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ICP-RIE Dry Etching Using Cl_2-based on GaN

(Punaran Kering ICP-RIE Berasaskan-Cl_2 pada GaN)

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ABSTRACT

In this study, the plasma characteristics and GaN etch properties of inductively coupled Cl_2/Ar and Cl_2/H_2 plasmas were investigated. Our results showed that inductively coupled plasma (ICP) etching of gallium nitride by using Cl_2/Ar and Cl_2/H_2 were possible to meet the requirements (anisotropy, high etch rate and high selectivity). We have investigated the etching rate dependency on the percentage of argon and hydrogen in the gas mixture and the DC voltage. Surface morphology of the etched samples was checked by SEM and AFM. It was found that the etched surface was anisotropic and the smoothness of the etched surface is comparable to that of polished wafer. As results, gas mixture using Cl_2/Ar, we obtained highest etching rates; 5000 Å/min and ~0.5 nm rms roughness for n-GaN and for p-GaN, the etching rates was 3300 Å/min and ~0.7 nm for rms roughness. Meanwhile, for gas mixture using Cl_2/H_2, the etching was 1580 Å/min for n-GaN and 950 Å/min for p-GaN.

Keywords: Argon; gallium nitride; hydrogen; inductively coupled plasma etching

ABSTRAK

Dalam kajian ini, pencirian plasma dan kandungan punaran GaN pada gandingan teraruh plasma Cl_2/Ar dan Cl_2/H_2 telah dikaji. Kajian menunjukkan punaran plasma yang digandingkan secara teraruh (ICP) pada GaN menggunakan Cl_2/Ar dan Cl_2/H_2 akan menunjukkan keadaan yang anisotropik dengan kadar punaran dan peratusan kepilihan yang tinggi. Kadar punaran juga bergantung kepada peratusan argon dan hidrogen dalam campuran gas dan voltan DC. Morfologi permukaan pada sampel yang dipunar ditentukan menggunakan SEM dan AFM. Hasil menunjukkan bahawa permukaan GaN yang dipunar adalah anisotropik dan licin. Bagi campuran gas Cl_2/Ar, permukaan n-GaN memberikan kadar punaran tertinggi iaitu 5000 Å/min dan purata kekasaran ~0.5 nm. Manakala bagi permukaan p-GaN, kadar punaran tertinggi adalah 3300 Å/min dengan purata kekasaran ~0.7 nm. Bagi campuran gas Cl_2/H_2 pula, kadar punaran tertinggi adalah 1580 Å/min bagi permukaan n-GaN dan 950 Å/min bagi permukaan p-GaN.

Kata kunci: Argon; galium nitrida; hidrogen; punaran plasma digandingkan secara teraruh

INTRODUCTION

Group III nitrides have attracted much attention recently because of their wide spectrum of potential applications ranging from optoelectronic devices for the blue ultraviolet spectral region to high temperature devices. The high bond strength of gallium to nitrogen presents a challenge in achieving good etching characteristics in GaN. A number of methods have been employed to etch GaN and its related compounds, including photochemical wet etching, dry etching utilizing high density plasmas and conventional reactive ion etching (Oh et al.2004). However, to fabricate GaN-based optoelectronic devices successfully, reproducible etching processes with high etch rate and vertical etch profile are required. The highest dry etch rates for III-nitrides materials have been achieved with high density plasmas, produced via Electron Cyclotron Resonance (ECR) or Inductively Coupled Plasma (ICP) etching. Among ECR technique, ICP etching offers an attractive alternative high-density dry etching technique. ICP does not require the electromagnets or waveguiding technology (Patrick 2007). ICP plasmas are formed in a dielectric vessel encircled by an inductive coil into which rf-power is applied. A strong magnetic field is induced in the center of the chamber which generates high-density plasma due to the circular region of the electric field that exists concentric to the coil. At low pressures (≤ 10 mtorr), the plasma diffuses from the generation region and drifts to the substrate at relatively low ion energy. Thus, ICP etching is expected to produce low damage while achieving high etch rates (Lin et al. 2003). Cho et al. reported binary gas chemistries such as Cl_2/Ar, Cl_2/N_2 and Cl_2/H_2, and concluded that ICP discharges are well-suited to achieving smooth etched surfaces when appropriate plasma conditions are used (Cho et al. 2000). The inclusion of H_2 in the plasma was found to increase etch rates and also improve surface morphology. This was achieved by the removal of nitrogen through the formation of NH_x products.

Meanwhile, Sheu et al. (1999) reported that unintentionally doped GaN could be successfully etched by ICP using Cl_2/Ar as the etching gases to achieve a highly anisotropic etch with a high etching rate and had a smooth surface morphology. Noble gases such as argon and helium are added to stabilize the plasma or for cooling purposes. Argon addition causes inert ion bombardment of the surface, which results in enhanced anisotropic etching (Ledernez et al. 2009). Because chlorine-based gas chemistry is widely used in the processing of semiconductor devices and can be easily accommodated in nitride-based device processing, it would be desirable to use Cl_2-based plasma to etch GaN, to give a smooth etched surface by applying a suitable gas additive. However, to date, only a few reports on the effect of gas additives to Cl_2 plasmas have appeared. In this work, we showed that using inductively coupled plasma reactive ion etching on gallium nitrides by using Cl_2/Ar and Cl_2/H_2 it is possible to meet the requirement (anisotropy, high etch rate and high selectivity simultaneously).

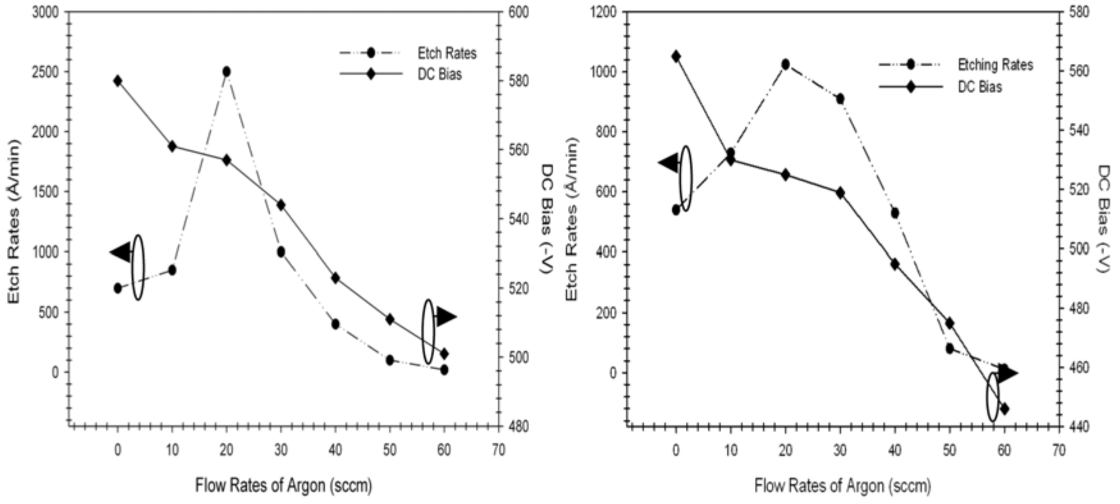
MATERIALS AND METHODS

The material used was nominally n-type and p-type GaN wafers. Seven samples were used for each experiment and prepared using similar photolithographic process. Before patterning, the samples were cleaned, dipped in DI water and dried using N_2 gas. Photo resist was spin coated onto all samples, forming ~ 1.5 μm layer. After that, all of them were etched by inductively coupled plasma etching using various gases in Oxford Plasmalab 80Plus system. For these experiments, etch rates were evaluated as a function of gas flow rate and DC bias. The conditions consisted of 100 W ICP power, 250 W RIE power and 600 W RF power. Prior to etching patterned samples, a simple set of experiments were conducted to get an understanding of how changes in gas composition affect the etch rate. For this experiment, the Ar flow rate was varied from 0 sccm to 60 sccm meanwhile the Cl_2 flow rates and the chamber pressure were held constant at 60 sccm and 5 mtorr, respectively. After that, individual sample was loaded into the chamber, centered on platters with the oxidized side exposed to the upper electrode. Immediately after the samples were removed from etching system, they were dipped into acetone to remove the photo resist. The etch rates were measured from the depth of the etched features with a scanning electron microscope (SEM) after the removal of the PR layer. Surface morphology, etch anisotropy, wall angle and sidewalls undercutting of the etched GaN was evaluated with SEM model JSM-6460 LV while ULTRAObjective AFM is used to measure the surface roughness. All the fabrication processes were repeated using Cl_2/H_2 gases while maintaining the same conditions; 100 W ICP power, 250 W RIE power, 600 W RF power, 60 sccm Cl_2 flow rates and 5 mtorr for chamber pressure.

RESULTS AND DISCUSSION

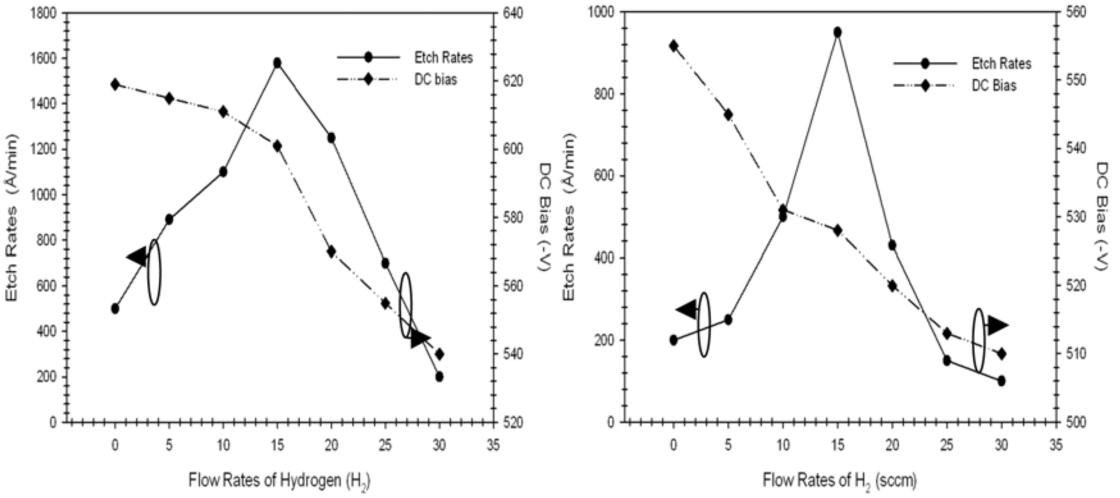
Figure 1(a) shows the etch rate and DC bias of n-GaN meanwhile Figure 1(b) shows the etch rate of p-GaN as a function of Ar flow rates. As can be seen from Figure 1, initially, the etch rate increased with respect to the flow rates of Ar until it reached the maximum value of 2500 Å/min at 20 sccm it for n-GaN and 1025 Å/min for p-GaN (33% of the total gas of Ar). It could be explained that the addition of a small amount of it can enhance the removal of etch product such as $GaCl_x$ by physical ion bombardment. However, the etch rates of n-GaN were then decreased abruptly and reached the minimum value of 25 Å/min for 60 sccm Ar and this results is similar for p-GaN; 11 Å/min for 60 sccm Ar. This suggests that the increase of Ar in Cl_2 will generally reduced GaN etch rates except for the small addition of Ar (≤ 20 sccm Ar). For gas Ar flow rate of 30 sccm and higher, it was found that the etch process decrease and the reduction of etching rate was due to less available Cl radicals, and more than 60 sccm Ar, the pattern was lost. For these reasons, we limited the Ar gas flow rates to 60 sccm in the following experiments. Figures 1(a) and (b) also show the DC bias (-V) of n-GaN and p-GaN as a function of flow rates of Argon (sccm). As can be seen, the DC voltage decreased as the flow rate of Ar increased. It showed that DC bias is also a function of the energy of the free electron. At higher concentration, electrons suffer more collisions; they gain less energy between collisions. Therefore, the electron energy decreases with the flow rates. From Figure 2(a), n-GaN etch rates were found to increase significantly between 0 sccm and 15 sccm, peaking around 15 sccm of H_2. It was found that the etch rate increase steadily with increased flow rates of H_2 and reached the maximum etch rates was 1580 Å/min at 15 sccm of H_2 and then decreased to the minimum etch rate of 200 Å/min at 30 sccm of H_2. Meanwhile, in Figure 2(b), p-GaN etch rates are shown as a function of flow rates of H_2. The etching rates increased and reached the maximum of 950 Å/min and rapidly abrupt to 100 Å/min after 15 sccm H_2.

It shows the same characteristics as in the Figure 2 (a) for n-GaN. The n-GaN and p-GaN etch rates in the ICP increased slightly as H_2 was initially added to the Cl_2 plasma (15 sccm H_2) implying a reactant limited regime. As the H_2 concentration was increased further, the Cl concentration reduced meanwhile the HCl concentration increased as the GaN etch rates decreased in both plasmas, presumably due to the consumption of reactive Cl by hydrogen. Although fast n-GaN etch rates have been observed in chlorine-based plasmas, the source of reactive Cl as well as the use of additive gases have not been discussed. Some researchers proposed that hydrogen might cause a decrease in the density of neutral atomic chlorine and the formation of HCl. Figure 3 shows the cross-sectional SEM view of the etching anisotropy. It shows a vertical wall etched in n-GaN and p-GaN with quite smooth trench surface etched was almost 90° from the surfaces. In addition, the anisotropy of the etching of GaN also decreased with increased flow rates of Ar. This is a result of the ion density and ion scattering enhancement. The roughness of etched surfaces was measured by atomic force microscopy (AFM) and it showed that the root-mean-square (rms) roughness of the sample etched with 60 sccm Cl_2/20 sccm Ar was ~0.5 nm



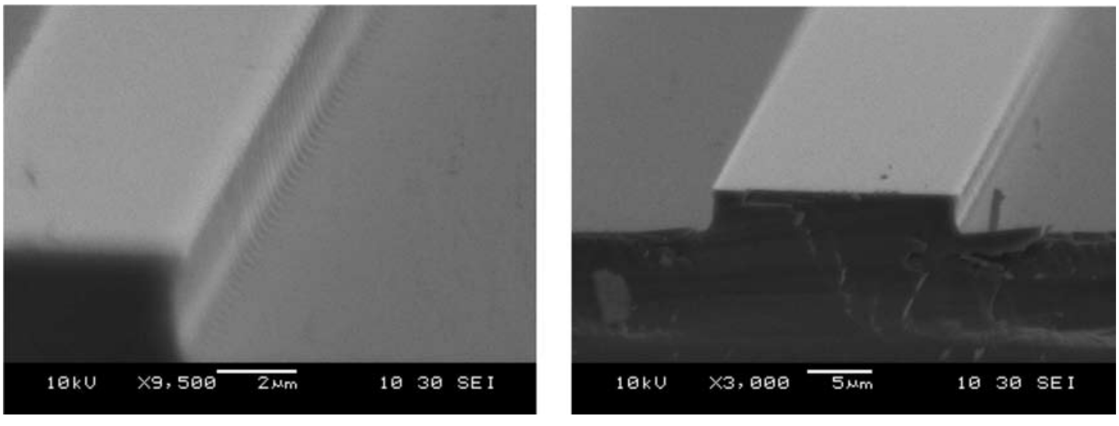
(a) (b)

FIGURE 1. Effect of flow rates of argon (sccm) on etching rates (Å/min) and DC bias (-V) with Cl_2/Ar chemistries for (a) n-GaN and (b) p-GaN



(a) (b)

FIGURE 2. Effect of flow rates of hydrogen (sccm) on etching rates (Å/min) and DC bias (-V) with Cl_2/H_2 chemistries for (a) n-GaN and (b) p-GaN



(a) (b)

FIGURE 3. Cross-sectional SEM micrograph of the etched patterns using 60 sccm Cl_2/20 sccm Ar for (a) n-GaN and (b) p-GaN

for n-GaN and ~0.7 nm for p-GaN. Meanwhile for 60 sccm Cl_2/15 sccm H_2, the rms roughness was 0.37 nm for n-GaN and 0.45 nm for p-GaN. The surface roughness for GaN remained relatively becomes rough as the Ar flow rate increased. Meanwhile, as the flow rates of H_2 increased, the surface roughness for GaN etched decreased. This is due to the removal of the needless by suppressing the scattering of mask materials by hydrogen (Rosli & Abdul Aziz 2005). The anisotropy of the etching of both samples in the etch profile of the sidewalls was decreased slightly as addition of H_2. This suggesting that more isotropic etching process took place, probably due to a decrease in the impinging ion.

CONCLUSIONS

The choice of 60 sccm of Cl_2 and 20 sccm of Ar, pressure of 5 mtorr and 200 W ICP power as the main recipe make it possible to meet those requirements; highest etching rates, smooth surfaces and anisotropic (5000 Å/min etch rates, ~0.5 nm rms roughness for n-GaN and 3300 Å/min etch rates, ~0.7 nm rms roughness for p-GaN). Meanwhile, 60 sccm of Cl_2, 15 sccm of H_2, pressure of 5 mtorr and 200 W ICP power is also possible to meet good etching rates; 1580 Å/min etching rates for n-GaN and 950 Å/min etching rates for p-GaN, and had smoother etched surface (rms roughness of 0.37 nm for n-GaN and 0.45 nm rms roughness for p-GaN) but resulting in more isotropy.

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