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Defect-free GaAs/AlGaAs Heterostucture Etching Process by Chlorine/Argon Mixed Gas Neutral Beam

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1. Introduction

Dry etching is a key technique in top-down processing for the fabrication of GaAs/AlGaAs heterostructure quantum dot/well devices such as heterojunction bipolar transistors (HBTs) and optoelectronic devices. When device dimensions keep reducing, the surface condition becomes crucial for the performance of quantum-effect devices, i.e., the minority carrier lifetime and quantum efficiency would be drastically reduced by the surface damage [1]. Therefore, it is important to suppress the harmful effects of the dry etching process which are etch defects, rough etched surface, pillar (grass) formation, vertical etch profile, and different etching selectivity of GaAs/AlGaAs.

Plasma dry etching techniques such as the reactive ion etching (RIE) process, which is widely used in micro- and nano-fabrication, can induce the etch defects because they have ultraviolet (UV) photon irradiation and high energy charged particles bombardment. The etch defects can substantially deteriorate the electrical and optical properties of the fabricated devices [2]. Alternatively, neutral beam etching has great potential for developing a defect-free dry etching process because it completely suppresses UV photon irradiation and only generates a low energy neutral beam [3].

Using neutral beam etching (NBE) technique, in this study, we developed a dry etching process promising for fabricating nanometer-scale GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructures. The process is defect-free, has etching selectivity of GaAs/$Al_{0.3}Ga_{0.7}As$ closed to 1, and creates an atomically smooth etched surface and vertical etch profile.

2. Experiment Method

The operating conditions of neutral beam system are described. The reaction gas was injected into the inductive coupled plasma (ICP) chamber via a mass flow controller. The plasma was generated by a radio-frequency (RF) generator (13.56-MHz) with RF power of 800-W. The plasma was also pulse-modulated with ON/OFF ratio of 50 μs/50 μs. Meanwhile, the top electrode was connected to a –100-V dc bias voltage, the bottom electrode was connected to a RF generator (600-kHz) with 20-W, and substrate temperature was kept at –16°C.

To eliminate the pillar formation problem and keep the etched roughness to be atomically smooth, here we used the chlorine (Cl_2)/argon (Ar) mixed gas neutral beam. For optimizing the gas mixing ratio, various gas mixing ratios of Ar/(Cl_2+Ar) were introduced into the ICP chamber, while the total gas flow rate was maintained at 40sccm. The (100) GaAs wafer and 2 μm thick $Al_{0.3}Ga_{0.7}As$ film grown upon GaAs substrate were used for GaAs and $Al_{0.3}Ga_{0.7}As$ etching tests, respectively. The etched profiles were observed by scanning electron microscope (SEM) and the etched surface roughness was measured by atomic force microscope (AFM). Additionally, the etch defects of GaAs by NBE and RIE were observed by high-resolution transmission electron microscopy (HRTEM).

3. Results and Discussions

Figures 1(a) and (b) show the SEM images of the (100) GaAs etched surface by pure Cl_2 gas and Ar/(Cl_2+Ar) gas mixing ratio of 78%, respectively. The etching time for each sample was 10 min. When the pure Cl_2 used, there was a serious pillar formation problem was observed on the GaAs surface. Oppositely, in the case of Ar/(Cl_2+Ar) gas mixing ratio of 78%, the pillar formation was completely eliminated and the etched surface was atomically smooth. The relationship between gas mixed ratio and root mean square (RMS) etched surface roughness of GaAs and $Al_{0.3}Ga_{0.7}As$ is plotted in Figure 2. When the Ar/(Cl_2+Ar) gas mixing ratio is larger than 60%, the RMS etched surface roughness of GaAs is less than 1 nm. However, the etched roughness of $Al_{0.3}Ga_{0.7}As$ is still larger than 1 nm until the Ar/(Cl_2+Ar) gas mixing ratio is larger than 78%. In our best results, when the Ar/(Cl_2+Ar) gas mixing of 78% was used, the RMS etched surface roughness of both GaAs and $Al_{0.3}Ga_{0.7}As$ were about 0.6 nm. The results are very close to the RMS of as-grown sample

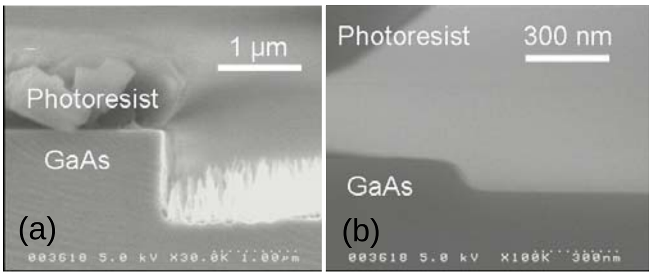

Fig. 1 SEM images of GaAs etched results by neutral beam with (a) 40 sccm Cl_2 reaction gas and (b) 9 sccm (22%) Cl_2 and 31 sccm (78%) Ar mixed gas.

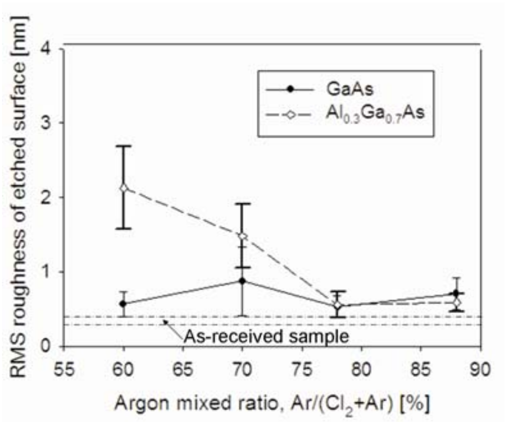

Fig. 2 RMS etched surface roughness of GaAs and $Al_{0.3}Ga_{0.7}As$ by NBE with different Ar mixed ratio gas.

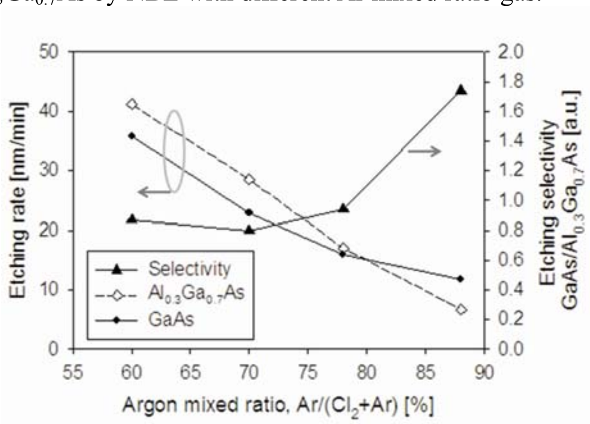

Fig. 3 Etching rates of GaAs and $Al_{0.3}Ga_{0.7}As$ by NBE with different Ar mixed ratio gas and the etching selectivity of $GaAs/Al_{0.3}Ga_{0.7}As$.

that is about 0.4 nm. Additionally, the etching selectively of $GaAs/Al_{0.3}Ga_{0.7}As$ was also investigated and shown in Figure 3. When the $Ar/(Cl_2+Ar)$ gas mixing ratio was 78%, the etching rates of GaAs and $Al_{0.3}Ga_{0.7}As$ were 16 nm/min and 17 nm/min, respectively, which means that the etching selectivity of $GaAs/Al_{0.3}Ga_{0.7}As$ was approximated to 1.

The above results indicate that the $Ar/(Cl_2+Ar)$ gas mixing ratio of 78% can atomically etch the surface roughness, and selectivity closes to 1. The etched profile and etched defect phenomenon were also investigated using this specific mix ratio.

The etched profile of (100) GaAs substrate and $Al_{0.3}Ga_{0.7}As$ film by $Ar/(Cl_2+Ar)$ gas mixing ratio of 78% are shown in Figures 4(a) and (b), respectively. The included angles between etched sidewall and horizontal level of GaAs and $Al_{0.3}Ga_{0.7}As$ were about 83^o and 87^o, respectively. Furthermore, a multi-layer heterostructure GaAs (5nm) $/Al_{0.3}Ga_{0.7}As$ (7nm) /GaAs (7nm) $/Al_{0.3}Ga_{0.7}As$ (30nm) /GaAs (200nm) upon GaAs substrate was prepared by molecular beam epitaxy (MBE) and etched about 80 nm deep by $Ar/(Cl_2+Ar)$ gas mixing ratio of 78% . Figure 4(c) shows the etched sidewall of heterostructure had the clear etched profile and the included angle of 78^o. Because the NBE has low beam energy, the etched profile of sidewall is strongly dependent on the edge profile of patterned photoresist. A higher included angle of GaAs or $Al_{0.3}Ga_{0.7}As$ could be achieved by using a photoresist pattern with a more vertical edge profile.

To demonstrate that NBE is a defect-free dry etching process, the crystalline defects of etched GaAs substrates prepared by NBE and RIE were compared using HRTEM. The best etching condition, $Ar/(Cl_2+Ar)$ gas mixing ratio of 78% , of NBE was used. An ICP RIE system was used with the same etching conditions of NBE. The etched depths of NBE and RIE were about 170 nm and 180 nm, respectively. For the sidewall of GaAs lattice etched by NBE (Figure 5(a)), there was no obvious etched defect near the etched surface. On the contrary, the surfaces of the etched sidewall by RIE have the clear crystalline defect about 2-4 nm in thickness (Figure 5(b)).

4. Conclusions

In summary, we developed a promising dry etching process for fabrication of nanometer-scale $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure, which has the advantages of defect-free, atomically smooth etching surface roughness, etching selectivity of $GaAs/Al_{0.3}Ga_{0.7}As$ closes to 1, and vertical etched profile.

References

1) G. Mayer et al, Appl. Phys. Lett. 56 (1990) 2016
2) B.-S. Yoo et al, J. Vac. Sci. Technol. A 13 (1995) 931.
3) S. Samukawa, Jpn. J. Appl. Phys. 45 (2006) 2395.

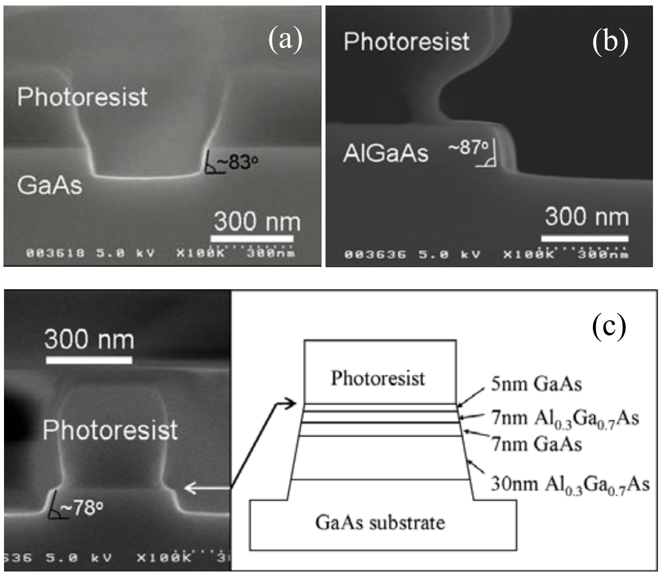

Fig. 4 SEM images of etched profiles of (a) GaAs and (b) $Al_{0.3}Ga_{0.7}As$ by 78% Ar mixed ratio NBE.

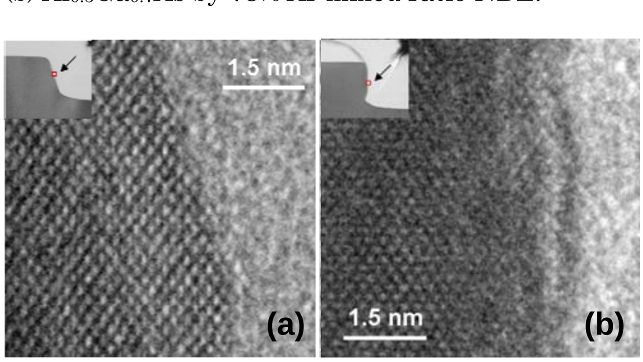

Fig. 5 HRTEM images of GaAs sidewall surfaces etched by (a) NBE and (b) RIE.