

High rate sapphire (Al_2O_3) etching in inductively coupled plasmas using axial external magnetic field

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Abstract

BCl_3/HBr inductively coupled plasmas magnetized by external magnetic fields was used to achieve high etch rate of sapphires and high etch selectivities over photoresist. The etch characteristics such as etch rates of sapphire and photoresist, etch selectivity over photoresist, plasma density, and etch profiles etc. were investigated as functions of applied external magnetic field strength, working pressure, and dc bias voltage. The obtained highest etch rate of sapphire was approximately $7700 \text{ \AA}/\text{min}$ at -800 V of dc bias voltage and 20 Gauss (G) of external magnetic field, when 1400 W of inductive power, 10 mTorr of $90\% \text{ BCl}_3/10\% \text{ HBr}$ were used. The etch selectivities over photoresist were varied from approximately 0.6 to 0.8 , where, it increased up to 0.8 with an increasing external magnetic field, however, it decreased with an increasing dc bias voltage.

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1. Introduction

For the past several decades, GaN-based III-nitrides have attracted many attentions, as materials for optoelectronic devices such as light emitting diodes (LEDs), and laser diodes (LDs), etc. Therefore, GaN-based III-nitrides have been studied intensively on the various fields such as epitaxial growth, dry etching, device design, etc. [1–7].

In the field of epitaxial film growth, sapphire (Al_2O_3) wafer has been widely used as the substrates due to its high thermal and chemical stability. However, until now, due to its physical and chemical stability, sapphire wafer shows problems in polishing, device isolations, and the formation of various device structures such as vertical device, etc. Most researchers have recognized the necessity of developing the sapphire etching for the various devices on sapphire wafers, therefore, several etch techniques such as ion beam etch (IBE), chemical wet etching after ion implantation, reactive ion etching (RIE), laser-assisted etching, etc. have been studied [8–12]. Nevertheless, due to physical and chemical stability of sapphire, the etch rates that can process various

devices successfully and satisfactorily have not been reported yet.

In this study, to achieve high etch rates of sapphire, BCl_3 -based magnetized inductively coupled plasma was used and especially HBr was used as the additive gas to obtain higher the etch selectivities over photoresist. The etch characteristics such as etch rates, etch selectivities over photoresist, plasma density, etch profiles etc. were investigated as functions of applied external magnetic field strength, working pressure, and dc bias voltage to the substrate.

2. Experimental details

In this study, sapphire etching was performed in a magnetized inductively coupled plasma (MICP) etch system. Fig. 1 shows the schematic diagram of the MICP system used in this study. The rectangular chamber was made of anodized aluminum to use corrosive gases and the inner size of the chamber was $210 \times 210 \text{ mm}$. Radio frequency (rf) power (13.56 MHz , $0\text{--}2 \text{ kW}$) was supplied to the center of a gold-coated three-turn square coil to generate inductive plasmas, while different 13.56 MHz of rf power was applied to the substrate to generate bias voltages to the wafer. To enhance the ion density by electron confinement and the helical motion

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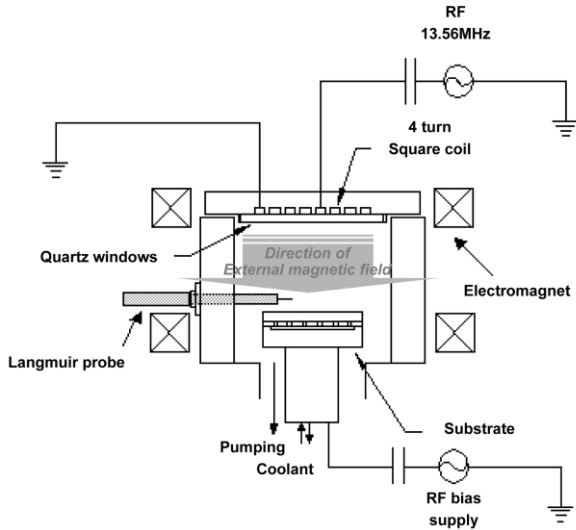


Fig. 1. The schematic diagrams of the magnetized inductively coupled plasma (MICP) etch system used in the experiment.

of the electrons, an axial external magnetic field was applied to the ICP system; a square (500×500 mm) shaped Helmholtz type of axial electromagnet was installed at the outside of the chamber. In addition, the separation (d) of the coils in our Helmholtz pair was fixed at 285 mm to apply a uniform magnetic field to the chamber inside, because the separation of the coils in our Helmholtz pair should be $250 \text{ mm} < d < 500 \text{ mm}$ for the uniform magnetic field. The strength of magnetic field was varied from 0 to 20 G. The uniformity of the magnetic field was less than 3.5% in the 6-inch diameter substrate.

Sapphire wafers with (0001) orientation were used as the etch samples. $24 \mu\text{m}$ thick photoresist (PR) etch mask was used by applying a double PR spin-on technique with AZ 9260 photoresist. The used gas combination was 90% BCl_3 /10% HBr because these gas combinations showed the most anisotropic etch profiles among the gas combinations studied in our previous work [13]. Inductive power was maintained at 1400 W and dc bias voltage to the substrate was varied from -350 to -800 V. The total gas flow rate was maintained at 100 sccm and the substrate temperature was maintained at 3°C during the etching to prevent PR from reticulating.

The etch rates of sapphire and selectivities over PR were measured by a depth profiler (alpha-step 500, TENCO) as a function of external magnetic field, working pressure, and dc bias voltage to the substrate. Especially, to investigate the plasma characteristics with variations of magnetic field strength and working pressure, ion current densities were measured by a Langmuir probe (EPS: Hiden analytical Inc.) as a measure of plasma density. The tip of the Langmuir probe was

made up of tungsten wire with 10 mm in length and 0.15 mm in diameter. Etch profiles of photoresist patterned sapphire were observed by a scanning electron microscopy (SEM).

3. Results and discussion

Fig. 2 shows etch rates of sapphire wafer and ion current densities measured as a function of external magnetic field. The magnetic field was varied from 0 to 20 G. Source power, bias voltage, total gas flow rates, and working pressure were fixed at 1400 W, -350 V, 100 sccm, and 10 mTorr, respectively. As shown in Fig. 2, with increasing external magnetic fields from 0 to 20 G, the sapphire etch rates increased from approximately 3000 to 5500 $\text{\AA}/\text{min}$ and PR etch rates were also increased from 5000 to 6900 $\text{\AA}/\text{min}$. In addition, the ion current density measured as an estimation of plasma density also increased approximately 50% by applying 20 G of external magnetic field. Therefore, the sapphire etch selectivity over PR was increased from 0.6 to 0.8 by applying 20 G of external magnetic field. It is believed that the increase of sapphire etch rates and PR etch rates is related to the increase of ion flux to the substrate due to the increased plasma density by applying external magnetic field. Also, the increase of etch selectivity with increasing magnetic field might reflect the increase of radical density such as BCl_x that reacts with sapphire, preferentially in addition to the ion density by increased dissociation of the feed gases [13]. If the electron temperature of the plasma is increased with increasing external magnetic field at the same plasma density, the ion flux to the substrate can also be increased. However, a previous study [14] showed that the electron temperature is decreased with increasing

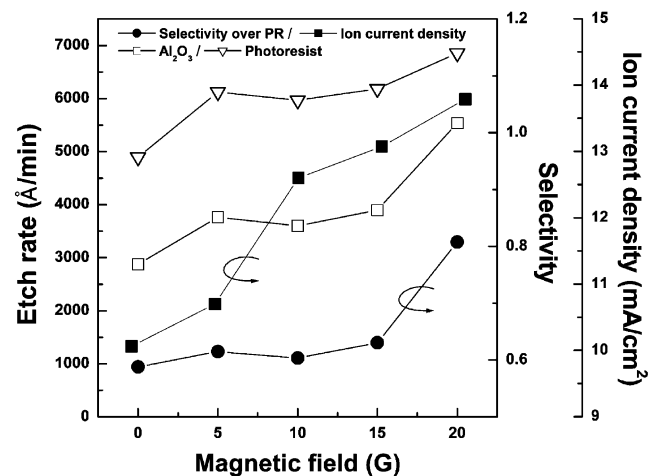


Fig. 2. Measured etch rates of sapphire and PR and ion current densities as a function of external magnetic field. (Process conditions: inductive power 1400 W, bias voltage -350 V, pressure 10 mTorr, total flow rate 100 sccm of 90% BCl_3 /10% HBr).

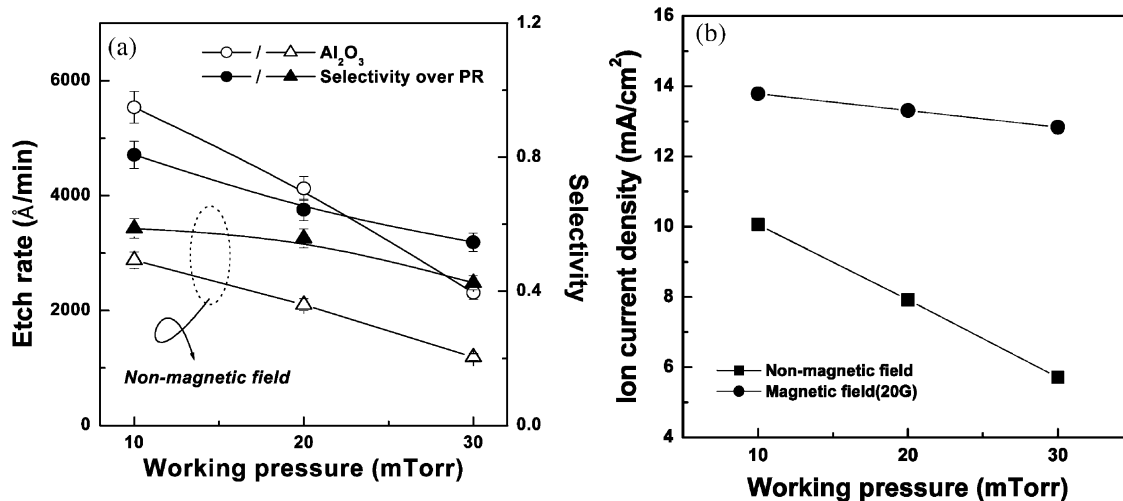


Fig. 3. (a) Measured etch rates of sapphire and etch selectivity over PR as a function of working pressure with/without 20 G of external magnetic field. (Process conditions: inductive power 1400 W, bias voltage -350 V, total flow rate 100 sccm of 90%BCl₃/10%HBr). (b) Measured ion current density as a function of working pressure with/without 20 G of external magnetic field. Process conditions were the same as those in Fig. 3a.

external magnetic field, therefore, the increase of ion flux with increasing external magnetic field, responsible for the increase of the etch rates is related to the increase of plasma density. Even though we did not measure the etch uniformity in this experiment, the previous study [14] showed that the etch uniformity was less than 8.8% in 4 inch diameter wafer under the 20 G of external magnetic field.

Fig. 3a shows the effect of pressure on the sapphire etch rates with/without external magnetic field strength. The strength of applied external magnetic field was 20 G. Total gas flow rate, inductive power, and dc bias voltage were fixed at 100 sccm, 1400 W, and -350 V, respectively. As shown Fig. 3a, whether 20 G of external magnetic field was applied or not, the etch rates of sapphire and PR were decreased with increasing working pressure. The etch selectivities over PR were also decreased with increasing working pressure regardless of the application of the magnetic field. However, for the range of working pressure investigated, the sapphire etch rates and etch selectivities with 20 G of external magnetic field was higher than those without the magnetic field.

Fig. 3b shows ion current densities measured using a Langmuir probe with increasing working pressure. The operation conditions were same as in Fig. 3a. As shown in Fig. 3b, ion current densities were decreased with increasing working pressure for both with and without 20 G of the external magnetic field. The variation trends of ion current density with increasing working pressure was similar to the trends of etch rates as shown in Fig. 3a. Therefore, the decrease of sapphire etch rates with increasing working pressure appears to be related to the decrease of ion density with increasing working pres-

sure. The decrease of ion density with increasing working pressure might be related to the decrease of effective inductive coupling at high pressures by the loss of energetic electrons to the wall by enhanced scattering. The smaller decrease of the ion density with increasing working pressure for the condition with the external magnetic field compared to that without the magnetic field might reflect the lower scattering loss by the application of the axial magnetic field. Even though the decrease of sapphire etch rate is related to the decrease of ion density with increasing working pressure, the decrease of sapphire etch rate with increasing working pressure was faster than the decrease of ion density with working pressure. Therefore, the redistribution of etch product onto the substrate and the decrease of ion energy, bombarding the substrate by increased scattering at higher working pressure might also be related to the decrease of sapphire etch rate.

Fig. 4 shows the etch rates of sapphire and PR with an increase of bias voltage from -350 to -800 V under 20 G of external magnetic field. The inductive power, working pressure, and total gas flow rate were 1400 W, 10 mTorr, and 100 sccm, respectively. As shown in Fig. 4, the increase of bias voltage increased the sapphire etch rates and PR etch rates almost linearly from 5500 to approximately 7700 Å/min and from 6900 to approximately 12000 Å/min, respectively. Therefore, the etch selectivity decreased from 0.8 to approximately 0.65. The increase of bias voltage increases the ion bombardment energy, therefore, the increase of sapphire etch rates and PR etch rate with increasing dc bias voltage appears to be related to the increased sputtering of substrate material and etch products. The decrease of etch selectivity with increasing dc bias voltage appears

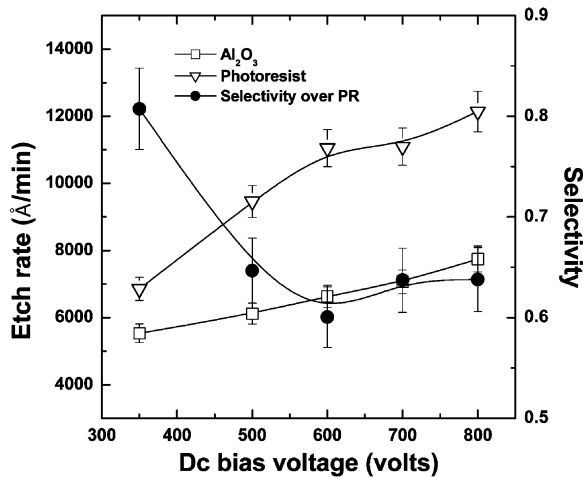


Fig. 4. Measured etch rates of sapphire, PR, and etch selectivities over PR as a function of dc bias voltage with 20 G of external magnetic field. (Process conditions: inductive power 1400 W, pressure 10 mTorr, total flow rate 100 sccm of 90%BCl₃/10%HBr.)

to be related to the lower sputter yield of sapphire and its etch products compared to PR.

Fig. 5 shows one of the sapphire etch profiles observed by SEM at -800 V of dc bias voltage, 1400 W of inductive power, 10 mTorr of working pressure, and 100 sccm of 90% BCl₃/10% HBr. The SEM picture was taken, after the photoresist was removed. As shown in Fig. 5, a highly anisotropic sapphire etch profile could be obtained due to the high etch rate of sapphire even though etch selectivity over PR is only 0.65.

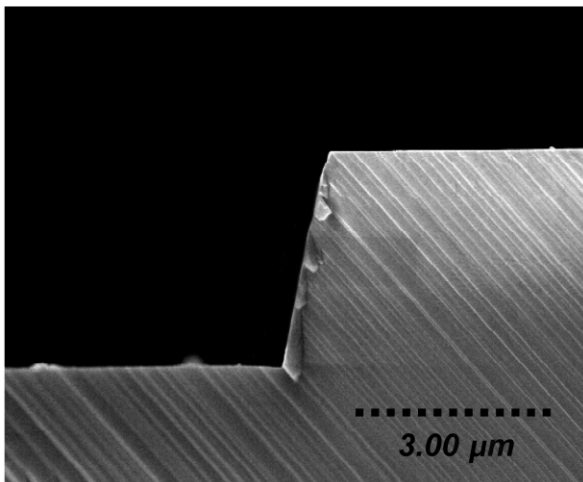


Fig. 5. Sapphire etch profile observed by SEM. (Process condition: inductive power 1400 W, bias voltage -800 V, pressure 10 mTorr, external magnetic field 20 G, total flow rate 100 sccm of 90%BCl₃/10%HBr.)

4. Conclusions

Sapphire etching was conducted in BCl₃/HBr, inductively coupled plasmas with applied external magnetic fields to achieve high etch rates and high etch selectivities over PR.

With an increase in external magnetic field, the sapphire etch rates and etch selectivities over PR was increased. The increase of sapphire etch rates and etch selectivities over PR appears to be related to the increase of ion density and radical densities with increasing external magnetic field. As the working pressure was increased, the sapphire etch rates and etch selectivities over photoresist were decreased, however the sapphire etch rates with the magnetic field showed always higher sapphire etch rates compared to those without the magnetic field. This decrease of sapphire etch rates and etch selectivities over PR with increasing working pressure appears to be related to the decrease of ion density and might also be related to the redeposition of etch products back to the substrate surface and scattering of the ions bombarding to the substrate with increasing working pressure. The increase of bias voltage decreased the etch selectivity over PR, however, increased the sapphire etch rate. At -800 V of dc bias voltage, 1400 W of inductive power, 10 mTorr of working pressure, and 100 sccm of 90% BCl₃/10% HBr, 7700 Å/min of sapphire etch rate with a highly anisotropic etch profile could be obtained in this experiment.

Acknowledgments

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