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High rate etching of sapphire wafer using $Cl_2/BCl_3/Ar$ inductively coupled plasmas

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Abstract

Sapphire wafers which are generally used for the fabrication of GaN-based optoelectronic devices are found to be very difficult in lapping, polishing, and cutting for packaging due to the chemical stability and hardness of sapphire. To study possibilities of replacing some of these processes by dry etching, (0001) sapphire wafers were etched using inductively coupled plasmas as a function of gas combination of Cl_2/BCl_3 and $Ar/Cl_2/BCl_3$. The increase of BCl_3 in Cl_2/BCl_3 increased the etch rates. Also, the increase of BCl_3 in Cl_2 improved the etch selectivity over photoresist. With the mixture of 50% Cl_2/50% BCl_3, sapphire etch rates of 362.7 nm min^{-1} could be obtained and, by the addition of 20% Ar in this mixture, the etch rates increased further to 377.5 nm min^{-1}. When the sapphire etching with 50% Cl_2/50% BCl_3 was applied to lapped wafers for polishing, the surface roughness was decreased from 12.95 to 1.43 nm and the smoothness was better than mechanically polished sapphire surface (5.3 8 nm).

Keywords: Sapphire; Etch rate; Roughness; Cl_2; BCl_3

1. Introduction

Sapphire wafers are widely used as the substrates for growing epitaxial films for optoelectronic devices such as GaN-based III-Nitrides. One of the problems in using sapphire wafers to GaN-based optoelectronic devices are the difficulty in cutting and backside mechanical polishing after completing the device due to the differences in the crystal orientation and the hardness of sapphire itself. Recently, research on the various etchings of sapphire such as ion beam etching [1], chemical wet etching after ion implantation [2], reactive ion etching [3,4] etc. have been carried out for the device isolation and backside processing of the sapphire wafer. In this study, inductively coupled plasmas were used to etch (0001) sapphire wafer as a function of gas combination of Cl_2/BCl_3 and $Ar/Cl_2/BCl_3$ and the sapphire etch rates, etch selectivity over photoresist, and the surface smoothness were investigated.

2. Experiment

Polished sapphire wafers with (0001) orientation were used as etch samples. To investigate the degree of smoothing by the etching, lapped blank sapphire wafers with the surface roughness of 12.95 nm were used and some of the polished wafers were patterned using a conventional photoresist to estimate etch selectivity. The etch characteristics of sapphire were measured as a function of gas combination of Cl_2/BCl_3 and $Ar/Cl_2/BCl_3$. The substrate temperature was fixed at 70°C. The etch rates of sapphire and photoresist were estimated using a stylus profilometer by measuring the feature depths before and after the removal of photoresist. Surface analysis was performed on selected samples by X-ray photoelectron spectroscopy (XPS) and surface roughness was examined by atomic force microscopy (AFM) before and after the etching of lapped samples.

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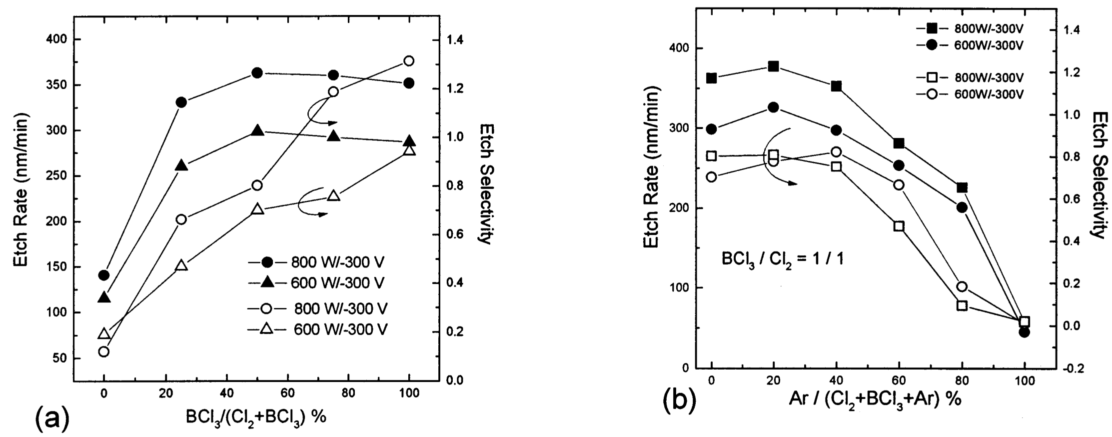

Fig. 1. Sapphire etch rates and selectivities as a function of (a) Cl_2/BCl_3 and (b) Ar in 50% Cl_2/50% BCl_3 for the operational pressure of 4.0 Pa, 600 and 800 W of inductive power, −300 V of bias voltage, and 70°C of the substrate temperature.

3. Results and discussion

Fig. 1 shows the sapphire etch rates and etch selectivities over photoresist for the gas combinations of (a) Cl_2/BCl_3 and (b) Ar/(50% Cl_2/50% BCl_3). Two different inductive powers of 600 and 800W were used at −300 V of d.c.-bias voltage, 4.0 Pa of operational pressure, and 70°C of substrate temperature.

As shown in Fig. 1(a), the increase of BCl_3 in Cl_2/BCl_3 to 50% generally increased the sapphire etch rates and the further increase of BCl_3 slowly decreased the etch rates. Higher inductive power showed higher sapphire etch rates. The highest sapphire etch rate obtained with Cl_2/BCl_3 was 362.7 nm min^{-1} with 50% Cl_2/50% BCl_3 and 800 W of inductive power. In the case of etch selectivity over photoresist, the increase of BCl_3 in Cl_2/BCl_3 generally increased the etch selectivity and the highest etch selectivity was obtained with pure BCl_3. Higher etch selectivity was obtained with higher inductive power (1.31 with pure BCl_3 and 800 W of inductive power). With Cl_2/BCl_3 gas ratio maintained at 1:1, the effects of Ar mixing to the 50% Cl_2/50% BCl_3 gas combination on the sapphire etch rates and etch selectivities were studied and the results are shown in Fig. 1(b). The addition of 20% Ar to 50% Cl_2/50% BCl_3 increased the sapphire etch rates slightly, however, the further increase of Ar in the gas mixture rapidly decreased the etch rates. The highest etch rate obtained with $Ar/Cl_2/BCl_3$ was 377.5 nm min^{-1} at 800 W of inductive power. The etch selectivities over photoresist generally decreased with the increase of Ar and were similar for both of the inductive power conditions.

The surface compositions of sapphire during the etching with Cl_2/BCl_3 and $Ar/Cl_2/BCl_3$ were studied using XPS for 4.0 Pa of operational pressure, 800 W of inductive power, −300 V of d.c.-bias voltage, and 70°C of substrate temperature. The results are shown in Table 1. The ratios of Al/O on the etched sapphire surfaces were normalized to the Al/O ratio measured for the non-etched sapphire. As shown in the table, the etched sapphire surface was a little Al-rich for pure Cl_2 and oxygen-rich for pure BCl_3. Therefore, the increase of BCl_3 in the Cl_2/BCl_3 plasmas changed the etched sapphire surface from Al-rich to oxygen-rich surface. The addition and increase of Ar into a fixed 50% Cl_2/50% BCl_3 increased Al on the etched sapphire surface. The most stoichiometric surface composition was obtained with 50% Cl_2/50% BCl_3.

Blank lapped sapphire samples were also etched using 50% Cl_2/50 %BCl_3 and 20% Ar/40% Cl_2/40 %BCl_3 at 800 W of inductive power, −300 V of d.c.-bias voltage, and 70°C of substrate temperature. The etch depth was about 12 μm and the roughness was measured using AFM. The results are shown in Fig. 2(a) for the lapped sample before etching or polishing, (b) for the etched sample with 50% Cl_2/50% BCl_{31} (c) for the etched sample with 20% Ar/40% Cl_2/40% BCl_3, and (d) for 12 μm mechanically polished sample.

As shown in the figure, after the 12 μm etching with 50% Cl_2/50% BCl_3, the roughness decreased from 12.95 to 1.43 nm and the roughness was less than that of 12 μm mechanically polished sample. The decrease of roughness by the etching appears to be related to the dependence of etch rate on the incident angle of the

Table 1
Variation of sapphire surface composition for different gas combinations measured by XPS

Gas	Normalized Al/O ratio
Control	1
100% Cl_2	1.037
100% BCl_3	0.615
50% Cl_2/50% BCl_3	0.986
40% Cl_2/40% BCl_3/20% Ar	1.108
30% Cl_2/30% BCl_3/40% Ar	1.182

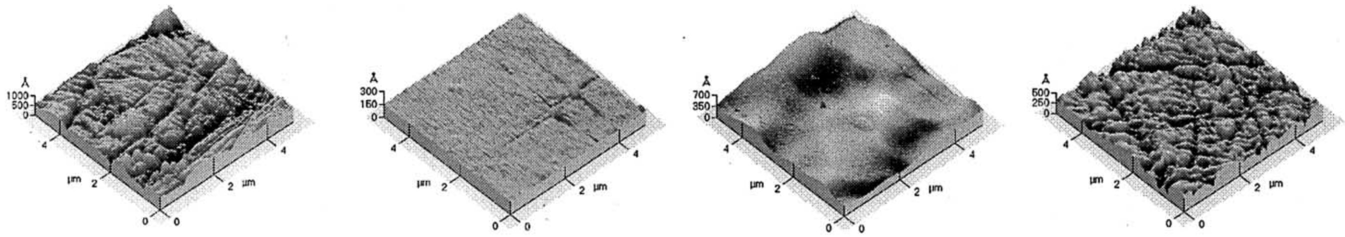

Fig. 2. AFM scans of (a) lapped sapphire wafer before etching, (b) after 12 μm etching with of 50% Cl_2/50% BCl_3 and (c) after 12 μm etching with 20% Ar/40% Cl_2/40% BCl_3, at the operational pressure of 4.0 Pa, 800 W of inductive power, −300 V of d.c.-bias voltage, and 70°C of the substrate temperature and (d) 12 μm mechanically polished sapphire wafer.

ions, therefore, a sharp feature tends to etch faster than a flat feature [5], and which results in the increase of smoothness after the etching.

In the case of the sample etched using 20% Ar/40% Cl_2/40% BCl_3, the roughness was more than the sample etched using 50% Cl_2/50% BCl_3. The smoother surface with 50% Cl_2/50% BCl_3 compared that with 20% Ar/40% Cl_2/40% BCl_3 appears to be related to the more stoichiometric removal of surface residue during the etching as observed by XPS [5,6].

4. Conclusions

In this study, the effects of gas combination such as Cl_2/BCl_3 and Ar/Cl_2/BCl_3 on the sapphire etch characteristics were investigated using inductively coupled plasmas.

The increase of BCl_3 in Cl_2/BCl_3 rapidly increased sapphire etch rates until 50% BCl_3 is reached and the further increase of BCl_3 percent slowly decreased the etch rate. With 50% BCl_3 in Cl_2/BCl_3 at 4.0 Pa, 800 W/−300 V, and 70°C of substrate temperature, the sapphire etch rate was 362.7 nm min^{-1} and the etch selectivity over photoresist was 0.8. The increase of BCl_3 in Cl_2/BCl_3 generally increased the etch selectivity over photoresist. The highest etch selectivity of 1.31 could be obtained with 100% BCl_3. The mixing of 20% Ar in the 50% Cl_2/50% BCl_3 gas mixture increased the etch rate further to 377.5 nm min^{-1}. AFM results showed that, after the etching of lapped samples, the surface roughness was decreased. Smoother etched surface was obtained with 50% Cl_2/50% BCl_3 compared with that with 20% Ar/40% Cl_2/40% BCl_3 possibly due to more uniform removal of surface residue. The smoothness of sapphire etched with 50% Cl_2/50% BCl_3 was better than that of mechanically polished sapphire.

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