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Effects of variously configured magnets on the characteristics of inductively coupled plasmas

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In this study, the effects of axial electromagnet, variously configured multidipole permanent magnets and their combinations, on the characteristics of a square shaped (210 mm×210 mm) inductively coupled plasma source were investigated using a single electrostatic probe for Ar plasmas. The use of multidipole magnets mainly changed the uniformity of the plasma without changing the ion density of the plasma greatly. An optimized shape of the permanent magnets increased the uniformity of the plasma, and the uniformity of the ion density less than 6.0% could be obtained when measured from the center of the chamber to 10 mm before the chamber wall at 600 W of inductive power and 2 mTorr of operational pressure. The use of axial electromagnet mainly increased the ion density with the decrease of the uniformity, and ion density up to $7.5 \times 10^{11} \text{ cm}^{-3}$ could be obtained with 25 G at 600 W of inductive power and 5 mTorr of operational pressure. The addition of the optimized multidipole magnet to the axial electromagnet also improved the uniformity, and it showed the lowest electron temperature (3 eV) and plasma potential ($34V_p$). The etch uniformities of polysilicon etched using Cl_2 gas showed the similar trends as the uniformities of the ion density measured for variously configured magnets. © 1999 American Vacuum Society. [S0734-2101(99)23004-7]

I. INTRODUCTION

Although high density plasma (HDP) sources have been employed for dry etching in microelectronics,^{1,2} their scale-up to process a large wafer such as the substrates used in the flat panel display (FPD) technology is not easy due to the uniformity problem over a large area wafer.^{3,4}

High plasma densities ($> 1 \times 10^{11} \text{ cm}^{-3}$) at low pressures desired for single wafer processing have been achieved with electron cyclotron resonance (ECR) sources,⁵⁻⁷ helicon wave sources,⁸ helical resonators,⁹ and inductively coupled plasma (ICP) sources.¹⁰⁻¹⁵ Among these high density sources, inductively driven plasma source can be easily scaled to large diameters while maintaining high plasma densities, making them ideal candidates for the applications of materials processing.

In this study, to enhance the plasma uniformity and density of an inductively coupled plasma source, the effects of variously configured magnets¹⁶ on the characteristics of the plasmas were investigated. An electrostatic probe was used to characterize ion density, plasma potential, and electron temperature of Ar plasmas across the chamber for variously configured magnets.

II. EXPERIMENT

The schematics of the inductively coupled plasma equipment used in the experiment is shown in Fig. 1(a). The chamber was designed as a square mainly for the FPD applications and was made of anodized aluminum. The inner size of the chamber was 210 mm×210 mm.

Radio frequency power (13.56 MHz, 0–1200 W) was supplied to the center of the Au-coated four-turn square coil to generate inductively coupled plasmas. A 24-mm-thick quartz plate separates the square coil from the plasma region. The distance between the quartz window and the substrate was set at 110 mm and it was variable. A square array of magnet housing made of anodized aluminum was used to install permanent magnets inside the chamber. 6 mm×8 mm×56 mm permanent magnets having 3000 G on the surface were inserted in the magnet housings made of aluminum, and arranged to form various types of magnet configuration as shown in Fig 1(b). Multidipole magnet types I and IV, types II and V, and type III have same magnetic field strengths on the chamber surface, respectively, and are arranged differently around the chamber. The spacing between the centers of the magnet types I, II, and III was 56 mm and eight pairs of magnets were arranged along the inside of chamber wall. In the case of types IV and V, the center-to-center spacing was 28 mm and 14 pairs of magnets were arranged. Helmholtz type axial electromagnets were also designed as a square (500 mm×500 mm), and were located outside the chamber as shown in Fig. 1(a).

To investigate the effects of variously configured magnets on the characteristics of inductively coupled plasmas, plasma parameters were measured using an electrostatic probe (Hiden Analytical Ltd.; model ESP). The probe tip was made of a tungsten wire with 10 mm long and 0.15 mm in diameter and was positioned 15 mm above the substrate surface. Ar ion density was measured using the electrostatic probe and the probe was swept across the plasma both at the center and the side (60 mm away from the center) to measure the uniformity of the plasmas. In measuring the Ar density, the simple collisionless zero magnetic field solution for the elec-

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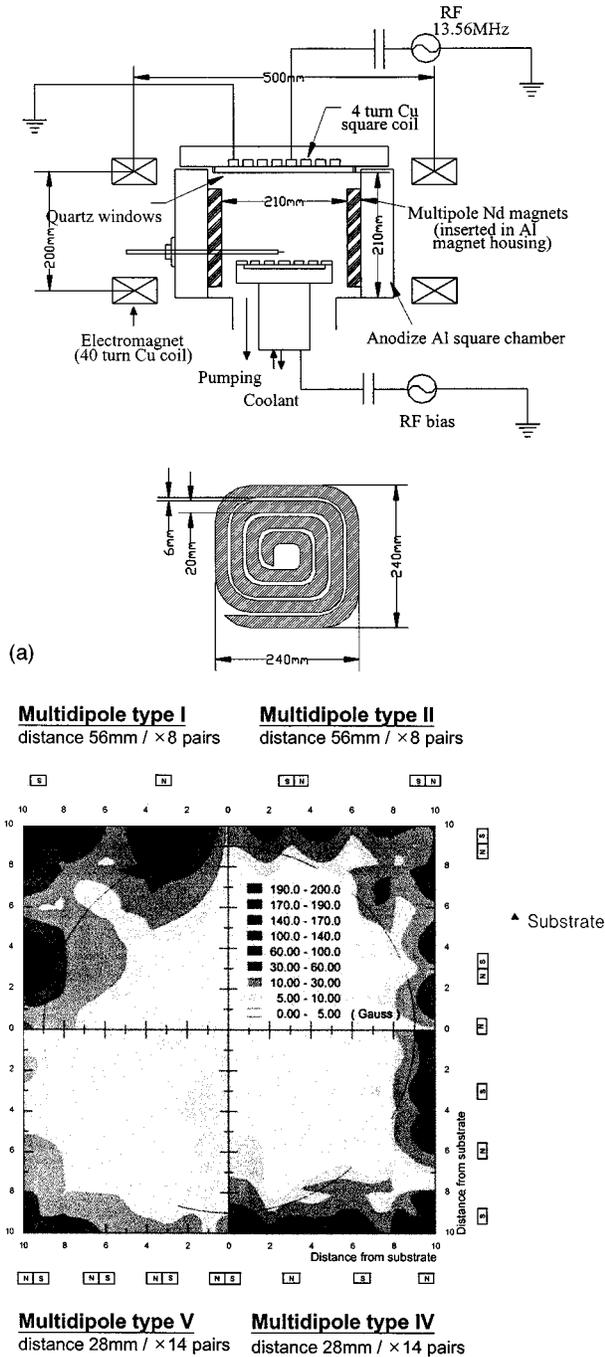


FIG. 1. (a) Schematics of the inductively coupled plasma equipment and (b) various multidipole magnets types used in the experiment and their magnetic field strength in the chamber for the strength of the magnet. Type III (not shown) had the same configuration as type I except each magnet for type III possessed 4300 G on the surface, while type I possessed 3000 G on the surface of the magnet.

trostatic probe was applicable because the radius of the probe was less than gyroradius of the electron (the magnetic field strength inside the chamber investigated was less than 200 G, therefore, the gyroradius of the electron was larger than 0.55 mm) and electron mean free path.¹⁷ The uniformity was calculated from the data using the equation as $\{(\max - \min) / 2 \times \text{average}\} \times 100\%$. The ion density, plasma

potential, and electron temperature were measured as a function of position.

To estimate the effects of an optimized multidipole magnet and an axial electromagnet (20 G) on the etch uniformity, 1- μm -thick undoped polysilicon/1000 Å silicon dioxide on silicon wafers was etched at 600 W of inductive power, 5 mTorr of operational pressure, and 30 sccm of Cl_2 flow rate. The wafers were biased at -50 V. The etch rates were estimated using a Nanospec (AFT model 200) by measuring the thickness of the polysilicon before and after the etching.

III. RESULTS AND DISCUSSION

The effects of different magnet types on the characteristics of the inductively coupled plasmas were investigated without applying the axial electromagnet. Using the electrostatic probe, ion saturation currents were measured at 15 mm above the substrate and along the substrate diameter. The results are shown in Fig. 2(a) for 5 mTorr of Ar and 600 W of inductive power. As a reference, the ion saturation current measured without the magnets was also measured. As shown in the figure, the application of different types of multidipole magnets increased ion saturation currents from 4% to 61% depending on the types of the magnets used in the experiment. The uniformity of the measured ion saturation current was also varied depending on the types of the magnets. The uniformity of the ion saturation current without the magnet was 16%, while the use of types I and III decreased the uniformity of the ion saturation current to 19% and 34%, respectively. The use of types II, IV, and V, however, increased the uniformity to 11%, 6%, and 14%, respectively. Therefore, for the magnet types used in the experiment, type IV showed the best uniformity of ion saturation current. The difference between type I and type IV is only the distance, and the type I has 56 mm between the centers of the magnets and the type IV has 28 mm. Therefore, the increase of uniformity for type IV may be originated from the decrease of the charged particle loss to the wall due to the decreased spacing of the magnets on the chamber wall. The difference between type III and type I is the strength of the magnetic field on the magnet surface (that is, on the chamber wall). Type I has 3000 G on the magnet surface and type III has 4300 G. Therefore, it appears that the penetration of stronger magnetic field into the reaction chamber appears to decrease the uniformity. From the above results, it appears that to obtain uniform plasmas with the multidipole magnets, not only the distance between the magnets but also the strength of the magnet needs to be optimized.

Using the electrostatic probe, ion densities of the Ar plasmas with the magnet types II and IV which showed the better uniformity of ion saturation current density compared to that without magnet were estimated and the results are shown in Fig. 2(b). The process condition was the same as the case of Fig. 2(a) and the ion density without the magnet was also included. The trend of uniformity of ion density was similar to that of ion saturation current density. Compared to the ion density without magnets (18.1%), the ion density with the

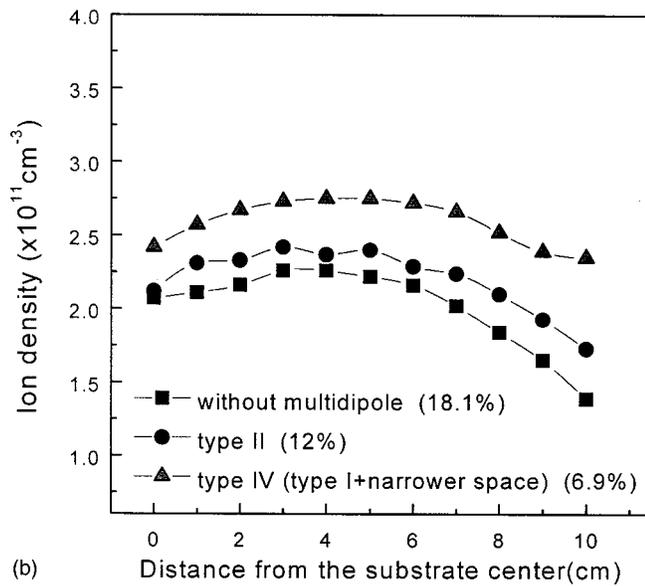
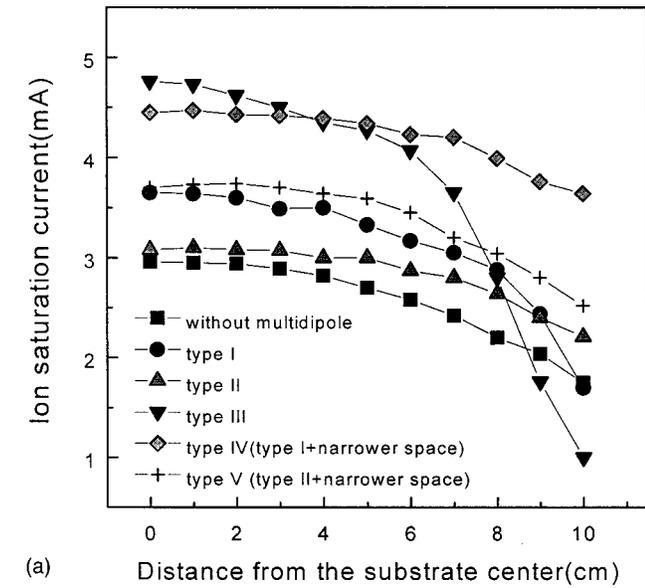


Fig. 2. (a) Ion saturation current and (b) ion density of various multidipole magnets measured using an electrostatic probe at 15 mm above the substrate along the radial direction for 5 mTorr Ar and 600 W inductive power.

magnet type IV (6.9%) showed a little higher ion density and better uniformity as shown in the figure.

The effect of the Ar pressure on the uniformity of ion density was also measured for the plasmas with and without the magnet type IV and the result is shown in Fig. 3 for 600 W of inductive power and at the pressure in the range of 2–10 mTorr. As shown in Fig. 3, the decrease of operational pressure decreased ion density in general, however, increased the uniformity of ion density for both with the magnet and without the magnet. At 2 mTorr of Ar pressure, the uniformity without the magnet was 10%, while that with the magnet type IV was 5.9%. The increase in the uniformity of ion density at the lower pressure appears to be related to the increase of mean free path of the ions. The decrease of operational pressure generally increased electron temperatures

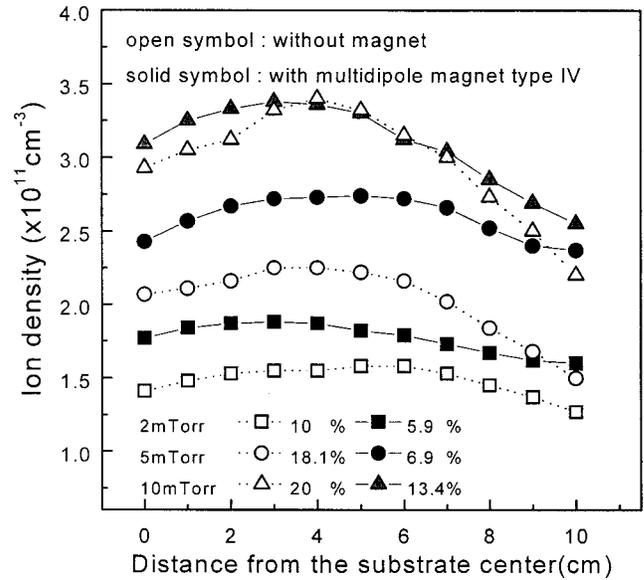


Fig. 3. Radial distribution of Ar ion density with/without the multidipole magnets of type IV at 600 W inductive power and various operational pressures.

(from 4.5 eV at 10 mTorr to 6.5 eV at 2 mTorr without the magnets and from 4.0 eV at 10 mTorr to 6.0 eV at 2 mTorr with the magnets at the center of the chamber) while the plasma potentials remain similar (36–38 eV with the magnets and at 40–43 eV without the magnets at the center of the chamber) (not shown).

The uniformity of the ion density was also measured at the side of the chamber located 60 mm away from the chamber center and parallel to the sideline of the chamber wall and the results are shown in Fig. 4 for 2 and 5 mTorr of Ar pressures and at 600 W of inductive power. When the data in

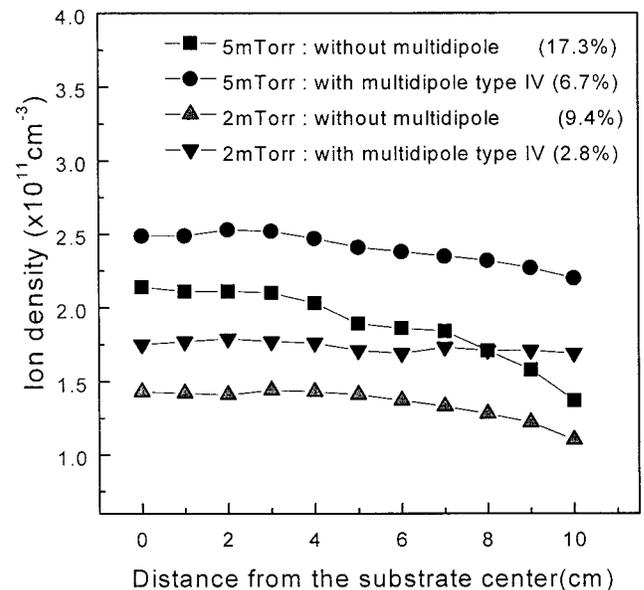


Fig. 4. Radial distribution of Ar ion density at the side of the chamber with/without the multidipole magnets at 2/5 mTorr with 600 W inductive power. The side is 60 mm away from the substrate center.

Fig. 4 are compared with the data in Fig. 3 for 2 and 5 mTorr, the uniformity of the ion density along the sideline of the chamber appears to be better compared to that along the radial direction even though we could not measure the ion densities at the locations where the inductive coil was bended 90°.

The effects of multipole magnets on the confinements of the plasmas could be found from the studies by other researchers.¹⁸⁻²⁰ Even though the results from those researchers were related to the improvement of plasma density for the plasma induced by hot filament not the inductively coupled plasma, their results showed the improvement of the ion density due to the installation of the multipole magnet. Also, among the various magnet configurations studied (such as checkerboard, broken line cusp, and full line cusp), the full line cusp showed the highest ion density. They claimed that confining the primary electron was responsible for the improvement of the ion density. Our results show the increase of ion density with the full line type magnet, therefore, our results agree with the results from the above researchers in general. Unfortunately, they did not change the distance of the magnet configuration, therefore, we could not compare the results directly.

The uniformity of the plasma with the magnetic cusping is explained by the following equation:²¹

$$\frac{n_s}{n_o} = \left[1 + \left(\frac{f_{loss} u_B l}{\pi D_a} \right)^2 \right]^{-1/2},$$

where n_s is the plasma density at $n(l/2)$, n_o is the plasma density at the center of the chamber, u_B is the velocity of the ion at the sheath, l is the length of the plasma, D_a is the ambipolar diffusion coefficient, f_{loss} is the fraction of the ion and electron pairs lost to the wall, where $f_{loss} = NW/2\pi R$, N is number of magnetic cusps, W is the effective leak width, and R is the radius of the chamber. Therefore, the uniformity of the plasma by the magnetic cusping depends on the f_{loss} . Lower f_{loss} improves the uniformity of the plasma. f_{loss} depends on the effective leak width W . The size of the leak width is not fully understood, however, it was shown by the following equation at the intermediate pressure:

$$W \approx \frac{2}{\pi} \frac{\overline{r_{ce}} \cdot \overline{r_{ci}}}{(\lambda_{me} \cdot \lambda_{mi})^{1/2}},$$

where $\overline{r_{ce}}$ is the mean electron gyroradius at the location where the magnetic field line enters the wall, $\overline{r_{ci}}$ is the mean ion gyroradius at the location where the magnetic field line enters the wall, λ_{me} is the mean free path of the electron, λ_{mi} is the mean free path of the ion, d is the distance between the magnets.

At the same magnetic field strength and operational pressure, the leak width is proportional to the distance between the magnets, therefore, W decreases with the shorter distance between the magnets. However, f_{loss} is proportional to NW , and N will be increased with the inverse of the distance d , therefore, the above equation appears not to explain the effects of the variation of the distance between the magnets. At least, the decrease of the distance between the magnets im-

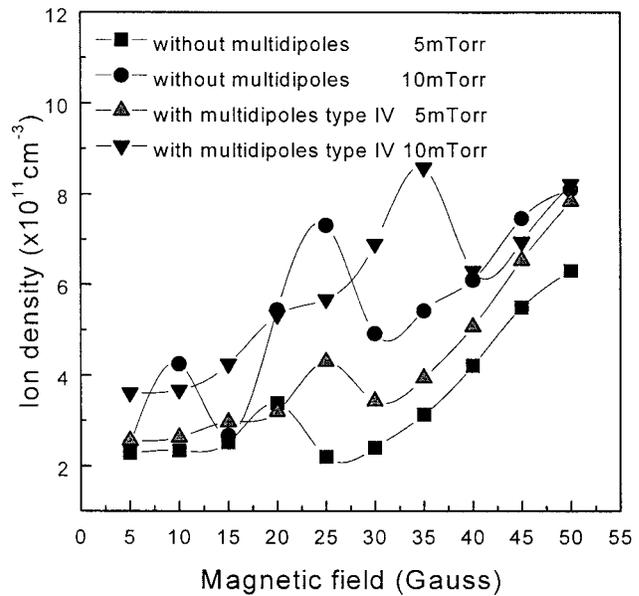
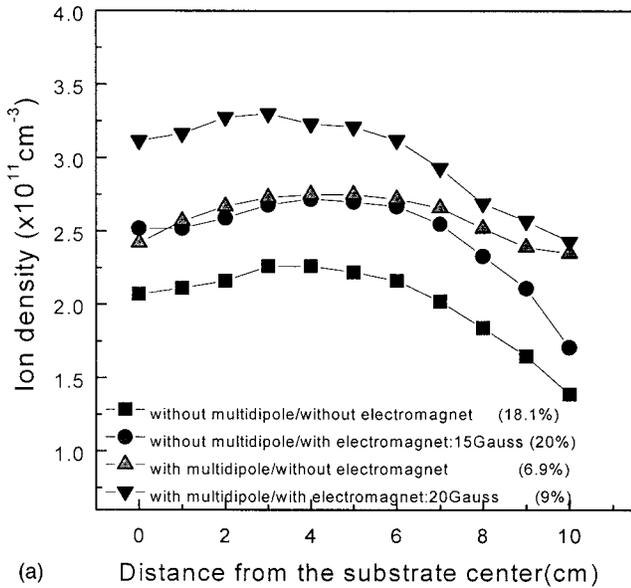


Fig. 5. Ion density as a function of axial electromagnetic field strength (Bz) measured 15 mm above the substrate center with/without the multidipole magnets of type IV at 5/10 mTorr and 600 W inductive power.

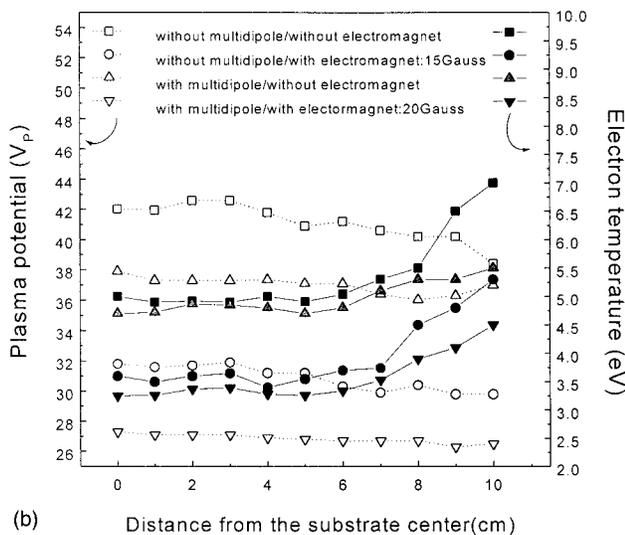
proves the uniformity of the plasmas, and it has to be related to the $f_{loss} \cdot f_{loss}$, in our case, is possibly related to $(r_{ce} \cdot d)/\lambda_{me}$ even though more investigation is required to prove this empirical equation.

The effects of Helmholtz type axial magnets on the characteristics of the plasmas were investigated without the multidipole magnets and with the magnet type IV. The ion densities were measured as a function of axial magnetic field strengths at 600 W of inductive power and at 5 and 10 mTorr of Ar pressure. The results are shown in Fig. 5. The addition of Helmholtz type axial magnets to the inductively coupled plasma generally increased the density of the ions for both with and without the multidipole magnets possibly due to the decrease of electron mobility along the radial direction. Especially, at the specific axial magnetic field strengths, huge jumps in the ion density were observed. These jumps appear to be from some kind of helicon excitation, however, more detailed investigation is needed.

The effects the axial magnets and the combination of the axial magnets and the multidipole magnets on the uniformity of the ion density along the radial direction of the chamber were investigated at 600 W of inductive power and 5 mTorr of Ar pressure. 15 or 20 G of the axial magnetic field strength was applied and the results are shown in Fig. 6(a). For a comparison, the ion density data without multidipole magnet/without the electromagnets and the data with the type IV magnets/without the electromagnets in Fig. 3 for 5 mTorr were redrawn in the figure. As shown in the figure, the addition of the electromagnets to the inductively coupled plasmas decreased the uniformity of the ion density for both with and without the multidipole magnets. However, the uniformity of the ion density with the multidipole magnets/with the electromagnets (9%) was better than that without the multidipole magnets/with the electromagnets (20%), there-



(a) Distance from the substrate center(cm)



(b) Distance from the substrate center(cm)

Fig. 6. Radial distribution of (a) Ar ion density and (b) plasma potential and electron temperature with/without the multidipole magnet type IV and axial electromagnets at 5 mTorr and 600 W inductive power.

fore, the use of the multidipole magnets on the chamber wall improved the uniformity of the ions regardless of the application of the axial electromagnets to the plasmas.

Figure 6(b) shows the effects of the multidipole magnets, the electromagnets, and the combination of the electromagnets and the multidipole magnets on the electron temperature and plasma potential for the same conditions as Fig. 6(a). As shown in the figure, the use of multidipole magnets alone decreased the plasma potential from about 42 to 38 eV, and the use of the electromagnets alone also decreased the plasma potential to 32 eV, therefore, more decrease of plasma potential could be obtained with the electromagnet. The largest decrease of the plasma potential (to about 27 eV) could be obtained with the combination of both the multidipole magnets and the electromagnets. Similar trend was also obtained for the electron temperature as shown in the figure.

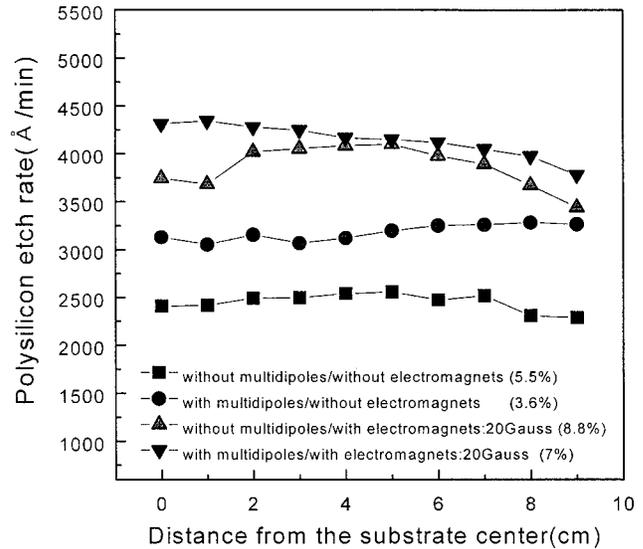


Fig. 7. Polysilicon etch rates measured as a function of distance from the substrate center with/without the multidipole magnet type IV and 20 G of axial electromagnets at 5 mTorr, 600 W inductive power, and 30 sccm Cl_2 .

Therefore, the use of the electromagnets (3.6 eV at the center) alone showed the lower electron temperature compared to the use of the multidipole magnets alone (4.75 eV at the center), however, the lowest electron temperature (3.25 eV at the center) was obtained with the combination of the multidipole magnets and the electromagnets.

To understand the effects of the above magnets on the etch rate and uniformity, polysilicon samples were etched using the etch condition described in the experimental section, and the results are shown in Fig. 7. As the multidipole magnets, type IV magnet was used and, for the electromagnetic field strength, 20 G was applied. As shown in the figure, the trends of etch rate and etch uniformity were similar to the trends of ion density and its uniformity with the magnets shown in Fig. 6(a). Therefore, the highest etch rate was obtained with both the multidipole magnets and the electromagnets and the etch uniformity was the highest with the multidipole magnets only as 3.6% while the etch uniformity without the magnets was 5.5%. With both the multidipole magnets and the electromagnets, 7% of etch uniformity was obtained.

IV. SUMMARY

The effects of various multidipole magnet types and Helmholtz type axial electromagnets on the plasma density of inductively coupled plasma and its uniformity along the chamber were investigated using an electrostatic probe for a square type of source and reaction chamber.

The various types of multidipole magnets changed the uniformity of ion density and, by choosing the adequate strength of the magnets and their arrangement, the uniformity of the ion density could be improved. Therefore, by using type IV magnets, Ar plasma uniformity measured from the center of the chamber to the 10 mm before the chamber wall was improved from 10% (without the magnets) to 5.9%

(with the magnets). The use of electromagnet, however, decreased the uniformity of the ion density. The addition of the multidipole magnets to the plasma with the electromagnets also improved the uniformity of the ion density, however, the uniformity was worse than that with the multidipole magnets only. The ion density was the highest with the combination of the multidipole magnets and the electromagnets.

Electron temperatures and plasma potentials were also measured using the electrostatic probe, and the plasma potential was the lowest for the plasma with both the multidipole magnets and the electromagnets. The application of the multidipole magnets or the electromagnets decreased the plasma potentials, respectively. Similar trend was obtained for the electron temperature, therefore, the lowest electron temperature was obtained by the combination of both the multidipole magnets and the electromagnets.

Polysilicon etch rates and etch uniformities were estimated for the plasmas with the above magnets. The trends of polysilicon etch rate and etch uniformity were similar to the trends of ion density measured with and without the above magnets. Therefore, by using the type IV magnets only, the polysilicon etch uniformity improved from 5.5% (without the multidipole magnets) to 3.6% (with the magnets).

ACKNOWLEDGMENTS

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