Damage-free Neutral Beam Etching for High-performance GaN HEMT

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1. Introduction

Nitride semiconductors such as GaN have attracted much attention because of their various applications in optical and electrical devices, such as light emitting diodes, laser diodes, solar cells, and power transistors [1]. Plasma etching is a key technique in top-down processes for the fabrication of these GaN devices. However, plasma etchings can induce etch damages because they involve ultraviolet (UV) photon irradiation. The depths of the damage in etched bottoms and sidewalls from reactive ion etching (RIE) are usually larger than a few tens of nm [2], and this plasma-induced damage causes degradation in the optical and electrical performances of devices.

To solve this problem, we developed a neutral beam (NB) source apparatus and neutral beam etching (NBE) technique [3]. The apparatus can perform damage-free etching since the NB system almost completely eliminates electric charges particles and UV photons from plasma. Namely, only an energy-controlled NB is irradiated to samples. In the previous report, we successfully performed damage-free GaN etching by using NBE [4].

In this study, we precisely investigated the induced damages of plasma etching and the effects of neutral beam etching for GaN devices. Photoluminescence (PL) and the Hall effects of etched samples were measured to evaluate the magnitude and depth of etched surface damages. In particular, the influence of UV photon irradiation from plasma was investigated mainly by comparison between plasma etching and neutral beam etching. Additionally, we observed electrical characteristics in a high electron mobility transistor (HEMT) with an AlGaN/GaN hetero structure to understand the influence of surface defects on device characteristics.

2. Experiment

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. When plasma particles pass through the bottom electrode, they are neutralized by the bottom electrode and then reach the sample placed in the etching chamber. Meanwhile, the UV photons from the plasma are completely filtered by the aperture array.

At first, we investigated the optical and electrical characteristics of etched GaN by using Cl_2 -plasma and Cl_2 -NB. In this experiment, the GaN films were

commercially available Si-doped n-type GaN templates (Lumilog Inc.). The GaN layer was approximately 3- μ m thick. Before etching, the GaN surfaces were cleaned with an HCl solution. A pure Cl₂ gas with a flow rate of 40 sccm was used for both the plasma and NBE processes, and the beam energy (ion energy) and etching depth were fixed at 25e V and 50 nm, respectively. PL was measured at room temperature with a He-Cd laser (325 nm) as an excitation light source to investigate the optical characteristics of the GaN surface within a few tens of nm in depth before and after the etchings. The electrical characteristics of the GaN bulk before and after etching were characterized with Hall effect measurements by using the van der Pauw method at room temperature.

We also investigated actual electrical characteristics in HEMT after plasma etching and NBE. In this experiment, we etched the following hetero structure: AlGaN (20 nm)/GaN (3 μ m)/sapphire substrate. The samples were cleaned with an HCl solution. After that, the surface AlGaN layer was etched about 5 nm in depth. Then, Au as a Schottky electrode and Al as an Ohmic electrode were deposited on the etched surface of AlGaN by using a lift-off process. By using this device structure, we evaluated the Schottky characteristic at the interface between the Au electrode and AlGaN.

3. Results and Discussion

Figure 2 shows PL spectra before and after GaN etching. In general, two emission peaks can be seen from GaN: 3.4 eV assigned as the near-band-edge emission (I_{BE}) and 2.2 eV associated with defects such as Ga vacancies (I_{YE}) in the GaN [5]. By using the following equation (1), the normalized PL spectra before and after etching were evaluated for etching damage, as shown in Fig. 3 (a).

$$R = \frac{\left(I_{YE}/I_{BE}\right)_{initial} - \left(I_{YE}/I_{BE}\right)_{etched}}{\left(I_{YE}/I_{BE}\right)_{initial}}$$
(1)

The R value corresponds to the etching induced damages. Additionally, Hall effect measurements were also investigated with the same samples, as shown in Fig. 3 (b). The measurements were used to estimate carrier density and carrier mobility. Then, we normalized the carrier density and carrier mobility to precisely compare the damages between plasma etching and NBE. PL and Hall effect measurements proved that the NBE greatly inhibited etching damage more than did the plasma etching. The most important point between plasma etching and NBE is whether UV photons are irradiated or not. UV photon irradiation from plasma is considered to be responsible for the drastic increase in defect generation on the GaN surface and bulk. These results indicate that UV irradiation played a very important role for generating the damage because UV photons could deeply penetrate into the materials and efficiently generate defects [6].

Then, we investigated the Schottky characteristic to evaluate actual electrical devices rather than using PL and Hall effect measurements. A high quality Schottky contact is necessary for electrical devices. When fabricating a HEMT with an AlGaN/GaN hetero structure, gate recess etching is indispensable. The leak current density, calculated Schottky barrier height, and ideality factor by using Cheung methods [7] are shown in Fig. 4 and Table 1. Usually, when a high quality Schottky contact was realized, we could obtain a low leakage current density and high Schottky barrier height. Additionally, the ideality factor is usually very close to one. However, plasma etching degraded Schottky characteristics in HEMT. Conversely, NBE drastically suppressed the degradation. There are some reports that damages such as N or Ga vacancy and oxygen bonding cause degradation of Schottky characteristics due to high leakage current of AlGaN [8, 9]. We think these damages were related to UV photon irradiation from the plasma. We found that our NBE technique performed damage-free hetero structure etching on actual HEMT devices.

4. Summary

On the basis of the results of PL and Hall effects before and after the etching process, it was clarified that NBE could drastically reduce damages during GaN etching because of the lack of UV photon irradiation from plasma. As a result, the NBE process could keep a low leakage current, higher Schottky barrier height, and good ideality factor in HEMT with an AlGaN/GaN hetero structure. Our NBE technique has great potential for damage-free etching for high performance optical and electrical devices based on GaN.

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Figure 1. Schematic illustration of neutral beam etching system



Figure 2. Photoluminescence spectra of GaN samples (a) before etching, (b) after neutral beam etching, and (c) after plasma etching



Figure 3. Results of (a) photoluminescence measurement and (b) Hall effect measurements by using GaN film



Figure 4. Result of electrical characteristic by using a hetero structure

Table 1. Leak current density, Schottky barrier height, and ideality factor before etching, after plasma etching, and after neutral beam etching when voltage was applied at -5 V

	Before etching	After Plasma etching	After neutral beam etching
Leak current density(A/cm2)	1.81×10^{-3}	1.39×10 ⁻¹	1.81×10 ⁻²
Schottky barrier height(eV)	0.81	0.66	0.74
Ideality factor	1.65	2.01	1.92