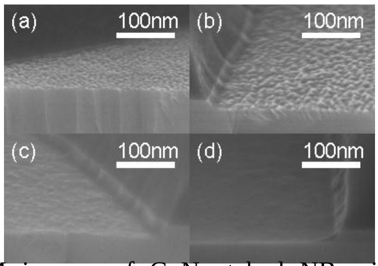

Fig.2 SEM images of GaN etched NB with bias conditions of (a) GND, (b) 6W, (c) 10W and (d) 16W.

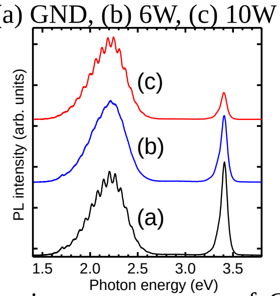

Fig. 3 Photoluminescence spectra of GaN samples. (a) before etching, (b) after NBE with beam energy of 40eV, and (c) after ICP etching with ion energy of 60eV.

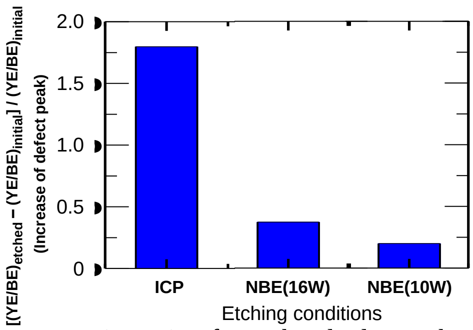

Fig. 4. Intensity ratio of near-band-edge peak against defect peak in photoluminescence spectra using NBE in comparison with ICP etching.

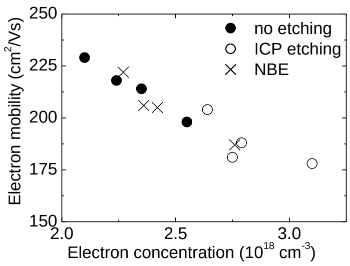

Fig. 5 Electron mobility of GaN substrate using Hall effect measurement after NBE (40eV) and ICP etching (60eV) in comparison with no etching.