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Etch characteristics of optical waveguides using inductively coupled plasmas with multidipole magnets

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In this study, silica glass etch characteristics of inductively coupled plasmas with and without the multidipole magnets were investigated using CF_4 and SF_6 as the etch gases. A Langmuir probe and optical emission spectroscopy were used to investigate the characteristics of the plasmas. When the silica glass was etched with the multidipole magnets, a significant increase in etch rate was obtained with the magnets for both CF_4 and SF_6 together with an increase in ion saturation current as measured by the Langmuir probe. F radicals estimated by Ar actinometry also increased with the addition of the magnets. When the etch characteristics of CF_4 and SF_6 with magnets were compared at the same etch conditions, SF_6 showed the higher etch rates (>800 nm/min) while CF_4 showed the higher etch selectivity (>70:1) over the Cr mask material used in the study. With the magnets, a vertical etch profile was obtained with CF_4 while the etch profile with SF_6 was a little re-entrant. A 10 μm deep anisotropic silica glass etch profile with a smooth sidewall could be obtained using CF_4 and with the magnets at 7.5 mTorr of operational pressure, 1000 W of inductive power, and -100 V of dc self-bias voltage. The silica glass etch rate and the etch selectivity over Cr under these etch conditions were 700 nm/min and 70, respectively.
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I. INTRODUCTION

Silica-based optical waveguides, fabricated on silicon or silica wafer substrates, are potential building blocks of planar lightwave circuits (PLCs) that are becoming increasingly important for future telecommunications systems.[1–3] To fabricate optical waveguides, 6–10 μm deep silica glass has to be etched using dry etching techniques with anisotropic etch profiles and smooth sidewalls to reduce optical scattering loss.[1,4]

To etch the silica glass, dry etching techniques similar to those used in silicon integrated circuit processing can be utilized.[5–8] However, in the case of optical waveguide etching, the materials to be etched are much thicker ($\leqslant 1$ μm) than those in silicon integrated circuit processing, therefore, higher silica glass etch rates and etch selectivities over the mask material are required. In the case of silicon processing, a possibly local nonuniform plasma due to the nonuniform magnetic field in our etching system may damage the devices in the silicon wafer electrically by charging the wafer nonuniformly. However, in the case of optical waveguide etching, such electrical damage may not have to be considered because the devices are not as electrically sensitive as the silicon devices.

Currently various high density plasma sources such as electron cyclotron resonance plasma,[9] helicon plasma,[10] helical resonators, and inductively coupled plasma[11] are developed to etch materials at high rates. Among these high density plasma sources, inductively coupled plasma sources are widely studied for their simplicity in addition to their easy scalability. The use of magnets with inductively coupled plasma sources could be beneficial in the etching of optical waveguides by reducing the electron and ion loss to the chamber wall, thereby increasing ion densities.[12,13]

In this study, an inductively coupled plasma source with a multidipole magnet configuration was studied using CF_4 and SF_6 for application to the etching of silica glass optical waveguides. Differences in the characteristics of the plasmas with and without the magnets were investigated and basic silica glass etch properties such as etch rates, etch selectivities, and etch profiles were studied.

II. EXPERIMENTAL METHODS

The inductively coupled plasma equipment used in this study was composed of a five-turn spiral Au-coated copper coil located on the top of a chamber and separated by a 1 cm thick quartz window. A rf power of 13.56 MHz was applied to the coil to generate inductively coupled plasmas and a separate 13.56 MHz rf power was applied to the substrate to induce dc self-bias voltage to the substrate. The distance between the quartz window and the substrate was 7.5 cm and the substrate diameter was 6 in. For the magnet configuration, eight equally spaced 10 cm long permanent magnets (2000 G on the surface) were set around the chamber wall as shown in Fig. 1. The inductive power was varied from 800 to 1500 W, the dc self-bias voltage from 0 to -200 V, and the operating pressure from 3.5 to 7.5 mTorr. CF_4 and SF_6 were used to study the silica glass etch characteristics for the fabrication of optical waveguides with and without the multidipole magnets.

The 10 μm thick silica glass layers on Si substrates that were used in our study were prepared by plasma enhanced chemical vapor deposition (PECVD). For the etch mask, 300 nm of Cr was evaporated onto the 10 μm thick, silica glass deposited Si substrate. Following photolithography, Cr pat-

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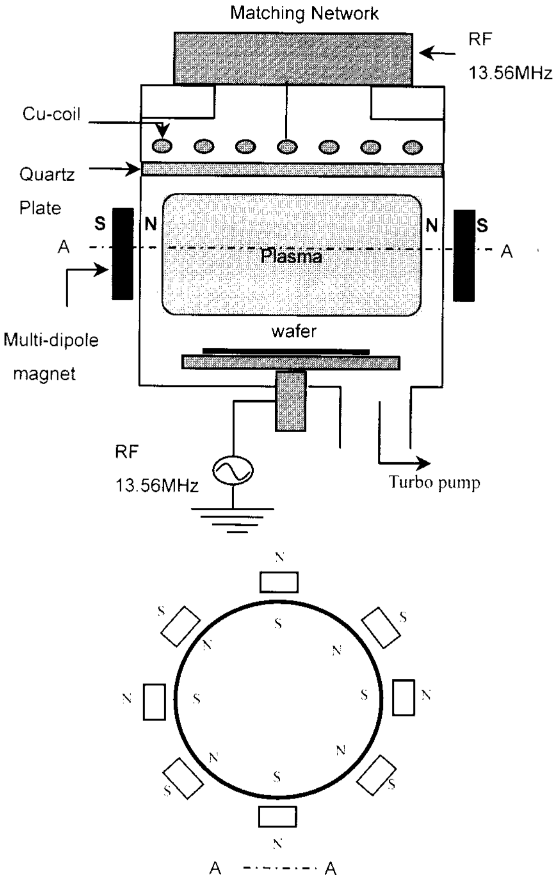


FIG. 1. Schematic of an inductively coupled plasma equipment using multidipole magnets.

terns were made by wet chemical etching (etchant: CR-7S). Various Cr pattern shapes were used in the experiment, however, for fabrication of the optical waveguide, a 8 μm Cr line pattern was used to form a waveguide with 8 μm deep and 8 μm high silica glass bars on the silicon wafer. The etch rate and the etch selectivity were measured with a surface profiler before and after removing the remaining chrome mask.

To investigate the effects of multidipole magnets on the characteristics of the plasmas and etch properties, ion saturation currents using a Langmuir probe and F radicals using optical emission spectroscopy (OES) were measured with and without the multidipole magnets. In the case of OES analysis, Ar actinometry was used by adding 8% Ar and dividing the F* intensity (703.8 nm) by the Ar* intensity (750.3 nm). The etch profiles were observed with a scanning electron microscope (SEM).

III. RESULTS AND DISCUSSION

The effects of the multidipole magnets attached to the sidewall of the chamber on the uniformities of the ion saturation current and silica etch rate were studied using C_4F_8 in the previous study and the results are described elsewhere.[14] The ion saturation current was measured using a Langmuir probe between the magnets along the centerline of the wafer and at 1 cm above the substrate holder. The previous study showed that the uniformity of ion saturation current within the 6 in.-diameter of the substrate holder measured with the magnets on the sidewall of the chamber was higher than that measured without the magnets, which is possibly due to a decrease in charged particle loss to the chamber wall by the magnets. The 6-in.-diam silica glass etch rate measured with the magnets also showed a higher uniformity compared to that measured without the magnets.

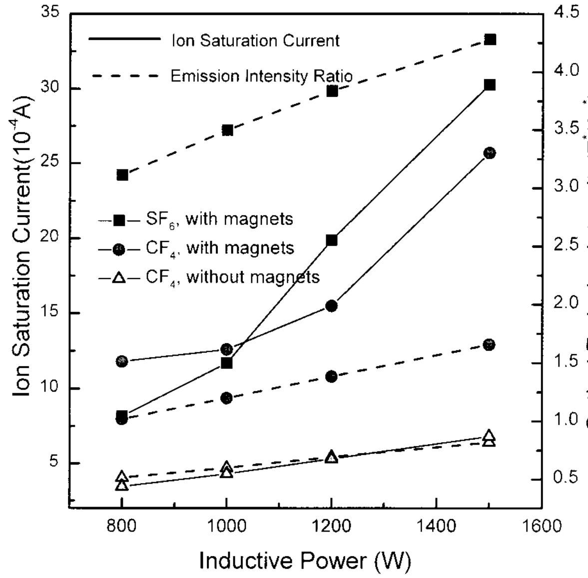


FIG. 2. Ion saturation current measured by a Langmuir probe as a function of inductive power for CF_4 and SF_6 plasmas with/without the magnets. No self-bias voltage was applied to the substrate holder.

In this study, the effects of the multidipole magnets on the characteristics of CF_4 and SF_6 inductively coupled plasmas were investigated using a Langmuir probe and OES for various inductive powers from 800 to 1500 W at 5 mTorr of operational pressure, and the results of the ion current density and relative F radical densities are shown in Fig. 2. As shown in Fig. 2, the increase of inductive power increased the ion saturation current, possibly due to the higher power deposition to the plasma with increasing inductive power. If the ion saturation currents with the multidipole magnets and without the magnets are compared for CF_4 plasmas, an increase of more than two times the ion saturation current was observed for those with the magnets. Also, the differences between the ion saturation current with and without the magnets increased at the higher inductive power although the ion saturation currents of SF_6 and CF_4 were similar to each other. The F radical densities estimated by Ar actinometry also increased with the increase of inductive power and the F radicals for CF_4 with the multidipole magnets were about two times higher than those without the magnets. The F radicals for SF_6 were higher than those for CF_4 at a given inductive power. The increase in ion saturation current and F radical density with the magnet is probably related to the decrease in ion and electron loss to the chamber wall due to the multidipole magnets used in the experiment.[14] The higher F radical densities for SF_6 compared to those for CF_4 are probably due to the lower dissociation energy of SF_6.

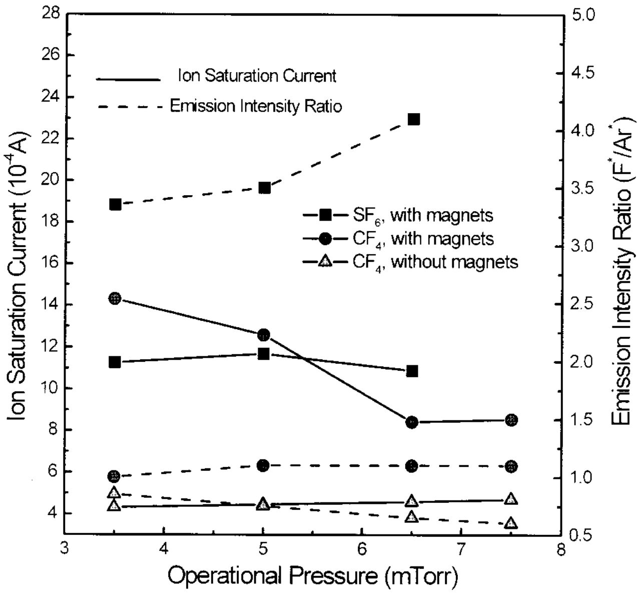


FIG. 3. Ion saturation current measured by a Langmuir probe and F radical intensity measured by actinometric OES in CF_4 and SF_6 inductively coupled plasmas as a function of operation pressure with/without the magnets. The applied inductive power was 1000 W and no self-bias voltage was applied to the substrate.

Figure 3 shows the effect of operational pressure on the ion saturation current and F radical densities at 1000 W of inductive power without applying dc self-bias voltage. The percent of measured error of the ion saturation currents and F radical densities in our experiment was less than 5%. As shown in Fig. 3, an increase in operational pressure slightly increased the ion saturation current in the case of CF_4 plasma without the magnets, however, in the case of the CF_4 plasma with the magnets, the ion saturation current decreased with an increase in operational pressure. In the case of SF_6 plasma with the magnets, the ion saturation current appeared to decrease after 5 mTorr of operational pressure. Instead, an increase in operational pressure appeared to increase the F radical density in both the CF_4 plasma and the SF_6 plasma with the magnets while the F radical density in the CF_4 plasma without the magnets appeared to decrease. The higher F radical density was observed for the CF_4 plasma with the magnet compared with that of the CF_4 plasma without the magnet. Also, the F radical intensity of the SF_6 plasma with the magnet was higher than that of the CF_4 plasma with the magnet. The decrease in ion saturation current with an increase in operational pressure is possibly related to the loss of the magnetic confinement effect of the multidipole magnets due to increased scattering. The higher F radical density for the case with the magnets appears to suggest increased dissociation by the existence of magnets used in the experiment.[15]

Figure 4(a) shows the effect of inductive power at −100 V of dc self-bias and the effect of bias voltage at 1000 W of inductive power on the silica glass etch rate. SF_6 and CF_4 at 5 mTorr of operational pressure were used. As shown in Fig. 4, the silica glass etch rate increased with an increase of inductive power and also increased with an increase of bias voltage applied to the substrate. More than two times the silica glass etch rates was obtained for the CF_4 plasma with the magnet compared to that without the magnet. The silica glass etch rates for the SF_6 plasmas were higher than those for the CF_4 plasmas. The increase in silica glass etch rate with increasing inductive power appears to be related to the increase of both ion saturation current and F radical density shown in Fig. 2 and, therefore, is related to the increased ion flux to the substrate at a given substrate bias voltage as well as to the increase in the reactive radicals. The increase of the glass etch rate with an increase of bias voltage is related to the increase of ion energy at a given ion flux to the substrate. The higher silica glass etch rate for the CF_4 plasma with the

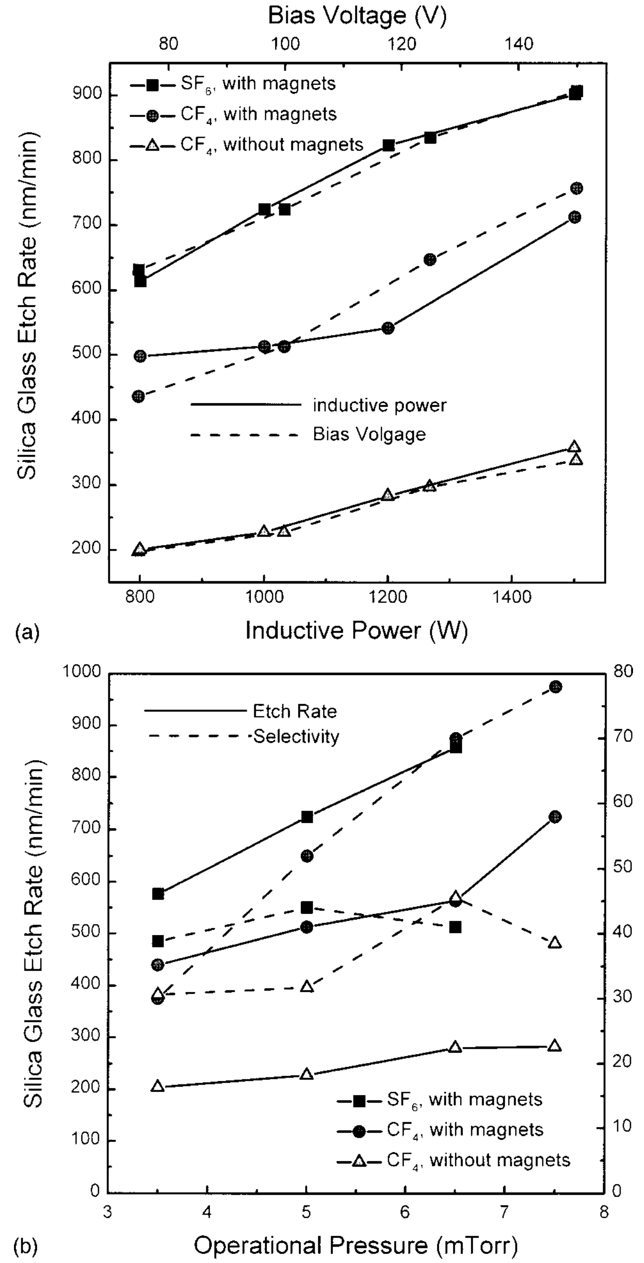


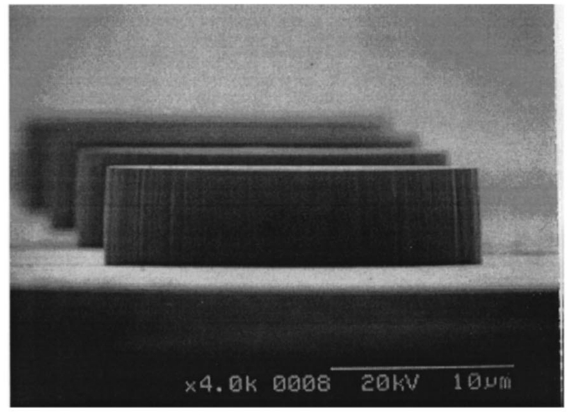
FIG. 4. Silica glass etch rate and etch selectivity over Cr by CF_4 and SF_6 plasmas as a function of (a) inductive power and bias voltage and (b) operational pressure with/without the magnets.

magnets compared to that for the CF_4 plasma without the magnets at a given inductive power and bias voltage also appeared to be related to the increased ion saturation current and radicals of the CF_4 plasma with the magnet shown in Fig. 2. In Fig. 2, the ion saturation currents for the CF_4 plasmas with the magnets are similar to those for the SF_6 plasmas with the magnets, however, the silica etch rates for the SF_6 plasmas are higher than those for the CF_4 plasmas. However, also in Fig. 2, we see that the F radical density for the SF_6 plasma with the magnets is higher than that for the CF_4 plasma with the magnet. Therefore, the higher silica etch rate with SF_6 compared to that with CF_4 appears to be related more to the higher density of reactive radicals.

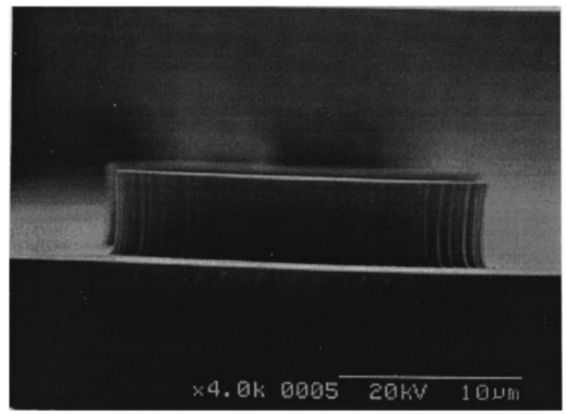
Figure 4(b) shows the effect of operational pressure on the silica glass etch rate at 1000 W of inductive power and −100 V of bias voltage. Also, the etch selectivity over the Cr used for the etch mask is included. The increase in operational pressure generally increased the silica glass etch rates for all of the conditions possibly due to the combined positive effect on the silica etch rates of the ion flux and radical density. The increase in operational pressure also increased the etch selectivity over Cr for the CF_4 plasma with the magnets. In the cases of the SF_6 plasma with the magnets and the CF_4 plasma without the magnets, the etch selectivities remained similar regardless of the change in pressure and were in the range of 30–45. However, in the case of the CF_4 plasma with the magnets, an etch selectivity close to 80 could be obtained at the pressure range investigated. The increased etch selectivity of CF_4 plasmas with the magnets at the increased operational pressure was related more to the decrease in the mask erosion rate than the increase in the silica etch rate. The decrease in the mask erosion rate appears to originate from a decrease in the physical sputtering of the Cr mask resulting from a decrease in the ion flux with increasing operational pressure.

Using 300 nm thick Cr as an etch mask, silica glasses were etched by CF_4 and SF_6 plasmas with magnets, and their etch profiles were investigated using SEM. The results are shown in Fig. 5(a) for CF_4 plasma with the magnets and in Fig. 5(b) for SF_6 plasma with the magnets. The etching was conducted at 1000 W of inductive power, −100 V of bias voltage, and 5 mTorr of operational pressure. As seen in Fig. 5, 5–6 μm deep silica glass was etched and an anisotropic etch profile could be obtained with the CF_4 plasma with the magnets, while a little re-entrant etch profile was obtained with the SF_6 plasma with the magnets. The re-entrant etch profile of the SF_6 plasma with the magnets appears to be related more to the F radicals associated to the SF_6 plasma with the magnets.

Silica glass 10 μm deep was etched again by increasing the operational pressure of the CF_4 plasma to 7.5 mTorr while the other conditions were kept the same as those shown in Fig. 5 for CF_4, and the result of the silica glass etch profile is shown in Fig. 6. A near vertical etch profile similar to that in Fig. 5 was also obtained. The slight positive angle at the top of the etch profile is due to the slope of the wet etched Cr mask. The silica glass etch rate and etch selectivity over Cr under these conditions were 700 nm/min and 70, respectively. Therefore, a highly anisotropic silica glass etch profile with a high silica glass etch rate and etch selectivity which is applicable to the fabrication of an optical



(a)



(b)

FIG. 5. SEM micrographs of the silica glass etch profiles: (a) CF_4 and (b) SF_6 at 1000 W of inductive power, 5 mTorr of operational pressure, and −100 V of bias voltage with the magnets.

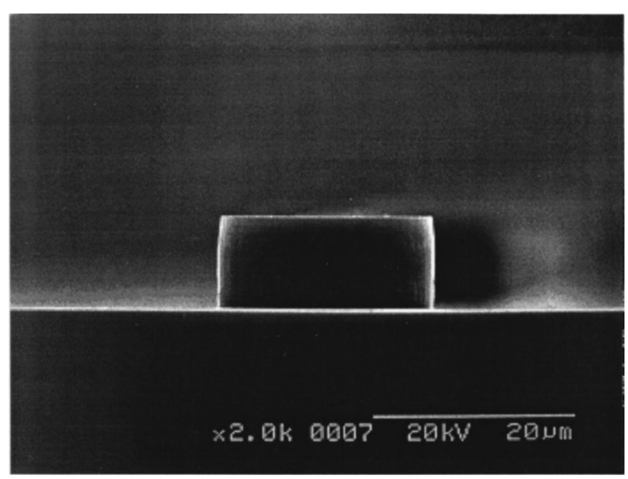


FIG. 6. SEM micrograph of the silica glass etch profile by a CF_4 plasma with the magnets at 1000 W of inductive power, 7.5 mTorr of operational pressure, and −100 V of bias voltage.

waveguide could be obtained with CF_4 inductively coupled plasmas by the application of a multidipole magnet around the chamber wall.

IV. CONCLUSIONS

In this study, the effects of inductively coupled CF_4 and SF_6 plasmas with multidipole type magnets on the characteristics of the plasmas and their silica glass etch characteristics were investigated for the fabrication of optical waveguides.

The application of the multidipole magnets to the inductively coupled plasma generally increased the ion saturation current measured by a Langmuir probe and the F radical density measured by optical emission spectroscopy. Silica glass was etched by CF_4 plasmas with and without magnets and by SF_6 plasma with magnets. At the same etch conditions, the silica glass etched by the SF_6 plasma with the magnet showed a higher etch rate compared to that etched by the CF_4 plasma with the magnet. When the silica glass etch rate for the CF_4 plasma with the magnets is compared with that for the CF_4 plasma without the magnets, the silica glass etch rate for the CF_4 plasma with the magnet showed a more than two times higher silica glass etch rate. The etch selectivity over Cr also improved by the addition of the magnets to the CF_4 plasma. The Cr masked silica glass etching by the SF_6 plasma with the magnets showed a re-entrant etch profile while that by the CF_4 plasma with the magnets showed a vertical etch profile.

A highly anisotropic 10 μm deep silica glass etch profile with a high silica glass etch rate of 700 nm/min and a high etch selectivity of 70, which is applicable to the fabrication of an optical waveguide, could be obtained with CF_4 inductively coupled plasmas by the application of multidipole magnets around the chamber wall.

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