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Dry etching of sapphire substrate for device separation in chlorine-based inductively coupled plasmas

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Abstract

In this study, sapphire wafers were etched using magnetized inductively coupled plasmas (MICP) and their etch characteristics were investigated as a function of gas combination of Cl_2/BCl_3, operation pressure, and additive gases such as Ar, Xe and $SiCl_4$. The characteristics of plasmas were estimated using a Langmuir probe and optical emission spectroscopy, and the profiles of the etched sapphire wafers were evaluated with a scanning electron microscopy (SEM). The increase of BCl_3 in Cl_2/BCl_3 increased the etch rate and improved the etch selectivity over photoresist, SiO_2 and Cr until 80% BCl_3 was reached. The decrease of operating pressure also increased the sapphire etch rate. The maximum etch rate over 3300 °C min^{-1} could be obtained using $20\%Cl_2/80\%BCl_3$ and, by the addition of 10%Ar or 10%Xe in this mixture, the etch rates increased further to over 3500 °C min^{-1} at 2.0 Pa of operating pressure, 1.6 kW of inductive power, −250 V of bias voltage, and 70 °C of substrate temperature. When the sapphire etching was performed with 10% Ar in $20\%Cl_2/80\%BCl_3$, sharp sidewall trenches required for stress concentration during the device separation could be observed on the sapphire etch profiles. © 2002 Published by Elsevier Science B.V.

Keywords: Sapphire; Etch rate; Trenching; Device separation; BCl_3/Cl_2

1. Introduction

Sapphire wafers are currently used in the optoelectronics industries as the substrates due to its high chemical and thermal stability. One of the problems in using sapphire wafers to optoelectronic devices such as GaN-based devices is 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 [1]. Especially, to obtain reliable device separation, more than 50 °C wide scribe line width is required for mechanical cutting using a diamond wheel or for scribing using a diamond scriber. However, if the device separation can be replaced by the dry etching, the scribe line width could be reduced to 5–10 °C, therefore the yield per wafer could be increased by 30%.

To replace for the mechanical cutting or scribing, high sapphire etch rates with high etch selectivities over mask materials are required. Recently, the sapphire etching techniques, ion beam etching (IBE) [2], chemical wet etching after ion implantation [3], reactive ion etching [4,5], laser-assisted etching [6] and inductively coupled plasma (ICP) [1]. In this study, a high density plasma etching equipment, a magnetized inductively coupled plasma (MICP) etcher, has been used and the effects of Cl_2/BCl_3 gas combination and additive gases on the etch rates and etch selectivities has been studied to obtain high etch rates and high etch selectivities over mask materials. Also, the effect of gas combination on the sidewall etch profile has been studied to obtain a sharp sidewall trench for easier device separation using a simple roller.

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2. Experiment

To etch sapphire, a specially designed MICP etcher was fabricated that can hold a permanent magnetic bucket inside the chamber and Helmholtz-type axial electromagnets around the chamber wall. The details of the characteristics of the plasmas and the magnet configurations used in this experiment can be found elsewhere [7].

The specimens were both-side polished sapphire wafers with (0001) orientation. These wafers were patterned using a conventional photoresist (AZ9262), SiO_2, and Cr to measure the etch rates, etch profile, and etch selectivity. The sapphire was dry etched using various combinations of Cl_2/BCl_3 at operating pressures of 2.0–4.0 Pa while inductive power, bias voltage, total flow rates, and substrate temperatures were fixed at 1.6 kW, −250 V, 100 sccm, and 70 °C, respectively. Also, additive gases such as Ar (0−40 sccm), Xe (0−40 sccm), and $SiCl_4$ (0–40 sccm) were added to the chemistry of 20%Cl_2/80%BCl_3 while maintaining the total flow rate at 100 sccm to study the effect of additive gas on the etch characteristics.

The sapphire etch rates and the etch selectivities over PR, SiO_2, and Cr were estimated from the depth of the etched features measured by a stylus profilometer. A single Langmuir probe inserted in the center of the chamber and biased at −60 V was used to measure ion current densities of the Cl_2/BCl_3 based magnetized inductively coupled plasmas as a measure of total positive ion densities. Optical emission spectroscopy was used to estimate radical densities in the plasmas. The profile of etched sapphire was evaluated with a scanning electron microscope (SEM).

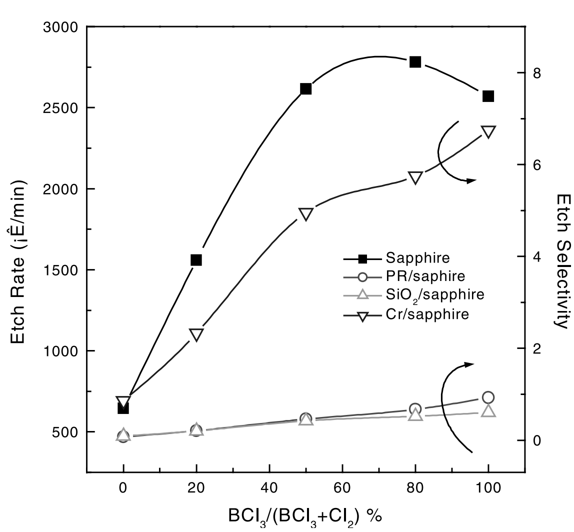


Fig. 1. (a) Sapphire etch rates and etch selectivities over photoresist, SiO_2, and Cr as a function of gas combination of Cl_2/BCl_3 in a magnetized inductively coupled plasma etcher.

3. Results and discussion

Fig. 1 shows the effect of BCl_3 in Cl_2/BCl_3 gas mixtures on the sapphire etch rates and the etch selectivities over photoresist, SiO_2, and Cr while inductive power, bias voltage, operating pressure, total flow rates, and substrate temperatures were fixed at 1.6 kW, −250 V, 2.73 Pa, 100 sccm, and 70 °C, respectively. As shown in the figure, the addition and increase of the BCl_3 to about 80% increased the sapphire etch rates from 600 to 2800 °C min^{-1} and the further increase of BCl_3 decreased the etch rates slightly. In the case of the etch selectivities over photoresist, SiO_2, and Cr, they increased monotonically with the increase of BCl_3 in Cl_2/BCl_3 and showed the highest etch selecivities with 100% BCl_3. The highest etch selectivities obtained with 100% BCl_3 for photoresist, SiO_2, and Cr were 0.67, 0.52 and 5.75, respectively. Therefore, Cr mask showed the highest sapphire etch selectivity among the investigated mask materials.

The effect of operating pressure on the sapphire etch rates and etch selectivities over photoresist, SiO_2 and Cr were investigated while maintaining the Cl_2/BCl_3 mixture ratio at 20%/80%. Other etch parameters were maintained the same as before. As shown in the Fig. 2, the decrease of operating pressure from 4.0 to 2.0 Pa increased the sapphire etch rates from 2000 to 3380 °C min^{-1}, however, the etch selectivities over photoresist, SiO_2, and Cr did not show significant change with the decrease of operating pressure. The increase of sapphire etch rate with the decrease of operating pressure appears to be related to the reduced scattering of the incident ions to the sapphire wafer at lower pressure. No significant change of etch selectivity with the decrease of operating pressure is due to the increase of the etch

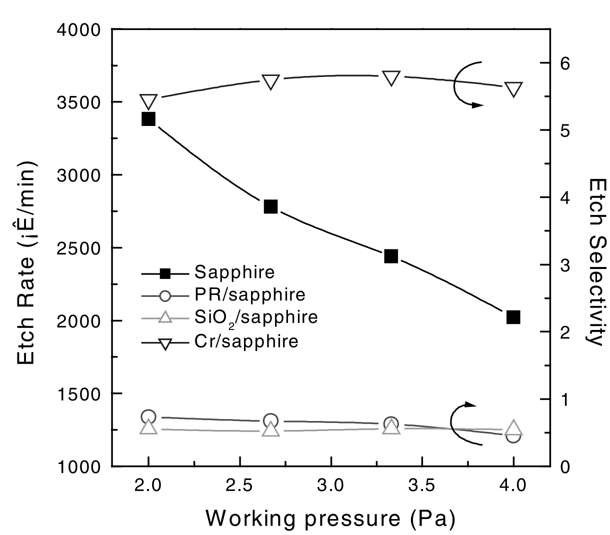


Fig. 2. The effect of pressure on the sapphire etch rate and selectivities over photoresist, SiO_2 and Cr.

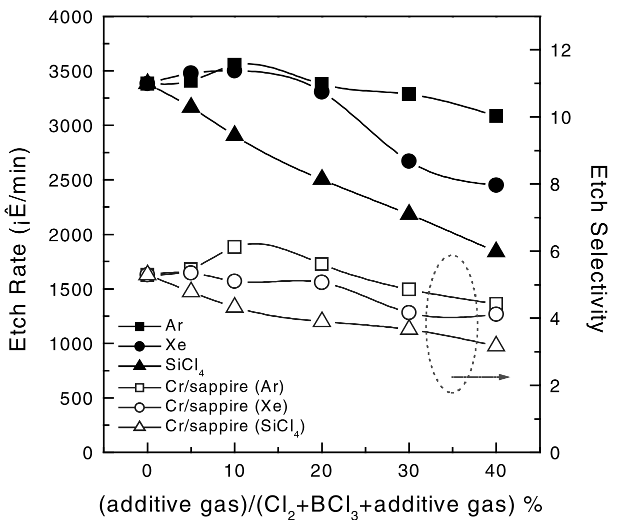


Fig. 3. Sapphire etch rates and etch selectivities over Cr as a function of additive gases such as Ar, Xe, and $SiCl_4$ in a 20% Cl_2/80% BCl_3 gas mixture.

rates of mask materials similar to the increase of sapphire etch rate.

Fig. 3 shows the effect of additive gases such as Ar, Xe and $SiCl_4$ to 20% Cl_2/80% BCl_3 on the sapphire etch rate and its selectivity over Cr. The operating pressure was kept at 2.0 Pa because it showed the highest sapphire etch rates in Fig. 2. Other etch parameters were also kept the same as the conditions in Fig. 2. The addition and increase of heavy inert gas may increase physical ion bombardment effect, therefore, it could increase the sapphire etch rates. As shown in Fig. 3, the addition of Ar or Xe up to 10% increased the sapphire etch rate even though the increase of etch rate is small and the further increase of additive Ar or Xe slowly decreased the etch rates. The addition of $SiCl_4$ to 20%Cl_2/80%BCl_3 decreased the etch rates monotonically. The etch selectivity over Cr also showed the similar trend as the sapphire etch rates. The highest etch rate obtained with the 10%Ar was 3550 °C min^{-1} and that with the 10%Xe was 3500 °C min^{-1} and the etch selectivities over Cr were 6.1 and 5.1, respectively.

Fig. 4 shows the effect of BCl_3 in the Cl_2/BCl_3 and Cl_2/BCl_3/10%Ar mixtures on the BCl optical emission intensity measured by optical emission spectroscopy [8] and ion current measured by a Langmuir probe. BCl intensity was measured as a measure of BCl radical density in the plasma and ion current was measured as a measure of total ion density in the plasma. The inductive power, bias voltage, operating pressure, and total flow rate were 600 W, −250 V, 2.73 Pa, and 30 sccm, respectively. Therefore, the operation condition shown in the figure is not exactly same as the conditions shown in Figs. 1 and 3, however, the results in the figure could be compared with the results shown in Figs. 1 and 3. As shown in the figure, the BCl intensity showed the maximum at 80%BCl_3 in both Cl_2/BCl_3 and Cl_2/BCl_3/10%Ar mixtures similar to the etch maximum shown in Figs. 1 and 3. In the case of ion current, the maximum showed at 10%BCl_3 and the further increase of BCl_3 decreased the ion current. Therefore, BCl radical intensity appears to be important in the sapphire etching. The ion bombardment effect is also important in the etching of sapphire to break the strong bond of Al–O in the sapphire. The relative insensitivity with the increase of Ar or Xe (physical ion bombardment) shown in Fig. 3 may reflect practically sufficient ion bombardment by BCl_2^+ ions and BCl_3^+ ions in the BCl_3-rich Cl_2/BCl_3 plasmas as measured by a quadrupole mass spectrometer in [8].

Fig. 5 shows the sapphire etch profiles for (a) 20%Cl_2/80%BCl_3, (b) 10%Ar in 20%Cl_2/80%BCl_3, and (c) 10%Xe in 20%Cl_2/80%BCl_3. In the figure, Cr etch mask layer is still remaining on the top of the etched sapphire. As shown in the figure, etch profiles were similar, however, the addition of 10%Ar to 20%Cl_2/80%BCl_3 appears to show sharper sidewall trenches. The formation of trenches appears to be related to the enhanced ion bombardment on the sidewall bottom area by the reflection of ions from the sidewall. However, the differences shown in the figure as a function of gas chemistry are not currently understood in full and the further investigation is needed. The formation of sharp trench is important in the case of device separation by dry etching because it enhances the stress concentration.

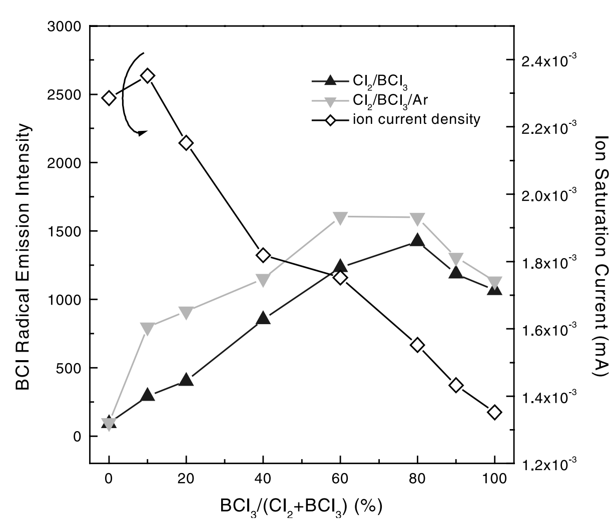
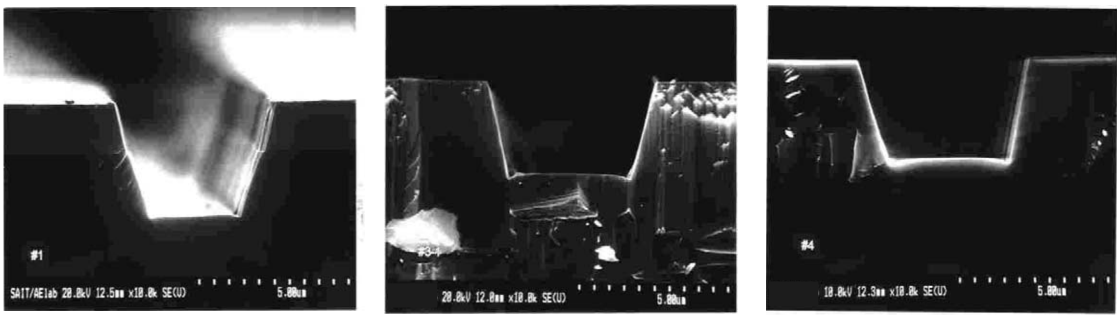


Fig. 4. BCl optical emission intensities measured by optical emission spectroscopy and ion currents measured by a Langmuir probe as a function of BCl_3 in Cl_2/BCl_3.



(a) (b) (c)

Fig. 5. SEM micrographs of sapphire etch profiles; (a) 20% Cl_2/BCl_3, (b) 10% Ar in 20% Cl_2/80% BCl_3 and (c) 10% Xe in 20% Cl_2/80% BCl_3. Cr etch mask is still remaining on the top of the etch profiles. Process condition: 1.6 kW of inductive power, −250 V of bias voltage, 70 °C of substrate temperature.

4. Conclusion

In this study, sapphire wafer was etched using magnetized inductively coupled Cl_2/BCl_3 based plasmas, and the effects of various gas combination, additive gas and operating pressure on the sapphire etch rates, etch profiles, and the etch selectivities over photoresist, SiO_2 and Cr were investigated as the application for the device separation by dry etching.

Eighty percent BCl_3 in Cl_2/BCl_3 showed the highest sapphire etch rates and etch selectivities over mask materials due to the enhanced removal of oxygen by BCl radicals. The additions of 10% inert gases such as Ar and Xe to 20%Cl_2/80%BCl_3 also increased sapphire etch rates even though the amount of increase was not significant. With 10%Ar in 20%Cl_2/80%BCl_3 (100 sccm), 1.6 kW of inductive power, −250 V of bias voltage, 2.0 Pa of operating pressure, and 70 °C of substrate temperature, 3550 °C min^{-1} of the sapphire etch rates with the etch selectivity over Cr higher than 6 could be obtained. Also, with this condition, sharpest sidewall trenches could be observed which is required for the device separation by dry etching.

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