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A study on the characteristics of inductively coupled plasma using multidipole magnets and its application to oxide etching

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Abstract

In this study, the effects of multidipole type of magnets on the characteristics of the inductively coupled plasmas and SiO_2 etch properties were investigated. As the magnets, four pairs of permanent magnets were applied and C_2F_6, CHF_3, C_4F_8, H_2, and their mixtures were used to etch SiO_2. When SiO_2 was etched using the fluorocarbon gases, the significant increase of SiO_2 etch rate and also the increase of etch uniformity could be obtained by applying the magnets. By optimizing the process parameters at 1000 W of inductive power with the magnets, the highest SiO_2 etch rate of 800 nm/min with the SiO_2: photoresist etch selectivity about 4 could be obtained for C_4F_8 and the highest etch selectivity more than 15 with the SiO_2 etch rate of 400 nm/min could be obtained for C_4F_8/50% H_2.

Keywords: Inductively coupled plasma; Oxide etching; Multidipole magnets; Waveguide

1. Introduction

Dry etching of silicon oxide is one of the key steps not only in silicon integrated circuit fabrication but also in other applications such as the fabrication of optical waveguides [1,2]. In case of the fabrication of optical waveguides, to obtain a square waveguide with low loss properties, dry etching characteristics of anisotropic etch profiles, low sidewall roughness to reduce scattering loss, and high SiO_2 etch rates with high etch selectivities to mask materials to etch the films thicker than 10 μm are required [3].

To obtain high SiO_2 etch rates for the fabrication of silicon integrated circuits, high density plasma sources such as inductively coupled plasma sources, helicon plasma sources, electron cyclotron resonance plasma sources, etc. have been investigated [4–6]. The application of high density plasmas to the etching of optical waveguides is also believed to be beneficial in obtaining high etch rates with vertical etch profiles similar to the cases in the fabrication of silicon integrated circuits. As mask materials, hard mask materials such as Al, Cr, and amorphous silicon are used in the silica waveguide etching because of low etch selectivities to conventional photoresist [3]. However, the use of photoresist as the mask material can reduce process steps and can increase productivity in the fabrication of optical waveguides.

In the study, an inductively coupled plasma source with a multidipole magnet configuration was studied for the application to the etching of silica waveguides. Differences in the characteristics of the plasmas with and without the magnets were investigated and their relation to basic SiO_2 etch properties such as etch rates and selectivities were studied using various fluorocarbon gas combinations.

2. 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 the chamber and separated by a 1 cm thick quartz window. 13.56 MHz RF power was applied to the coil to generate inductively coupled plasmas and separate 13.56 MHz RF power was applied to the substrate to induce DC-self bias voltages to the substrate. The distance between the quartz window and the substrate was 7.5 cm. As the magnet configuration, 10 cm long and equally spaced four pairs of permanent magnets having 2000 Gauss on the surface were located around the chamber wall by making the long axis of the magnets parallel to the chamber axis as shown in Fig. 1. The inductive power was varied from 400–1000 W, the DC-self bias voltage from 0–150 V, and the operating pressure from 0.7–1.4 Pa. Ar was used to study the characteristics of the inductively coupled plasmas for the conditions with and without the magnets, and C_2F_6, CHF_3, C_4F_8, H_2, and the combination of these

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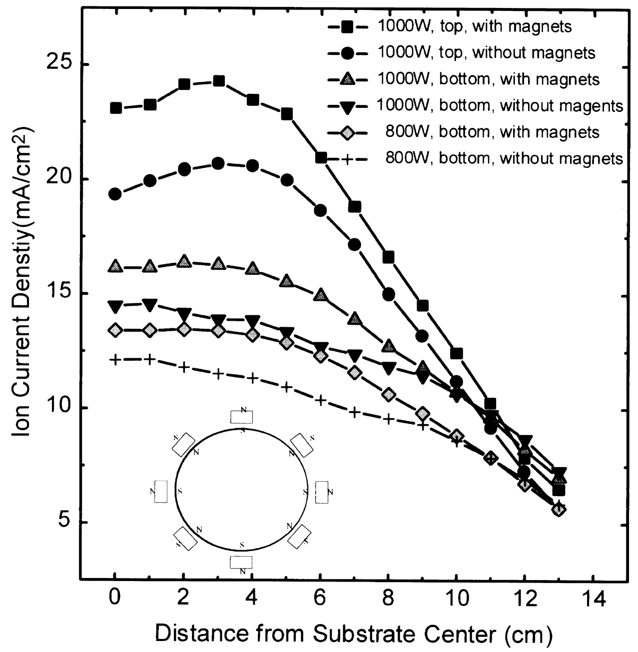

Fig. 1. The ion current densities measured at 1 cm above the substrate (bottom) and 1 cm below the quartz window (top) along the radial direction for 0.7 Pa. Ar, inductive power of 800/1000 W and with/without the magnets.

gases were used to study the etch properties. The characteristics of the inductively coupled Ar plasmas such as ion density, plasma potential, and electron temperature were measured using a single Langmuir probe and the results were compared with those of conventional inductively coupled Ar plasmas. In the case of the characteristics of the reactive gas plasmas, ion current density measured using the Langmuir probe and F radical intensity measured using optical emission spectroscopy (SC Technology: PCM-402) were investigated.

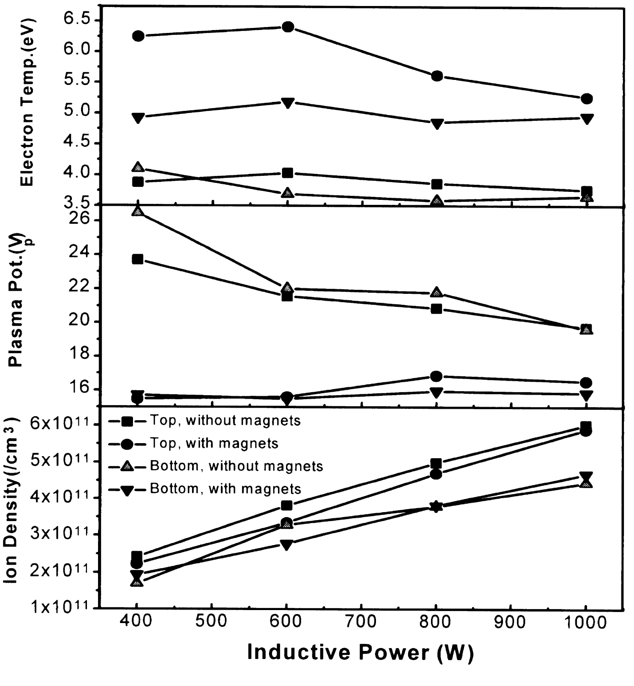

Fig. 2. Ion density, electron temperature and plasma potential at the center of the chamber calculated from the Langmuir probe data at 0.7 Pa. Ar as a function of the applied inductive power for the top/bottom locations and with/without the magnets.

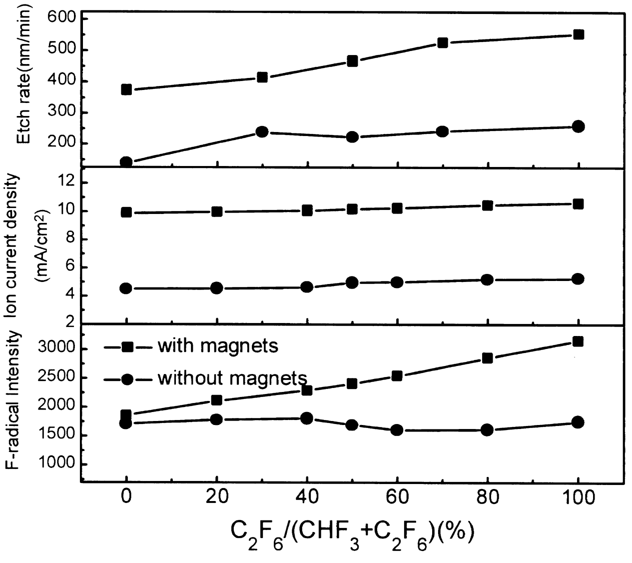

Fig. 3. SiO_2 etch rates, F-radical densities and ion current densities as a function of gas mixture of C_2F_6/ CHF_3 for the cases with/without the magnets at 0.7 Pa, 1000 W of inductive power and − 100 V of DC-self bias voltage.

3. Results and discussion

Fig. 1 shows the ion current densities measured at 1 cm above the substrate (bottom) along the radial direction for 0.7 Pa Ar, an inductive coupled power of 800 W or 1000 W, and with/without the magnets. The ion current densities measured at 1 cm below the quartz window (top) with the magnets are also included. As shown in Fig. 1, when measured at 1 cm above the substrate (bottom) without the magnets, the ion current density was highest near the center of the substrate and was decreasing monotonically as it moved toward the chamber wall. However, in the case with magnets, there was a plateau near the center of the chamber before the ion current density decreased drastically. Therefore, the overall uniformity was worse for the case with the magnets, however, if the uniformity from the center to 8 cm radius of the substrate is considered, the uniformity of the case with the magnets was better than the case without the magnets.

Ion density, electron temperature, and plasma potential at the center of the chamber were calculated from the Langmuir probe data, and are shown in Fig. 2 in dependence on applied inductive power at 0.7 Pa for the top/bottom locations and for with/without the magnets. The ion density increased linearly with the increase of inductive power

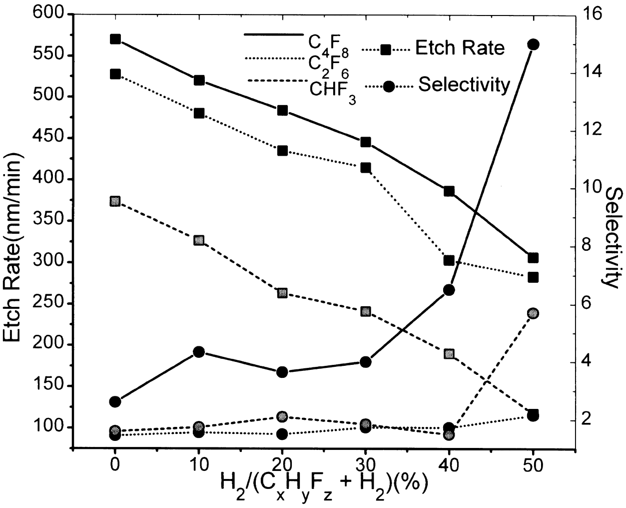

Fig. 4. The SiO_2 etch rates and the etch selectivities over photoresist as a function of hydrogen percentage in the fluorocarbon gases such as C_2F_6, CHF_3 and C_4F_8 for 0.7 Pa, 1000 W, − 100 V of DC-self bias voltage and with the magnets.

from about 2×10^{11} cm^{-3} at 400 W to about 6×10^{11} cm^{-3} at 1000 W and the top location showed higher ion density compared to the bottom location. However, no noticeable differences in the ion densities were found between the cases with and without the magnets. The measured plasma potential and the electron temperature did not change significantly with the increase of applied inductive power. However, the electron temperature of the case with the magnets (5–6 eV) were higher than that without the magnets (3–4 eV), and the plasma potential with the magnets (15–17 V) were lower than that without the magnets (20–27 V).

Using reactive gases, the characteristics of their plasmas and the relations to their etch characteristics were investigated and are shown in Fig. 3 for the SiO_2 etch rates, fluorine atom densities, and ion current densities as a function of gas mixture of C_2F_6/ CHF_3 for the cases with/without the magnets while other parameters were fixed at 0.7 Pa, 1000 W of inductive power, and − 100 V of DC-self bias voltage. As shown in Fig. 3, as the C_2F_6/ CHF_3 ratio is increased, the SiO_2 etch rates increased. Also, the case with the magnets showed the higher SiO_2 etch rates compared to that without the magnets. The measured ion current densities for the cases with and without the magnets did not change significantly with gas mixture. However, the measured ion current densities for the case with the magnets were about two times higher compared to those without the magnets as shown in Fig. 3. The increase of C_2F_6 in C_2F_6/ CHF_3 gas mixtures generally increased the fluorine atom intensity and the case with the magnets showed higher fluorine atom intensity similar to the trends of SiO_2 etch rates [7]. When SiO_2 etch rates in dependence on the distance were measured from the center of the substrates for the case with/ without the magnets, the increased etch uniformity along with the increase in SiO_2 etch rates could be obtained over the 5-inch-diameter substrates with the magnets as suggested by the measured ion current density in Fig. 1 (not shown). Etch selectivities to photoresist were also investigated (not shown). For the conditions applied in Fig. 3, the etch selectivities were less than 2 even though there was a slight increase of the selectivity with the increase of CHF_3 in the C_2F_6/ CHF_3 gas mixture.

To improve the etch selectivity over the photoresist for the case with the magnets, hydrogen was added to fluorocarbon gases and, the SiO_2 etch rates and the etch selectivities in dependence on hydrogen percentage in the fluorocarbon gases such as C_2F_6, CHF_3, and C_4F_8 for 0.7 Pa, 1000 W, − 100 V, and with the magnets were measured and the results are shown in Fig. 4. For all of the fluorocarbon gases used in the experiments, the addition of hydrogen at a constant pressure reduced the SiO_2 etch rates possibly due to reduction of reactive species not only by the reduction of partial pressures of fluorocarbon gases but also by the formation of HF between F atoms and H atoms from H_2 [8]. Among the fluorocarbon gases used in the experiments, C_4F_8 exhibited the highest SiO_2 etch rates as shown in Fig. 4. The etch selectivity was not improved until hydrogen was added up to or near 30%, and the further increase of hydrogen increased the selectivity slightly in the cases of C_2F_6 and CHF_3 and significantly in the case of C_4F_8. The insignificant effect of hydrogen addition up to 30% appears to be related to the excessive F atoms obtained in high density plasmas, therefore, the abundancy of CF_x ($x \leq 2$) radicals which are required for the polymer formation does not exist at those conditions. At 50% hydrogen, C_4F_8/ H_2 showed the highest selectivity ($\geq$ 15). The highest selectivity of C_4F_8/ H_2 appears to be related to the easier formation of CF_x ($x \leq 2$) radicals compared to other fluorocarbon gases used in the experiments [7].

From the experiments, the SiO_2 etch rate of 340 nm/min with the etch selectivity of higher than 15 could be obtained with the magnets using C_4F_8/50% H_2 at 0.7 Pa, 1000 W of inductive power, and − 100 V of DC-self bias voltage. When the operational pressure was increased to 1.4 Pa while other parameters were kept unchanged, the SiO_2 etch rate of 400 nm/min with the etch selectivity higher than 15 could be still obtained. Also, when pure C_4F_8 instead of C_4F_8/ H_2 and − 150 V of DC-self bias voltage were used, the etch rate of 800 nm/min with the selectivity of 4 was obtained.

4. Conclusion

In this study, the effects of multidipole type of magnets on the characteristics of the inductively coupled plasmas and SiO_2 etch properties were investigated. Four pairs of permanent magnets were applied to form a magnet bucket and, as etch gases, combinations of C_2F_6, CHF_3, C_4F_8, and H_2 were used.

The application of multidipole magnets increased the uniformity of the ion current density at a certain area of the chamber even though no significant increase of ion density was observed. The application of the magnets also increased the electron temperature and radical densities while reducing the plasma potential.

When SiO_2 was etched, the significant increase of etch rates and also the increase of etch uniformity were obtained with the magnets. Highest etch rate and etch selectivity to photoresist could be obtained with C_4F_8/ H_2 among the gas combinations used in the experiments.

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