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Characteristics of magnetized inductively coupled plasma source for flat panel display applications

Young-Jun Lee*, Hye-Rhee Han, Geun-Young Yeom

Department of Materials Engineering, Sungkyunkwan University, Suwon, 440-746, South Korea

Abstract

In this study, to improve the plasma uniformity in addition to the plasma density of an inductively coupled plasma source, both permanent magnets and a Helmholtz type axial electromagnet were installed to a conventional planar inductively coupled plasma source and the effects of various magnet combinations on the polysilicon etch rates and etch uniformities were studied. The application of weak axial electromagnetic field to a planar inductively coupled plasma showed increased plasma densities, therefore, increased polysilicon etch rates compared with those by conventional inductively coupled plasmas. However, the application of the electromagnetic field degraded the etch uniformity. By using both an optimized permanent magnets and the axial electromagnet around the chamber wall, we found the improvement of polysilicon etch uniformity in addition to the increase of polysilicon etch rate due to the combination of the better features of both magnets. Among the permanent magnet configurations used with axial electromagnetic field in this experiment, a permanent magnet configuration with two poles/site showed the polysilicon etch uniformity at approximately 3.0% up to 15 G of axial electromagnetic field. The use of the magnetized inductively coupled plasma also decreased the average ion energy to the wall from 20 to 15 eV, therefore, decreased the possible contamination of the substrate caused by sputtering of the chamber wall. © 2000 Published by Elsevier Science B.V. All rights reserved.

Keywords: Magnetized ICP; Dry etch; Uniformity; Flat panel display

1. Introduction

In order to achieve the performance required for high-resolution flat panel display (FPD) devices of next generation, improved dry etch techniques are required for volume manufacturing and superior critical dimension control. Most of the dry etching equipments available for FPD device processing are based on capacitively coupled plasma excitation. These types of etch equipments, however, suffer from relatively low plasma densities, therefore, low etch rates [1–4]. Up to date, several types of high-density plasma sources overcoming these requirements have been developed. Among those low pressure (< 0.67 Pa) and high density ($> 10^{11}$ cm^{-3}) plasma sources, much interest is focused on the planar inductively driven plasma sources due to their simple structure and scalablity to large area. Higher plasma density could be obtained for planar-type inductively coupled plasma sources by the application of weak axial magnetic fields, and it increases plasma density by a factor of 2 due to the reduction of radial transport of electrons compared with those of non-magnetized inductively coupled discharges [5].

One of the problems with the high-density plasma sources including inductively coupled plasma sources applied to FDP is the non-uniformity of the plasmas due to the large scale of the substrate size. Especially when the inductively coupled plasma sources are used with axial magnetic fields, worse uniformity makes it difficult to apply to FPD processing.

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[*] Corresponding author. Department of Materials Engineering, Sungkyunkwan University, 300, Chunchun-dong, Jangan-gu, Suwon, Kyunggi-do 440-746, South Korea. Tel.: +82-331-2907418; fax: +82-331-2907410.

E-mail address: leeyj@nature.skku.ac.kr (Y.-J. Lee).

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Therefore, in this study, to improve the plasma uniformity in addition to the plasma density of inductively coupled plasma source, permanent magnet cusping was applied to the planar inductively coupled plasma source with axial magnetic fields and the effects of various magnet configurations on the polysilicon etch rates and etch uniformities were studied.

2. Experimental

A schematic view of the inductively coupled plasma (ICP) equipment used in this study is shown in Fig. 1. The process chamber was designed as a square mainly for the FPD applications and was made of anodized aluminum. Radio frequency power (13.56 MHz, 0–1200 W) was supplied to the center of Au-coated 4-turn square coil to generate inductively coupled plasmas, while other 13.56 MHz r.f. power was applied to the water-cooled (25°C) substrate to induce bias voltages to the wafer. A 24-mm thick quartz plate separates the square coil from the plasma region. A square array of magnet housing made of anodized aluminum was used to install permanent magnets having 3000 G on the surface were inserted in the magnet housings made of aluminum, and arranged around the chamber wall to form a magnetic cusp. Three configurations of the permanent magnets were used in this study as denoted by type A (where, alternating magnet poles are separated by 56 mm, one pole/site), type B (where, the opposite magnet poles are in contact on its side each other and each set is separated by 56 mm, two poles/site), and type C (where, alternating magnet poles are separated by 28 mm, which is half of type A, one pole/site) in the figure. A Helmholtz type axial electromagnet was also designed as a square (500 × 500 mm), and was located outside the chamber as shown in the figure. Details of the system with different magnet configurations are described elsewhere [6].

To estimate the effects of variously configured magnets on the etch rates and uniformities, 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 using those magnet configurations. 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. The etch uniformity in the wafer was defined as $\{(\text{max.} - \text{min.})/(2 \times \text{average})\} \times 100\%$. Using a quadrupole mass spectrometer (QMS: Hiden Analytical Inc. PSM 500) attached on the sidewall of the chamber, positive ion densities such as Cl^+ and Cl_2^+ in a Cl_2 plasma were measured by turning off the filament and by integrating collected ions having different ion energies for various magnet configurations.

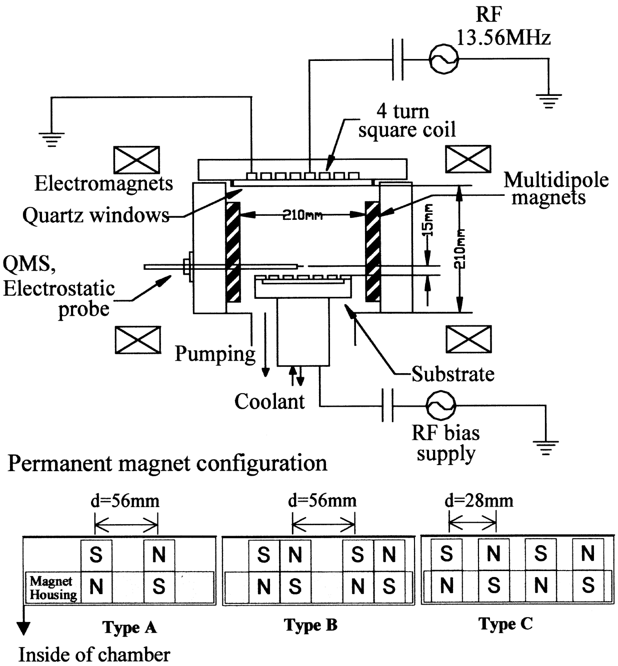

Fig. 1. Schematic diagram of the magnetized inductively coupled plasma etcher with a Helmholtz type electromagnet and with variously configured permanent magnets used in the experiment. Three different permanent magnet configurations were used: Type A: $d = 56$ mm, one pole/site, Type B: $d = 56$ mm, two poles/site, and Type C: $d = 28$ mm, one pole/site.

3. Results and discussion

To figure out the effects of Helmholtz type axial electromagnet and its combination with various permanent magnets (type A, B, and C) to an planar ICP etching equipment on the variation of etch rates and etch uniformities, polysilicon etch rates and etch uniformities were measured as a function of radial distance from the chamber center. These combinations of electromagnets and permanent magnets were chosen from the previous experiments conducted to understand the effects on the etch rates and etch uniformities by changing the electromagnetic field strengths and by changing the number of permanent magnets and their distances [6]. Fig. 2 shows etch rates and etch uniformities of polysilicon wafers etched with/without an Helmholtz type axial electromagnet in a planar ICP etching equipment. The inductively coupled plasma was operated using pure Cl_2 at 0.67 Pa, 600 W of inductive power, and -50 V of bias voltage. Using the Helmholtz type magnet, 15 G of axial electromagnetic field was uniformly applied to the inside of the chamber. To investigate the effect of the axial electromagnetic field to inductively coupled plasma etching, polysilicon wafers were etched without applying the magnetic field while keeping the same operating conditions. As shown in the figure, with the operating conditions used in the experiment, the conventional non-magnetized ICP showed polysilicon etch rates of approximately 250 nm/min with the uniformity of 5.5%. The addition of axial weak electromagnetic field (15 G) to the plasma increased the etch rates as shown in the figure, however, the etch uniformity deceased to 8.9%, where the etch rate decreased with the distance from the center. The increase of etch rate with the axial uniform electromagnetic field is not only from the increase of plasma density by the decrease of electron loss to the wall but also from the increase of skin depth, where the electromagnetic field can penetrate deeper into the plasma volume, therefore, more power is transferred to the plasma [5]. However, the application of axial electromagnetic field is known to cause a uniformity problem as we see in the experiment. In our case, even though the applied axial magnetic field strength is low, because the non-uniform electromagnetic field generated by the spiral coil [7] can penetrate near the substrate position through the plasma, the non-uniform etching appears to be the result.

To improve the etch uniformity without decreasing enhanced etch rates by the application of Helmholtz type axial electromagnetic field to the conventional planar ICP source, in addition to the 15-G axial electromagnetic field, variously configured permanent magnets described in the experimental section (type A, B, and C) were used around the chamber wall using specially designed anodized aluminum housings which contain alternating permanent magnets. These permanent magnet configurations were designed to form magnetic cuspings, therefore, to reduce the loss of plasma species including ions and electrons to the chamber wall. Fig. 3 shows the effect of those permanent magnetic configurations on the polysilicon etch rates and etch uniformities. The other etch parameters such as r.f. power, bias voltage, gas, and pressure were the same as those in Fig. 2. The polysilicon etch rates and etch uniformities for the 15-G axial electromagnetic field alone shown in Fig. 2 were also included in the figure to compare with those with permanent magnet configurations in addition to the axial electromagnet. As shown in the figure, the addition of permanent magnets around the chamber wall did not change the average polysilicon etch rates significantly. It appears to be from negligible change of plasma density with the application of a permanent magnet as studied by other researchers [8]. They showed that the use of magnetic cusping to a r.f. plasma system does not increase plasma density significantly compared to the hot filament system. However, the use of different types of permanent magnet changed the etch uniformity. The addition of type A magnet to electromagnet degraded the uniformity to 10.4% while the addition of type C magnet improved the uniformity to 5.1%. Among the three types of magnets, the best uniformity of 3.0% was obtained with the addition of type B magnet.

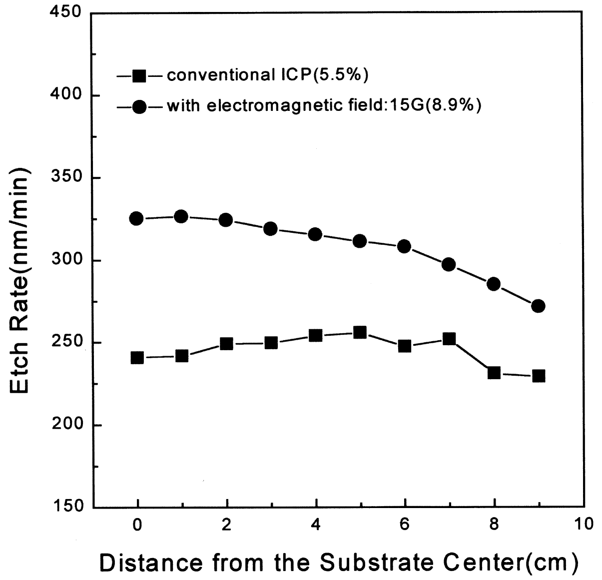

Fig. 2. Polysilicon etch rates measured as a function of distance from the substrate center for ICP with/without 15 G of axial electromagnetic field. Process condition: 600 W of inductive power, −50 V of bias voltage, and 5 mtorr (30 sccm).

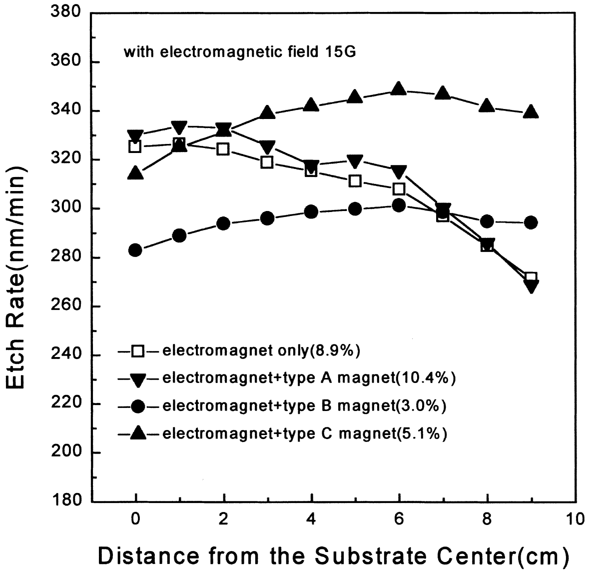

Fig. 3. Polysilicon etch rates measured as a function of distance from the substrate center for ICP with three types of permanent magnets shown in Fig. 1 in addition to the axial electromagnet (15 G). Process condition: 600 W of inductive power, −50 V of bias voltage, and 5 mtorr (30 sccm).

In the permanent magnet cusping, some of the surface magnetic fields generated with the permanent magnet poles penetrate into the plasma chamber and, if the penetration is too deep, the improvement of the plasma uniformity by the reduction of plasma species to the wall will be lost by the penetration of non-uniform magnetic field generated by those permanent magnets. The degree of penetration is dependent on the number of alternating permanent magnets/unit length. In the case of type A, the degradation of the etch uniformity appears to be from the shortage of the number of permanent magnets/unit length. Therefore, rather than improving the etch uniformity by using the permanent magnets, it appeared to degrade the uniformity. The improvement of etch uniformity for type C magnet appears to be both from the decrease of penetration depth of surface magnetic field and from the increased effect of magnetic confinement by doubling the number of permanent magnets/unit length. In the case of type B magnet, the number of magnets/unit length is the same as type B, however, the etch uniformity was further improved. The further improvement of the etch uniformity appears to be from the decrease of penetration of the magnetic field into the plasma by making the surface magnetic field generated by one permanent magnet pole to finish on the opposite permanent magnet pole contacting each other while keeping the similar effect on the plasma loss to the wall. In fact, if the entire chamber wall is covered with the alternating permanent magnets contacting side by side, the best uniformity could be obtained by maximizing the decrease of plasma loss to the wall and minimizing the penetration of the magnetic field into the plasma. However, in reality, various openings for view ports and valves are required on the sidewall of the plasma etching chamber, therefore, it is almost impossible to cover the sidewall with permanent magnets. Therefore, to improve the uniformity of the plasma with a certain degree of freedom to access the chamber through the sidewall, a permanent magnet configuration such as type B will be useful.

The effect of type B magnet with the axial electromagnetic field strength on the polysilicon etch rates and etch uniformities was further investigated by varying axial electromagnetic field strength from 6 to 21 G and the results are shown in Fig. 4. In this experiment, the etch rates were averaged along the radial positions (0–9 cm). The other etch parameters were the same as before. As shown in the figure, the increase of axial electromagnetic field up to 21 G generally increased the polysilicon etch rates. Also, the etch rates with type B magnet were similar to those without the permanent magnets. However, the etch uniformities with the axial magnet alone were in the range from 7 to 10% while those with axial electromagnet and type B permanent magnet were approximately 3% until 15 G of axial electromagnetic field is reached. The further increase of axial electromagnetic field strength also degraded the etch uniformity even with type B magnet. It is believed that by combining both low axial electromagnetic field (< 15 G) and an optimized permanent magnet (e.g. type B) to a larger inductively coupled plasma etching system applied to FPD, high etch rates with reasonably good etch uniformity could also be obtained throughout the substrate by decreasing plasma loss to the wall especially near the chamber edge.

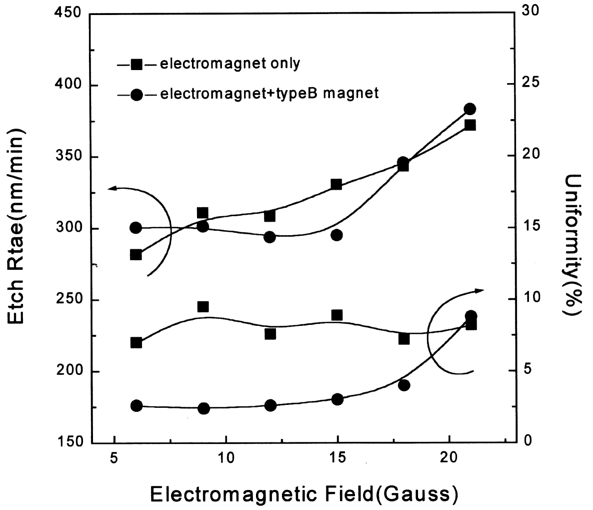

Fig. 4. Polysilicon etch rates and etch uniformities as a function of axial electromagnetic field with/without the type B magnet shown in Fig. 1. Process condition: 600 W of inductive power, −50 V of bias voltage, and 5 mtorr (30 sccm).

Using a quadrupole mass spectrometer attached with an ion energy analyzer, positive ion energy distributions of Cl^+ and Cl_2^+ were measured on the sidewall of the chamber for a conventional ICP, for the ICP with a 15-G axial electromagnetic field, and for the ICP with both 15 G of axial electromagnetic field and type B magnet. The operation condition was 600 W of r.f. power and 0.67 Pa Cl_2. The results are shown in Fig. 5a for Cl_2^+ and Fig. 5b for Cl^+. As shown in the figure, positive ions by the conventional ICP configuration showed an average energy of approximately 20 eV and those by the magnetized ICP configurations showed approximately 15 eV for both Cl^+ and Cl_2^+. There were no significant differences between the ICP with 15 G of axial electromagnetic field and the ICP with both the axial electromagnet and type B magnet even though more monoenergetic ions were obtained for the ICP with both the axial electromagnet and type B magnet. The lower ion energies to the wall measured for the magnetized plasmas appear to be from the decrease of the electron mobility to the wall by the axial electromagnetic field. Because the sheath potential on the wall is generated by the difference between mobilities of ion and electrons, the decrease of electron mobility (not the ion mobility due to heavy mass) by the application of the electromagnetic field will decrease the sheath potential, therefore, ion energy to the wall. The lower ion energy to the wall by the magnetic confinement of the plasma has also been reported by other researchers [9]. The lower average energy of the positive ions in the magnetized system investigated in our

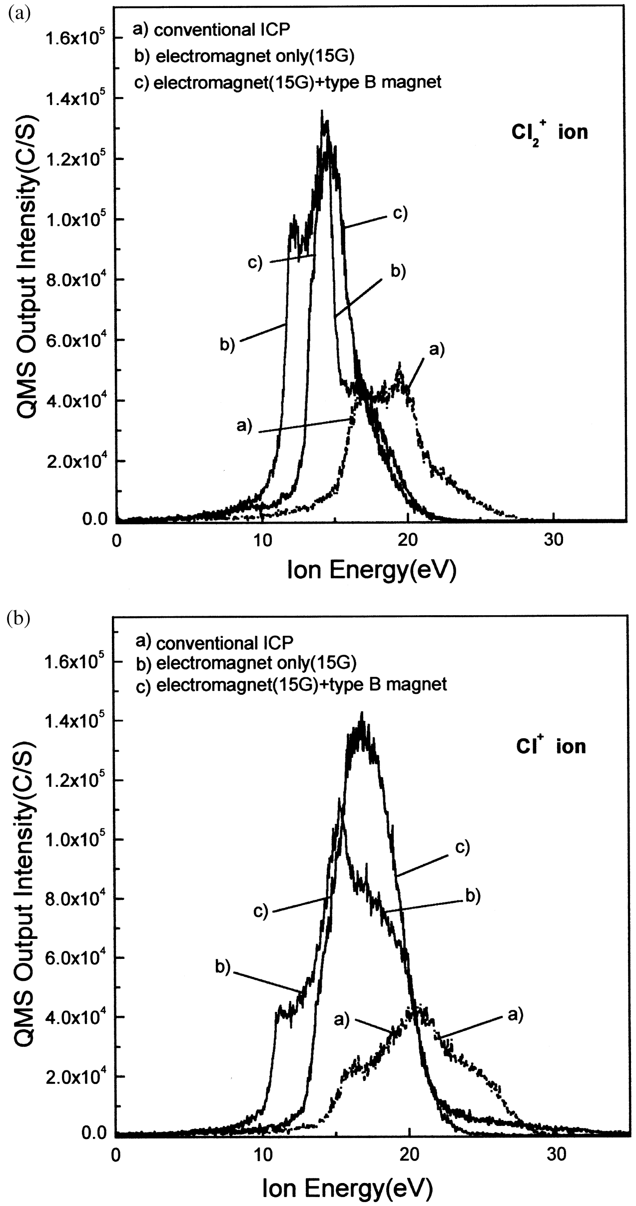

Fig. 5. Ion energy distributions of Cl_2^+ (a) and Cl^+ (b) in Cl_2 plasmas for conventional ICP with axial electromagnet (15 G), and with the type B magnet shown in Fig. 1 in addition to the axial electromagnet (15 G). Process condition: 600 W of inductive power and 5 mtorr (30 sccm).

study will be beneficial in reducing possible contamination during the etching.

4. Conclusions

In this study, the effects of the combination of a Helmholtz type axial electromagnet and variously configured permanent magnet cuspings to a planar inductively coupled plasma source on the polysilicon etch rates and etch uniformities were investigated for the application of FPD.

The application of uniform and weak axial electromagnetic fields of 15 G to an ICP increased the polysilicon etch rate by approximately 40%, however, it degraded the etch uniformity (from 5.5 to 8.9%) which is one of the most important factors in the FPD processing. The etch uniformity of the ICP system with the axial electromagnet could be improved by the addition of optimized magnetic cupsings even though etch rates did not change significantly with the addition of the magnetic cusping. Better etch uniformity could be obtained by arranging more permanent magnets/unit length along the chamber wall but if the number of permanent magnets/unit length is too small, the etch uniformity was degraded possibly due to the penetration of surface magnetic field into the plasma (type B and C compared to type A). For the same number of permanent magnets/unit length (type B and C), locating two opposite permanent magnet poles in one site side-by-side (type B) gave better etch uniformity than locating each opposite permanent magnet pole distributed equally along the chamber wall (type C). Using the optimized permanent magnet configuration (type B) with the axial electromagnetic field ($<$ 15 G) to ICP, the etch uniformity could be improved to 3.0% without significantly changing the increased etch rate obtained by the application of the axial magnetic field. The use of the magnetized ICP studied in our experiment decreased the average ion energy to the wall from 20 to 15 eV, therefore, decreased the possible contamination of the substrate caused by sputtering of the chamber wall.

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