Available online at www.sciencedirect.com

SCIENCE DIRECT®

Surface and Coatings Technology 177–178 (2004) 752–757

SURFACE & COATINGS TECHNOLOGY

www.elsevier.com/locate/surfcoat

Effects of multipolar magnetic fields on the characteristics of plasma and photoresist etching in an internal linear inductively coupled plasma system

K.N. Kim, Y.J. Lee, S.J. Kyong, G.Y. Yeom*

Department of Materials Engineering, Sungkyunkwan University, Jangan-Gu Chunchun-Dong 300, Suwon 440-746, South Korea

Abstract

The development of a large-area plasma source with high-density plasmas is desired for a variety of plasma processes from microelectronics fabrication to flat panel display device fabrication. In this study, high density (approx. $10^{11}/\mathrm{cm}^3$) and stable plasmas could be obtained by applying multipolar magnetic fields to a linear inductively coupled plasma source having the size of 1020×830 mm. The application of the magnetic fields decreased r.f. antenna voltage by half times and increased photoresist etch rates by three times. The plasma uniformity, which is considered as one of the most important factors in the large area plasma processing, could be maintained lower than 9%.

Keywords: Inductively coupled plasma; Multipolar magnetic fields; r.f. antenna voltage

1. Introduction

In the manufacturing of semiconductor devices and flat panel displays (FPDs) such as TFT-LCD, dry processes using plasmas are widely employed [1–3]. Also, due to the increase of substrate sizes and need for the higher processing rates in both microelectronics and flat panel display, high density plasma processing tools that can handle larger area uniformly are more intensively studied.

Among the various high density plasma tools, inductively coupled plasma (ICP) systems are widely studied because of their simple physics and scalability compared with other high density plasmas sources such as electron cyclotron resonance (ECR) plasma sources and helicon-wave-excited plasma sources, therefore, uniform large-area plasmas can be produced relatively easily [2,4–6]. However, when conventional inductively coupled plasma sources using external spiral antennas are applied to the processing of extremely large flat panel display substrates, due to the cost and thickness of the dielectric material required to transmit electromagnetic field to the plasmas, the conventional ICP systems show problems in extending the process area [5,6].

Internal-type inductively coupled plasma sources, where the antennas are installed inside of the vacuum chamber, can solve the problems related to the dielectric materials shown in the conventional external ICP systems [7–11]. Instead, the internal-type ICP systems show other practical problems such as higher electrostatic coupling with plasma. Due to the exposure of high voltage R.F. antenna to the plasma through a thin dielectric material, the high voltage sustained at the antenna is transferred to the plasma and it could increase the plasma potential and result in unstable plasmas having frequent arching due to the anomalous rise of the plasma potential [10,12]. Therefore, in the internal-type ICP source, it is essential to minimize the electrostatic coupling of R.F. antenna voltages to the plasma.

In this paper, multipolar magnetic fields was applied to a large-area internal-type ICP system and their effects on plasma characteristics such as suppression of the electrostatic coupling, plasma density, and uniformity were investigated. Also, the effect of the multipolar magnetic fields on the photoresist etch rate was also investigated.

---

*Corresponding author. Tel.: +82-31-290-7395; fax: +82-31-290-7410.

E-mail address: gyyeom@yurim.skku.ac.kr (G.Y. Yeom).

0257-8972/04/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.surfcoat.2003.08.017

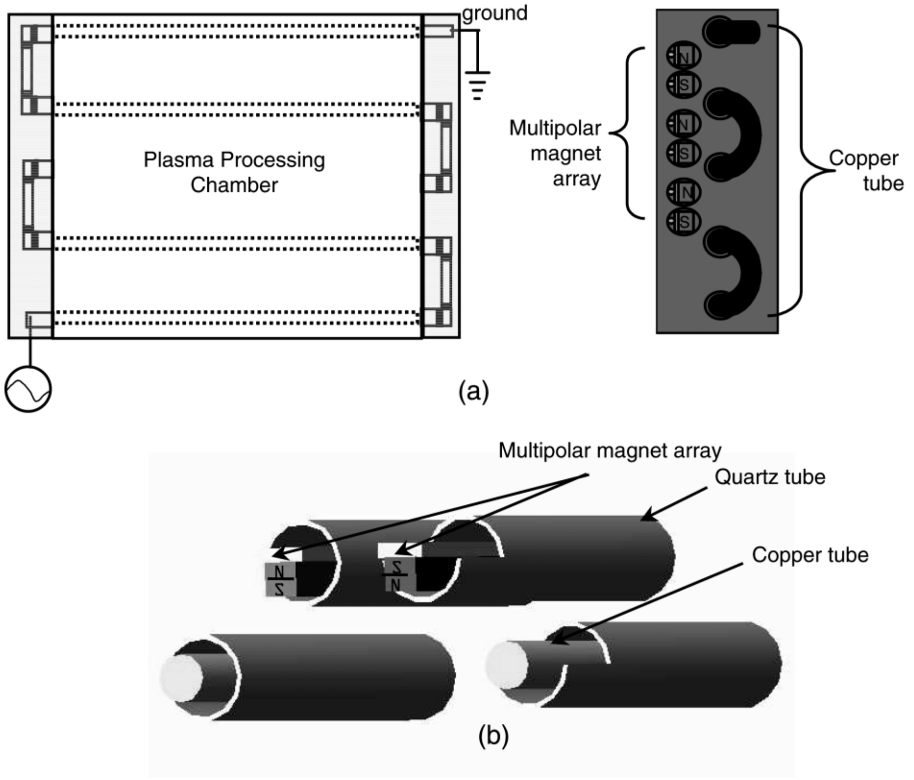

Fig. 1. (a) Schematic diagram of the linear internal-type inductively coupled plasma source used in the experiment. (b) Arrangement of the permanent magnets used in the experiment to form multipolar magnetic fields.

2. Experiment

Fig. 1 shows the schematic diagram of the experimental apparatus used in the experiment. The plasma-processing chamber has a rectangular shape for FPD applications. The inner size of the chamber was 1020×830 mm and the substrate size was 920×730 mm. Five linear antennas were embedded in the vacuum chamber and each linear antenna was connected in series as a serpentine type at the outside of the vacuum chamber as shown in Fig. 1. Total length of the antenna was approximately 7 m. The linear antenna was made of 10-mm diameter copper tubing with the outside shielded by quartz tubing. The outside diameter of the quartz tubing was 15 mm and the thickness was 2 mm. One end of the connected linear antenna was grounded and the other end was connected to an R.F. power supply (13.56 MHz, 0–3 kW) through a conventional L-type matching network. Multipolar magnetic fields were applied by inserting permanent magnets having 3000 G on the magnet surface in the separate quartz tubing located parallel to the linear current carrying antennas as shown in Fig. 1.

Plasma characteristics such as plasma density and plasma uniformity were measured using a Langmuir probe (Hiden Analytical Inc., ESP) located on the sidewall of the chamber. The Langmuir probe was installed 7.5 cm below the straight antenna. Radio frequency rms antenna voltages were measured by a high voltage probe (Tektronix, P6015A) on the antenna located close to the R.F. power input. Ar was used to measure the plasma characteristics. Photoresist etching characteristics were investigated using 6-μm thick, hard baked, photoresist (AZ9260) deposited on 4-inch silicon wafers and using oxygen instead of Ar. The etch rate was measured at the center of the substrate. For the photoresist etching, the substrate was located 5 cm below the antenna and -670 V of bias voltage was applied to the substrate through a separate r.f. power supply (12.56 MHz, 0–2 kW) and a matching network. The substrate temperature was kept at room temperature. The photoresist etch rate was estimated by measuring the step heights of the films before and after the etching with a stylus profilometer.

3. Results and discussion

Fig. 2 shows the effect of r.f. power to the antenna with/without the multipolar magnetic field on the plasma density measured by a Langmuir probe. Two Pacals of Ar gas was used and the r.f. power was varied from 600 to 2500 W. The Langmuir probe was located 7.5 cm below the antenna. As shown in the figure, the increase of r.f. power increased the Ar plasma density

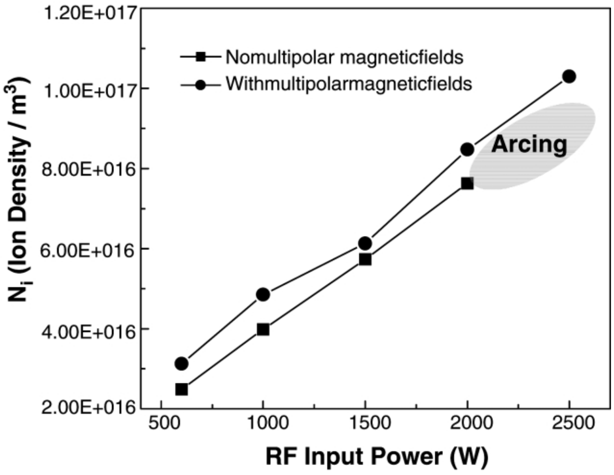

Fig. 2. Ar^+ ion density measured by a Langmuir probe at 7.5 m below the antenna as a function with/without multipolar magnetic fields. r.f. Input power to the antenna was varied from 600 to 2000 W and the operation pressure was maintained at 2 Pa.

linearly for both with and without the magnetic field. However, the Ar plasma densities with the magnetic field were higher than those without the magnetic field. The highest plasma density obtained was $1.03\times10^{11}/cm^3$ at 2500 W of r.f. power and 2 Pa of Ar with the magnetic field. The increase of Ar plasma density with the magnetic field appears related to the formation of ExB field near the current carrying antenna and the decrease of electron loss to the wall near the antenna, therefore, forming an effective confinement of energetic electrons in the plasmas. In fact, the effect on the confinement of energetic electrons by decreasing the diffusional loss to the wall has been already studied by other researchers by arranging alternating magnets all around the chamber wall [13]. However, in this experiment, by arranging the alternating magnets only near the current carrying linear antenna as shown in Fig. 1, higher plasma densities could be obtained.

The additional advantage with the magnetic field is the improved stability of the plasmas. When r.f. power higher than 2000 W was applied to the antenna without the magnetic field, the plasma showed instability with frequent arcing, therefore, it was impossible to measure the Ar plasma with the Langmuir probe. In fact, it has been reported by other researchers that, when the one side of the antenna was grounded, it is difficult to obtain stable plasmas for internal-type inductively coupled plasmas [10,14]. However, when the plasma was operated with the magnets installed, stable plasmas with no arcing could be observed for the range of operational parameters used in this experiment.

The instability observed in our internal-type ICP without the magnetic field appears related to the high electrostatic coupling between the antenna and plasma by the highly induced antenna voltage on the antenna. High voltage induced on the antenna could increase the plasma potential and lead frequent arcing. Fig. 3 shows the r.f. rms voltage of the internal-type ICP measured by a high voltage probe on the antenna located close to the r.f. power input for the condition with and without the magnetic field. Two Pascals of Ar was used and the r.f. power was varied from 100 to 2000 W. As shown in the figure, as the r.f. power is increased, the r.f. rms voltage increased continuously for both with and without the magnetic field. However, at a given r.f. power, the r.f. antenna voltage induced without the magnetic field was about two times higher than that with the magnetic field. The increased instability for the internal-type ICP without the magnetic field appears related to the higher r.f. antenna voltage induced on the antenna shown in Fig. 3. Also, as shown in Fig. 3, there was a change in voltage gradient at near 600 W. When the r.f. power was lower than 600 W, the r.f. rms voltage increased faster with the r.f. power and, when the r.f. power was higher than 600 W, the voltage increased slower with the r.f. power for both with and without the magnetic field. It is believed that, at the r.f. power lower than 600 W, the system operates as a capacitively coupled plasma system and, as the r.f. power increases higher than 600 W, due to the increased current flow to the antenna, the system appears to operate as an inductively coupled plasma system.

Using the oxygen plasmas generated by the internal-type ICP source with and without the magnetic field, photoresist was etched and the effect of the magnetic field on the photoresist etch rates was studied. Fig. 4 shows photoresist etch rates of the internal-type ICP system as a function of r.f. input power with and without

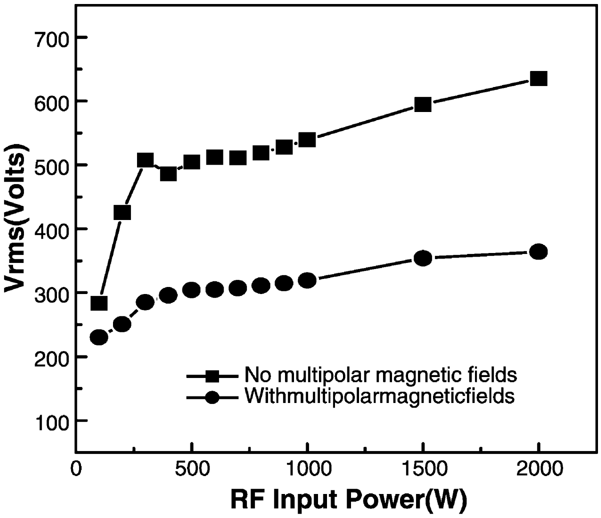

Fig. 3. Radio frequency rms voltage of the internal-type ICP measured by a high voltage probe on the antenna located close to the r.f. power input for the condition with and without the magnetic field. 2 Pa of Ar was used and the r.f. power was varied from 100 to 2000 W.

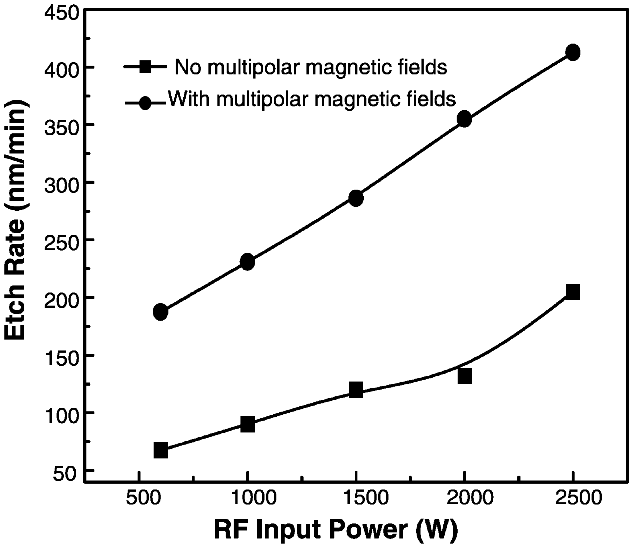

Fig. 4. Photoresist etch rates as a function of r.f. input power with/without the magnetic field. The substrate was located 5 cm below the antenna and was kept at room temperature. Oxygen pressure was maintained at 2 Pa and the bias voltage at approximately −670 V. The r.f. power was varied from 600 to 2500 W.

the magnetic field. The substrate having the photoresist covered silicon wafer was located 5 cm below the antenna and was kept at room temperature. Oxygen pressure was maintained at 2 Pa and the bias voltage at approximately −670 V. The r.f. power was varied from 600 to 2500 W. The photoresist covered silicon wafer was located on the center of the internal-type ICP system, therefore, only the etch rate at the center of the system was measured and no uniformity of photoresist etching was investigated at this experiment. As shown in the figure, the photoresist etch rates increased with the increase of r.f. power almost linearly for both with and without the magnetic field, however, the etch rates with the magnetic field was about three times higher than those without the magnetic field. The increase of photoresist etch rates with the magnetic field appears related to the increase of plasma density as observed in Fig. 2. However, the increase of the plasma density was approximately 10–30% by applying the magnetic field. In fact, when oxygen plasma is used, photoresist is etched more chemically than physically. Therefore, the increase of etch rate with the magnetic field appears not only from the increased ion density but also from the increase of dissociated oxygen atoms with the magnetic field.

Fig. 5 shows the effect of oxygen operating pressure of the internal-type ICP system on the photoresist etch rates with and without the magnetic field. The r.f. power to the antenna was 2000 W and the other conditions were maintained the same as the conditions in Fig. 4. As shown in Fig. 5, the increase of operating pressure increased the photoresist etch rates for both with and without the magnetic field. Also, similar to the results in Fig. 4, the photoresist etch rates with the magnetic field showed about two times higher etch rates compared to those without the magnetic field possibly due to the increase of both plasma density and dissociated oxygen atoms by the application of the magnetic field as investigated by other researchers.

Even though the application of the multipolar magnetic field to the internal-type ICP system increased the plasma density, the stability of the plasmas, and the photoresist etch rates, it could decrease the plasma uniformity significantly. Therefore, using a Langmuir probe, ion current density as a measure of ion density was measured below 7.5 cm from the antenna. Fig. 6 shows the measured ion current densities of Ar^+ measured along the perpendicular direction (a) and the parallel direction (b) to the antenna. Two Pascals of Ar was used and the r.f. power was varied from 1000 to 2000 W. As shown in the figure, the plasma uniformity within the substrate with the magnetic field was less than 9% for all of the r.f. power conditions used in the experiment. When the plasma uniformity was measured without the magnetic field, however, the uniformity within the substrate was less than 7% (not shown), therefore, the application of the magnetic field appears to decrease the plasma uniformity. Even though the uniformity of the plasma was decreased by the application of the magnetic field, the decrease of plasma uniformity was originated from the change of the uniformity near the edge of the substrate. It is believed that

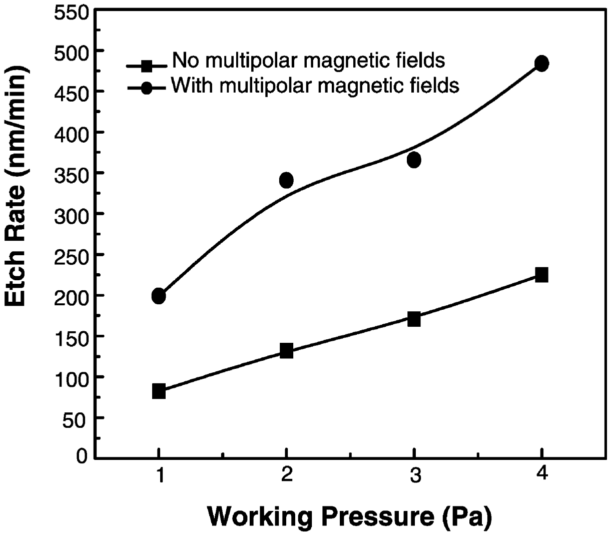

Fig. 5. Photoresist etch rates as a function of oxygen pressure with and without the magnetic field. The r.f. power to the antenna was 2000 W and the other conditions were maintained the same as the conditions in Fig. 4.

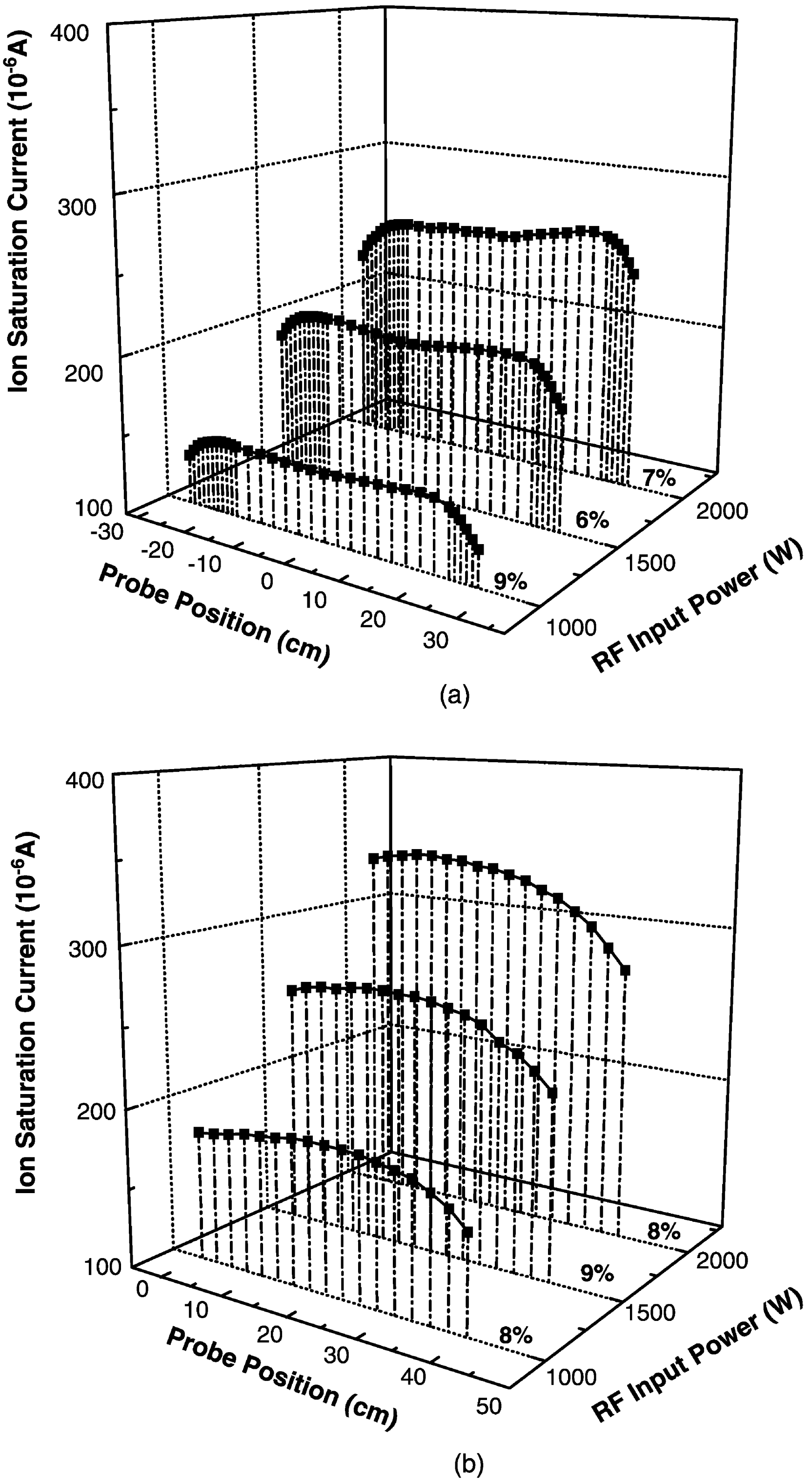

Fig. 6. Ion saturation currents measured by a Langmuir probe (a) perpendicular and (b) parallel to the antenna at 7.5 cm below the antenna as a function of position of the chamber with multipole magnetic fields. The r.f. power was varied from 1000 to 2000 W and 2 Pa of Ar gas was used.

the change of antenna distance with corrected arrangement of the magnetic field will improve the plasma uniformity and the improvement of plasma uniformity is under study.

4. Conclusions

In this study, the effects of multipolar magnetic field on the plasma density, plasma stability, and plasma uniformity of a large-area internal-type linear ICP source have been investigated. Also, using the system, photoresist was etched and the effect of the magnetic field on the etch rate was investigated.

The application of multipolar magnetic fields near the antenna of the internal-type ICP source increased the plasma density approximately 10–25% possibly due to the decrease of the diffusional loss of the electrons to the chamber wall close to the antenna by the confinement of energetic electrons and also by the formation of ExB field near the antenna. Especially, the application of the magnetic field improved the stability of the plasma by decreasing the r.f. antenna voltage. The highest Ar density obtained in the experiment with the magnetic field was 1.03×10^{11} $/\mathrm{cm}^3$ at 2500 W of r.f. power and 2 Pa of Ar pressure. When the photoresist was etched using oxygen plasmas, the application of the magnetic field increased the photoresist etch rates about three times and the increase of the etch rates appears related not only to the increase of plasma density and but also to the increased dissociation of oxygen molecules. The application of the multipolar magnetic field decreased the plasma uniformity slightly from less than 7% to less than 9%; however, the uniformity is believed to be improved by the rearrangement of the magnets and the antenna.

Acknowledgments

This work was supported by National Research Laboratory (NRL) Program of the Korea Ministry of Science and Technology.

References

[1] C.Y. Chang, S.M. Sze, ULSI Technology, McGraw-Hill, New York, 1996, p. 329.

[2] J. Hopwood, Plasma Sources Sci. Technol. 1 (1992) 109.

[3] M. Schmitt, M. Elyaakoubi, L. Sanaonnens, Plasma Sources Sci. Technol. 11 (2002) A206.

[4] P.W. Lee, S.S. Kim, S.H. Seo, C.S. Chang, H.Y. Chang, T. Ickhiki, et al., Jpn. J. Appl. Phys. 39 (2000) L548.

[5] J. Yu, D. Shaw, P. Gonzales, G.J. Collins, J. Vac. Sci. Technol. A 13 (3) (1995) 871.

[6] M.H. Khater, L.J. Overzet, J. Vac. Sci. Technol. A 19 (2001) 785.

[7] Y. Wu, M.A. Lieberman, Appl. Phys. Lett. 72 (1998) 777.

[8] Y. Setsuhara, S. Miyake, Y. Sakawa, T. Shiji, Surf. Coat. Technol. 136 (2001) 60.

[9] T. Meziani, P. Colpo, F. Rossi, Plasma Sources Sci. Technol. 10 (2001) 5419.

[10] M. Kahoh, K. Suzuki, J. Tonotani, K. Akoi, M. Yamage, Jpn. J. Appl. Phys. 40 (2001) 5419.

[11] K. Suzuki, H. Sugai, K. Nakamura, T.H. Ahn, M. Nagatsu, Vacuum 48 (1997) 659.

[12] Y. Horiike, H. Okano, T. Yamazaki, H. Horie, Jpn. J. Appl. Phys. 20 (1981) L817.

[13] J. Hopwood, C.R. Guarnieri, S.J. Whitehair, J.J. Cuomo, J. Vac. Sci. Tecnol. A 11 (1993) 152.

[14] Y. Sethuhara, S. Miyake, Y. Sakawa, T. Shoji, Jpn. J. Appl. Phys. 38 (1999) 4263.