Effect of neutral beam etching of *p*-GaN on the GaN device characteristics

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GaN materials were etched using a CF_4-based neutral beam, and its etch damage characteristics were compared with those etched with a CF_4-based inductively coupled plasma (ICP). Photoluminescence data showed that the neutral beam etched GaN materials show fewer defects on the surface compared to the GaN materials etched by ICP. Also, the current–voltage characteristics of GaN light emitting diodes fabricated with *p*-GaN etched by the neutral beam showed less damage compared to those fabricated with *p*-GaN by the ICP. When a photonic crystal-like structure having 2-μm-diameter microlens array was formed using the neutral beam etching on the *p*-GaN of the GaN device, an increase of 20% in the optical emission intensity could be observed without significantly increasing the forward voltage (0.7 V).
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I. INTRODUCTION

Recently, various methods have been investigated to increase the emission efficiency of GaN-based light emitting diodes (LEDs) for application to flat panel displays, printers, traffic signals, backlight for cell phones, exterior automotive lighting, etc. Among the various methods, one method was to change the LED epitaxy layer through the change of the thickness, the change of doping density, or through band gap engineering.[1,2] Another method was to change the device structure by forming a photonic crystal (PC) by etching the device from *p*-GaN layer to the multiquantum well layers.[3–6] Also, another method to increase the efficiency, an increase of *p*-GaN surface roughness has been investigated to increase the light extraction using the methods such as photoenhanced wet etching of *p*-GaN.[7] Among these methods, the formation of surface roughness is the easiest way to improve the device efficiency; however, the wet etching of GaN is difficult and does not provide reliable and repeatable surface roughness in general.

Using plasma etching instead of the wet etching, more controlled surface roughness could be obtained on the GaN device. However, the *p*-GaN layer located on the top of a conventional GaN device is known to be easily damaged by the species in the plasma.[8,9] Even during the formation of PC, the degradation of the device properties due to the damage on the *p*-GaN layer and the multiquantum well by the plasma etching has been reported.[10,11]

In this study, as a method in decreasing the damage to the *p*-GaN layer during the surface PC formation by plasma etching, a neutral beam etching method instead of a conventional plasma etching method such as inductively coupled plasma (ICP) etching was used, and its effects on the properties of GaN materials and device were investigated. The neutral beam uses only neutral particles which do not include charged particles; therefore, some damage problems related to the plasma etching such as charged damage, microloading, and undercut, etc., are known to be removed by using the neutral beam etching technique.[12,13] By etching GaN materials using the neutral beam and a conventional ICP, differences in the etched material characteristics were compared using photoluminescence (PL) and, by forming a PC-like lens structure on the *p*-GaN layer of the GaN LED device, the device characteristics were compared.

II. EXPERIMENT

The neutral beam etching source used in this experiment was composed of an ICP ion gun with two grids and a planar reflector. Figure 1 shows a schematic diagram of the neutral beam source. The rf power applied to the ion gun was 400 W with a frequency of 13.56 MHz. To form a neutral beam, 400 V was applied to the first grid located close to the plasma of the ion gun (acceleration grid) while grounding the second grid located outside the gun to extract a parallel ion beam from the gun. The extracted ion beam was reflected on the low angle (5°) reflector made from a parallel stack of polished stainless steel to neutralize the ion beam. In order to measure the neutralization efficiency, the ion flux (J_a) extracted from the ion source before reflecting on the reflector and the ion flux (J_b) extracted from the reflector after the reflection were measured at the same process conditions using a Faraday cup, and the ratio of $(J_a - J_b) \times 100 / J_a$ was taken as the neutralization efficiency. The measured neutralization efficiency of the reflector was approximately 99.7% for the experimental conditions. This and more details of the neutral beam etching system can be found elsewhere.[14–16] The ICP etching equipment used to compare with the neutral beam etching apparatus was a conventional planar ICP having a three-turn copper coil on the top of the chamber as the ICP source. To operate the ICP, 400 W was applied to the source and −350 V was applied to the substrate to have a similar particle bombardment energy to that of neutral beam etching.[17]

Using both equipments, undoped GaN, *p*-GaN (hole density of 2×10^{17} cm^{-3} by Mg doping), and *n*-GaN (electron

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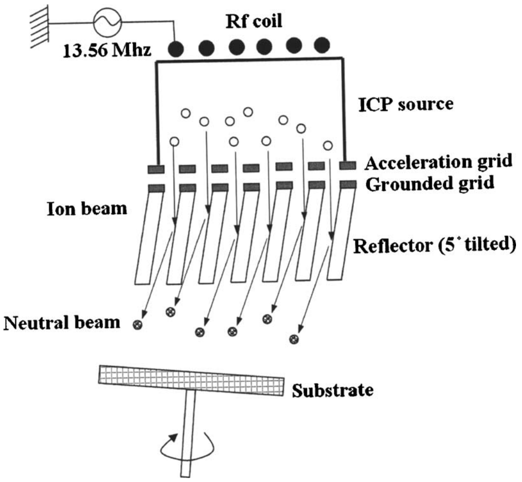

FIG. 1. Schematic diagram of the low-angle forward-reflected neutral beam etching system.

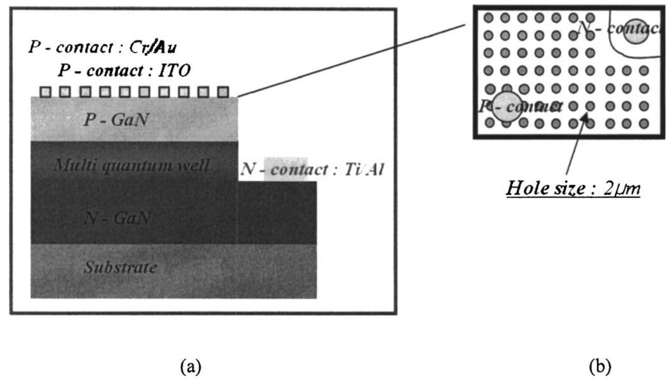

FIG. 2. (a) Conventional LED structure with a PC-like lens structure. (b) Two dimensional arrays of PC-like lens structure.

density of 7×10^{17} cm^{-3} by silicon doping) were etched about the same thickness using 15 SCCM (SCCM denotes cubic centimeter per minute at STP) CF_4 gas, and their differences in the PL characteristics were compared. Also, the *p*-GaN on a GaN LED device was patterned with a photoresist, as shown in Fig. 2, and was etched to have a two dimensional PC-like structure. The diameter of PC formed on the GaN device was 2 μm and the distance between the PC was also 2 μm. The used GaN LED structure was consisted of a 0.5-μm-thick Mg-doped GaN grown at 950 °C, an InGaN/GaN multiple quantum well with five pairs of InGaN(3 nm)/GaN(9 nm) grown at 800 °C, and a 2-μm-thick Si-doped GaN grown at 1050 °C by low-pressure metal organic chemical vapor deposition on sapphire substrates. Then, an indium tin oxide (ITO) (1500 Å) layer was deposited by sputter deposition on the *p*-GaN layer to form a *p*-side contact layer and a current spreading layer. Finally, Cr/Au (rapid thermal annealed at 600 °C for 1 min in N_2 after deposition) and Ti/Al (rapid thermal annealed at 300 °C for 1 min in N_2 after deposition) were deposited on the ITO layer and the *n*-GaN layer, respectively, as the electrodes, by electron beam evaporation.

The etch rate of GaN was measured using a step profilemeter (Tencor Inc., Alpha-Step 500). The PL was measured using a photoluminescence measurement system [He–Cd laser (325 nm), room temperature]. Luminescence from the sample is dispersed through a single-grating monochromator (spectral resolution <0.1 nm) and detected by a cooled photomultiplier (spectral range of 280–1700 nm) connected to a lock-in nanovoltmeter.) Current–voltage (I–V) characteristics of the GaN LED devices were measured using a semiconductor parameter analyzer (HP4145A) and the emitted intensities of the fabricated GaN LED devices were measured using an optical emission spectroscopy (OES) (SC Tech. PCM402) by collecting the light emitted from the LED in a probe station using the combination of lenses/optical fiber and by dispersing onto the OES.

III. RESULTS AND DISCUSSION

Figure 3 shows the PL data of (a) undoped GaN, (b) *p*-type GaN, and (c) *n*-type GaN after the etching by the ICP (1500 Å/min) and the neutral beam (25 Å/min) using 15 SCCM CF_4. The PL data of GaN without etching were included as references. For both systems, the rf power was maintained at 400 W. The dc bias voltage of the ICP system was kept at −350 V and the acceleration grid voltage of the neutral beam system was also maintained at 400 V to give similar physical bombardment energy to the GaN substrate. Also, the etch depth was maintained at 750 Å for both etch systems. As shown in Fig. 3(a), compared to the PL intensities of the reference, the intensity of the neutral beam etched GaN was a little lower and that of the ICP etched GaN was the lowest. However, the intensities of undoped and Mg-doped GaN etched by both etching methods showed much smaller peaks compared to those of references. When the intensities of the etched GaN materials were compared for each etch method, the intensities of GaN etched by the neutral beam system were higher than those of GaN etched by the ICP. Therefore, it appeared that *p*-GaN was the most significantly damaged among the GaN materials investigated, and the damage by the ICP etching was higher than that by the neutral beam etching. Higher damage to the *p*-GaN by the etching appears to be related to the generation of point defect layers and the creation of a number of impurity states by the bombardment of energetic particles that may remove elements from the GaN surface by sputtering.[18,19] Especially, in the case of *p*-GaN, the preferential loss of nitrogen, N vacancy, in Mg-doped GaN acts as a defect, while the N vacancy acts as a donor for *n*-GaN. Another possible reason will be the oxidation of Mg and Ga during the etching process, where oxygen for the oxidation is originated from the erosion of quartz window by the plasma in the plasma source (ICP).[20] From the facts that the acceptors are the isolated Mg atoms and Ga vacancies and that the donors are the isolated Si atoms and N vacancies for GaN, the recombination between acceptors and donors may be strongly suppressed for *p*-GaN, resulting in the lower PL intensity. On the other hand, the preferential loss of nitrogen may donate an electron to the donor level for *n*-GaN. There-

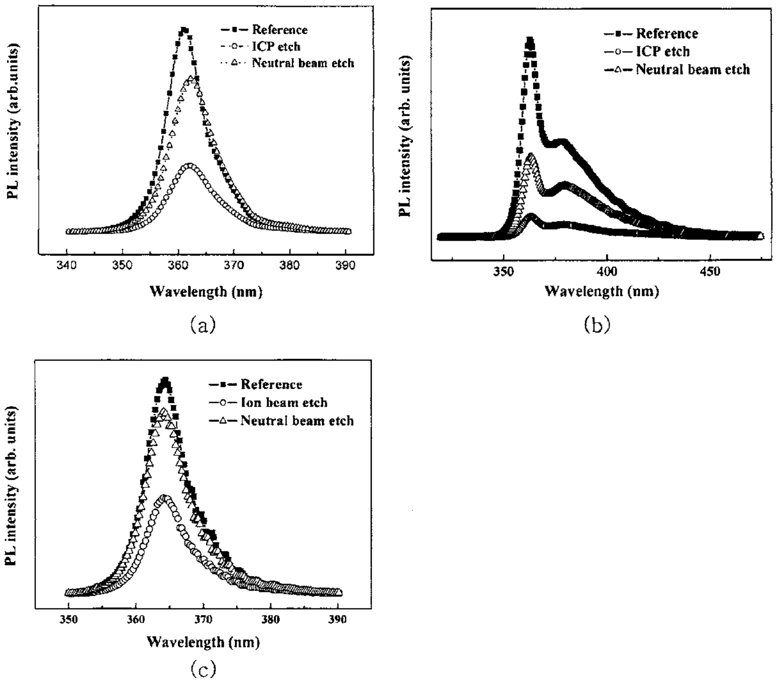

FIG. 3. PL data of (a) undoped GaN, (b) *p*-type GaN, and (c) *n*-type GaN after the etching by the ICP and the neutral beam using 15 SCCM CF_4. The PL data of GaN without etching were included as references. Process conditions: rf power: 400 W, dc bias voltage of the ICP system: −350 V, and acceleration grid voltage of the neutral beam system: 400 V. The etch depth was maintained at 750 Å.

fore, it will not be expected that nitrogen vacancy (V_N) is responsible for the reduction of donor-acceptor pair emission. Defect formation and implantation as interstitial impurities in GaN by energetic fluorine-based particle bombardment during the etching decrease the PL intensity. Defect formation and implantation can occur for both the ICP etching and the neutral beam etching due to the similar particle bombardment energy to the GaN surface during the etching. However, the lower damage obtained by the neutral beam etching compared to that by the ICP etching appears to show the effect of charge during etching, which is possibly related to the charge-induced defect formation.

On the *p*-GaN surface of the GaN LED device, before forming *p*-type contact by the evaporation of Cr/Au, a PC-like lens structure was formed by photoresist patterning and etching by the ICP and the neutral beam, as shown in Fig. 2, and the effects of the etching methods on the *I–V* characteristic were investigated and the results are shown in Fig. 4. As a reference, the characteristic of the GaN LED device fabricated without forming the PC-like structure was included in the figure. As shown in the figure, after the formation of PC-like lens structure on *p*-GaN, the electrical characteristic was degraded for both ICP etching and neutral beam etching. However, the electrical characteristic of the ICP etched GaN showed a significant degradation, while the electrical characteristic of the neutral beam etched GaN was close to that of reference. For the neutral beam etched GaN, at 20 mA of operating current, about 0.7 V was increased compared to the reference. Degradation of the electrical characteristics after the formation of the PC-like lens structure is believed to be related to the damage formed on the *p*-GaN during the etching, as shown in Fig. 3. Due to the higher damage to *p*-GaN by the ICP etching compared to the neutral beam etching, the worse device characteristics were believed to be obtained for the GaN LED device etched by the ICP. In general, the formation of lens structure on the surface increases the surface area and can increase the sheet resistance of the GaN surface. Therefore, the degradation of electrical characteristics of the GaN LED devices with the PC-like structure is believed to be partially related to the increase of the *p*-GaN surface area.

Using the reference and PC-formed GaN LED devices in Fig. 4, the optical emission characteristics were compared by using an optical emission spectroscope. The results are shown in Fig. 5 for the optical emission spectra of the refer-

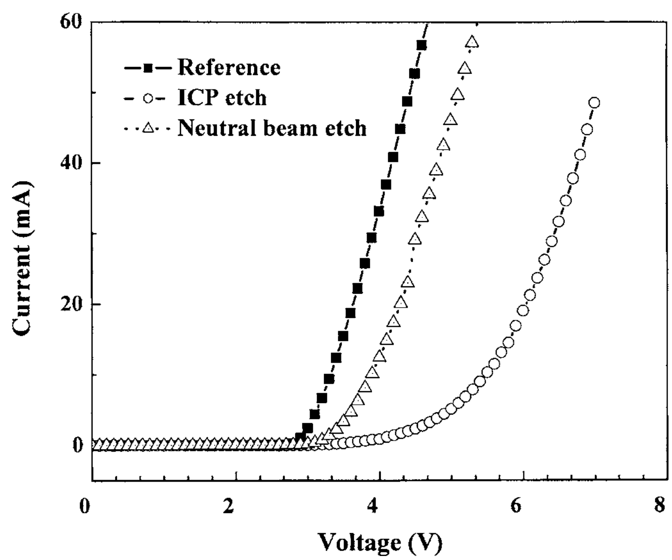

FIG. 4. *I–V* characteristics of lateral GaN LED devices with *p*-GaN etched by the ICP and the neutral beam using CF_4 with the condition shown in Fig. 3.

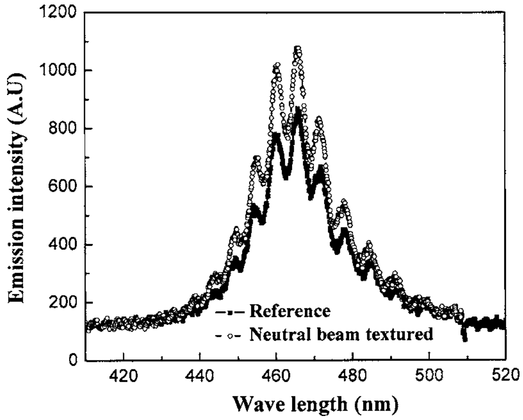

FIG. 5. Optical emission characteristics observed by OES. For the optical emission spectra of the reference and neutral beam etched GaN devices, 20 mA of device current was employed.

ence and neutral beam etched GaN devices at 20 mA of device current. In the case of the GaN LED device fabricated after etching by the ICP, no light emission could be observed, possibly due to the severe damage on *p*-GaN even though it showed diodelike current–voltage characteristics, as shown in Fig. 4. In fact, a research carried out by other researchers[21] shows the increase of light emission (20%) of the GaN LED device with PC structure formed by an ICP etching. In their device, the *p*-contact area was protected during the formation of PC; therefore no plasma damage existed on the *p*-GaN at the contact area. In our experiment, however, all the *p*-GaN surface was exposed during the PC-like structure formation by both ICP etching and neutral beam etching. Therefore, the lack of light emission of the GaN LED device obtained in our experiment is believed to be partially related to the high contact resistance of the *p*-GaN contact or the leakage of the device near the contact after contact metal formation by severe damage of *p*-GaN by the ICP etching. When the emission intensities were compared between the GaN LED devices etched by ICP and neutral beam, as shown in Fig. 5, even though there was a little increase of forward voltage at 20 mA after the formation of PC-like structure by the neutral beam etching, the emission intensity was increased about 20% at the wavelength of 464 nm compared to the reference due to the formation of PC-like structure on *p*-GaN. In this experiment, the GaN devices were not fabricated with the *p*-GaN contact area protected and, therefore, the electrical and light emission characteristics of the GaN devices with a PC-like structure formed by ICP etching and neutral beam etching, while *p*-GaN contact area was protected, could not be compared even though it is required to understand the effect of neutral beam etching on the damage of GaN materials further.

IV. CONCLUSIONS

In this study, GaN was etched by a conventional ICP and a neutral beam using CF_4, and the effects of neutral beam etching on the damage to the GaN surface and GaN device properties were investigated. The use of a neutral beam instead of ICP decreased the defect density on GaN materials as observed by the PL measurement. When a PC-like structure was formed on the *p*-GaN surface of the GaN device by ICP etching and neutral beam etching, the GaN device showed an increase in emission intensity of about 20% compared to the reference even though there was an increase in the forward voltage of about 0.7 V at 20 mA, possibly due to surface damage and surface roughening. However, the device formed after the formation of PC-like structure by the ICP etching showed a significant degradation in the electrical characteristics and did not emit the light. The improved performance of the neutral beam etched GaN LED device compared to that etched by the ICP is believed to be related to the lack of charge-induced defect formation on GaN surface.

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