*Transactions of the Materials Research Society of Japan* 25 [1] 287-291 (2000)

# Low-Pressure High-Density RF Plasma Production

Shoji Miyake
Joining and Welding Research Institute, Osaka University, Osaka 567-0047, Japan
Fax: +81-6-6879-8641; E-mail: miyake@jwri.osaka-u.ac.jp

High density plasma production at low pressures based on the inductively-coupled plasmas by an RF power at 13.56 MHz is described for the application to varieties of PVD processes. The effect of the antenna termination to be grounded or floated to the plasma parameters has been studied for the conventional helical coil antenna of 100 mm diameter in an ICP assisted magnetron sputtering system. It was possible to operate the the source at high powers to generate Ar plasmas with densities as high as $10^{12}$ cm$^{-3}$ and a remarkable reduction in the plasma potential has been verified in the case of the floated antenna. In a large-diameter ICP system, RF plasmas have been produced in a discharge chamber of 400 mm diameter and 200 mm height. A double half-loop antenna of 320 mm diameter was employed for reducing the antenna inductance and the plasma source could be operated stably at RF input powers of up to 3 kW to attain a plasma density again as high as $10^{12}$ cm$^{-3}$. These types of plasmas are expected to be applicable for example, as a tool for enhanced ionization in the sputtering process as well as for plasma immersion ion implantation (PIII).
Keywords: Inductively-Coupled Plasma, Large Diameter Plasma, Low Inductance, PVD,

## 1.INTRODUCTION

Development of low-pressure high-density and/or large-diameter plasma sources is desired for a variety of next-generation plasma processes from microelectronics device fabrications to advanced PVD technologies including plasma immersion ion implantation (PIII).

Among varieties of high density plasma source at low pressures, we have been interested in inductively-coupled plasma (ICP) with internal antenna for the application to PVD. In the internal antenna configurations it is usual that the low voltage side of the antenna conductor is terminated at ground potential, and the discharge becomes likely to be unstable with increasing RF power due to considerable arcing in the chamber induced by an anomalous rise of the plasma potential, which is mainly caused by the significant loss of electrons out of the plasma through the antenna in the positive phase of a high RF voltage[1]. Thus it is essential to minimize the electrostatic coupling of RF voltages to the plasma.

In this paper we demonstrate the feasibility of obtaining high-density plasmas with suppressed electrostatic coupling by the low-voltage operation of the internal antenna. It is based on (i) termination of a coil antenna with insertion of a blocking capacitor to satisfy the impedance balance, (ii) employment of a double half-loop antenna for the reduction of antenna inductance, and (iii) full covering of the antenna conductor with an insulator tubing for dielectric isolation of the antenna conductor from the plasma.

Two types of plasma sources are studied; one is inductively-coupled plasmas (ICP) with a conventional helical antenna used for the assistance of the magnetron sputtering process and the other is a large-diameter inductively-coupled plasma source sustained with a low inductance double half-loop antenna to be used for various PVD processes. In both systems the antenna is located within the vacuum chamber and is terminated to the

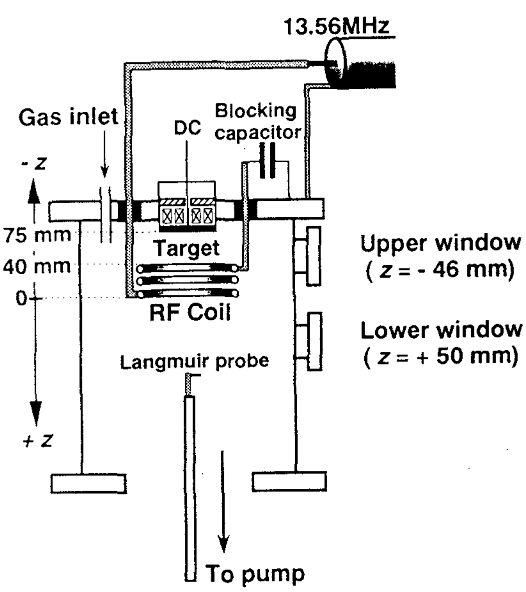


Fig. 1. Schematic diagram of ICP-assisted planer magnetron system with a conventional helical coil antenna

grounded earth potential via a blocking condenser.

In the first system the effects of antenna termination to be grounded or floating to the plasma parameters have been studied without any power supply to the sputtering target. In the second system a double half-turn antenna of 320 mm diameter is employed for reducing the antenna inductance via a blocking condenser to satisfy the amplitude of the RF voltage to be reduced to 1/2 of the terminal voltage. The effect of dielectric insulation of the antenna and the controllability of the azimuthal density distribution will also be studied in this system

## 2. EXPERIMENTAL PROCEDURES

The experimental setup for the ICP-assisted planar magnetron discharge[2] with a conventional helical antenna is schematically shown in Fig. 1. A 2.5-turn helical antenna 100 mm in diameter and 40 mm in length along the axis is coupled to an RF power generator at 13.56 MHz via a matching network. It is noted that the lower end of the helical antenna is connected to the RF power electrode from the matching box whereas the upper end of the antenna conductor is terminated either by ground potential or floating. In the grounded antenna condition, the low-voltage side of the antenna conductor is directly connected to the chamber at a ground potential. In the case of the floating antenna, a blocking capacitor (400pF) is inserted between the low-voltage side of the antenna and the chamber to electrically float the antenna.

In the figure the z axis is taken along the axis of the discharge system as given in the figure, and the z = 0 position lies in the same plane as the bottom end of the RF coil and the positive z values are taken in the direction from the target to the substrate. The base pressure of the discharge system, evacuated with a 300-l/s turbo-molecular pump, is 1.1x$10^{-4}$ Pa and the RF discharge is produced in argon pressures of 0.2-5.2 Pa.

A large-diameter RF plasma has been produced by inductive coupling of an internal-type double-half turn antenna 320mm diameter in a discharge chamber of 400 mm diameter and 200 mm height as shown in Fig. 2. To examine the effect of the dielectric isolation, the antenna conductor is fully covered with an insulator tubing made of high-purity alumina (99.6 at% $Al_2O_3$). The base pressure of the discharge system, evacuated with a turbo-molecular pump, is 2x10-3 Pa and the RF discharge is produced in an argon pressure of ~1 Pa.

## 3. ICP WITH FLOATING HELICAL ANTENNA[2]

Figure 3 shows the variation of plasma density in 5.2 Pa Ar obtained by the grounded and floating antenna in the ICP assisted magnetron sputtering system as a function of the RF power.. In this study no DC powere is supplied to the sputtering target. Here the blocking condenser in the floating antenna is selected to nearly satisfy the balance condition. The probe measurements were performed at a distance of 50 mm below the bottom end of the antenna coil (z = +50 mm) and the magnetron sputtering target voltage was fixed at a floating potential. In the case of the grounded antenna, the plasma density was of the order of $10^{11}$ $cm^{-3}$ and the discharge became quite unstable in the RF power region above 400 W due to the considerable arcing in the plasma

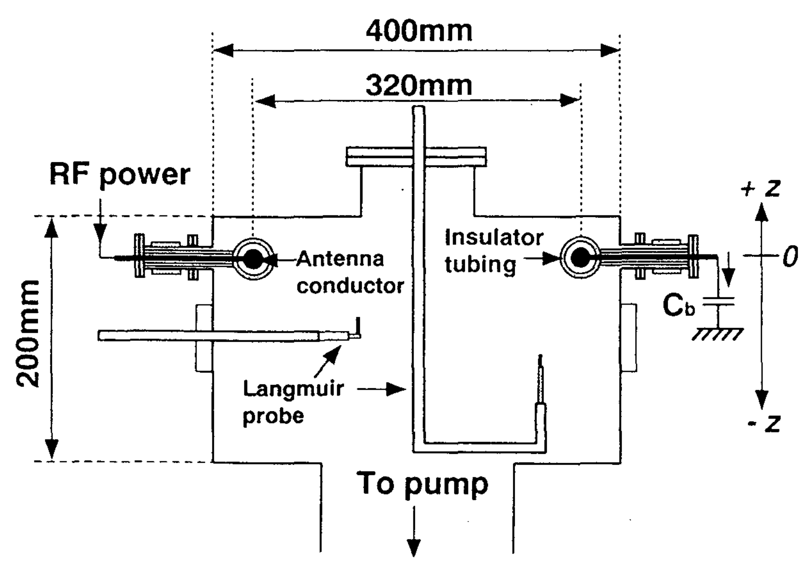


Fig. 2 Schematic diagram of large diameter ICP system with double half-loop antenna

chamber, which was caused by the anomalous rise of the plasma potential. In the floating antenna case, on the other hand, the RF discharges were stable even at higher RF powers and the plasma density increased with RF power approaching to $1.5x10^{12}$ $cm^{-3}$ at 800 W.

The electron temperatures were measured to be in the range of 2-3 eV at 2-5 Pa and about 4 eV at 0.2-0.3 Pa for both of the regimes. Here it is noted that the density in the floating antenna regime is found to be approximately two fold higher than that obtained in the grounded one for the same input RF power.

The floating potential of the plasma is compared for the difference in the termination as a measure of evaluating the electrostatic coupling and the result is given in Fig. 4. As can be found in the figure, the floating potential becomes substantially lower in the floating case than in the grounded one, which may be attributed to the significant suppression of the net extraction of electrons from the plasma to the grounded antenna, as well as to the minimization of the RF voltage by satisfying the impedance balance condition.

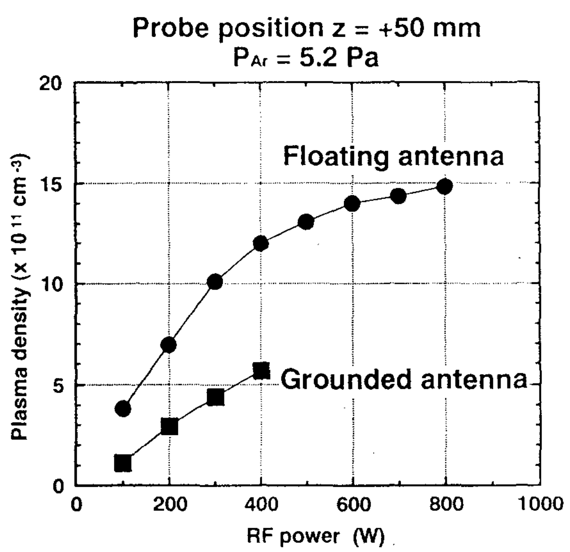


Fig. 3. Variation in the plasma density as a function of RF power for the grounded and the floating antenna regime

## 4. LARGE-DIAMETER ICP WITH DOUBLE-HALF-LOOP ANTENNA[4-5]

Figure 5 shows the pressure dependence of the Ar plasma density sustained at an RF power of 3 kW. Here the Langmuir probe measurements were performed at a distance of 65 mm below the center of the antenna (z = -65 mm, r = 0 mm). The RF discharges is stable even at an input RF power of 3 kW and the plasma density increases with Ar pressure in the pressure range of 0.4-4 Pa. It is quite remarkable for the density approaches to be as high as $\sim 1x10^{12}$ $cm^{-3}$ at 0.8 Pa Ar pressure even with the double half-loop antenna with a reduced inductance. From this result it is suggested that simultaneous achievement of high-density large-diameter plasmas and reduced inductance of the antenna is feasible by appropriately designing antenna configurations including a non-looped geometry, and even a combination of straight lines.

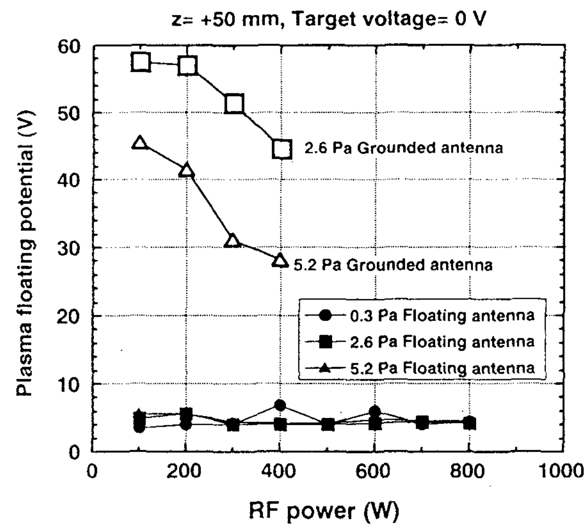


Fig. 4. Variation of floating potential for the grounded and floating antenna as a function of RF powers.

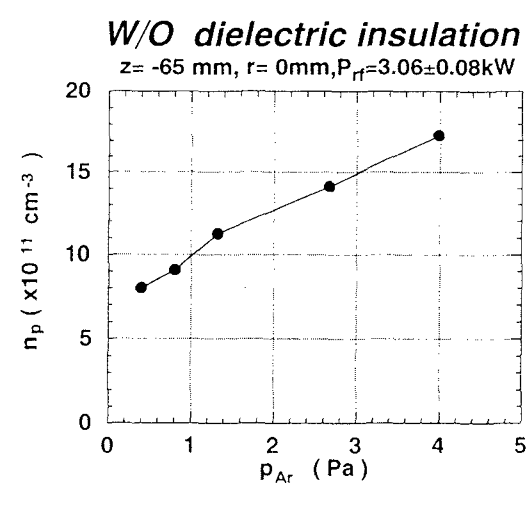


Fig. 5. Variation of plasma density as a function of Ar pressure in a large diameter ICP.

RF power dependence of the plasma density sustained by the double half-loop antenna with dielectric insulation is shown in Fig. 6 for the grounded and the floating antenna conditions. The discharges were stably sustained and no anomalous arcing was observed even in the grounded antenna case, where the low-voltage end of the antenna conductor was directly terminated to the ground electrode.

As we can find in the figure no significant difference is observed in the obtained density for both cases of the antenna termination, which increases with RF power to attain a value as high as $5\times10^{11}$ $cm^{-3}$ at 2.5 kW. While the plasma density

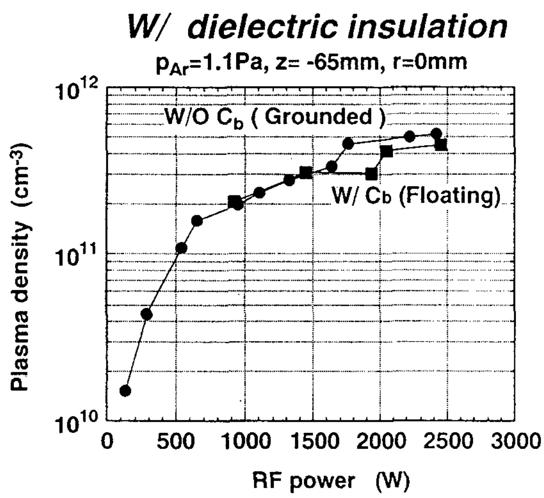


Fig. 6. Variation of plasma density sustained with dielectric insulation as a function of RF power.

obtained with the dielectric insulation is found to be slightly lower than that attained without the insulation. This kind of reduction in the attained density is also observed in the case of the Faraday shield.

Figure 7 shows the azimuthal distribution of the ion current density for various ratios $V_L/V_H$ of the RF voltage, where $V_L$ and $V_H$ denote the RF voltage on the input side to and output side of the antenna, respectively. Here the distribution was measured along the loop located at z = -60 mm and r = 110 mm and the azimuthal angle $\theta$ is plotted by taking the RF feeder side as 0 degree. In the nearly balanced floating regime ( i.e. $V_L/V_H = 0.8$) the densities at both ends of the antenna conductor becomes nearly equivalent, however, the distribution shows an m=2 mode nonuniformity, where the densities in the middle part ( $\theta \sim 90$ and ~270 deg. ) are found to be relatively smaller than those at the both ends. In reducing the argon pressure to 0.27 Pa, however, the nonuniformity in the balanced floating regime was considerably reduced. These results indicate that the balance

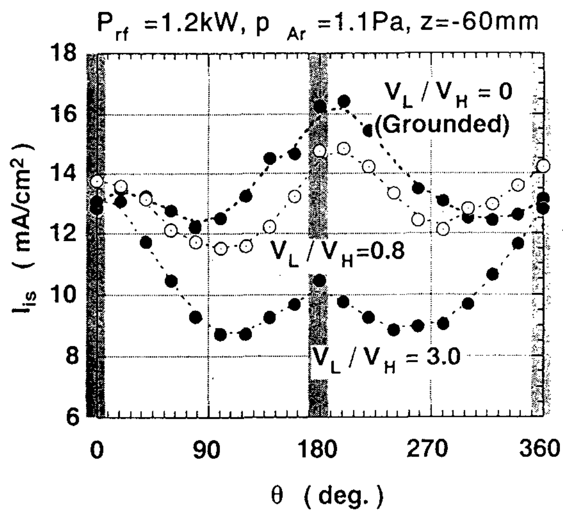


Fig. 7 Azimuthal distribution of the ion-saturation current density for various $V_L / V_H$.

between the stagnation and the diffusion of the electrons accelerated along the azimuthal element of the induction electric field may contribute to the formation of the m=2 mode nonuniformity.

As an application to PVD of large diameter ICPs strudied here,we are willing to apply them for plasma immersion ion implantation (PIII), where large volume high density plasmas are expected at low pressures. Specifically plasma production in molecular gases will be more important than in Ar gas for materials processing. We have tried to obtain a high density plasma in $N_2$ and $H_2$ gas environments and the result will be published elsewhere.

5. SUMMARY

In the ICP-assisted planar magnetron sysytem with a conventional helical coil antenna, the floating antenna condition resulted in obtaining a stable inductive discharge without arcing in the chamber up to RF power input as high as 800W, where the achieved plasma density was considerably higher than that obtained by the grounded antenna.

In the internal-type inductive plasma production using a double half-loop antenna, suppression of the electrostatic coupling was obtained based on the reduction of the antenna inductance and the dielectric isolation of the antenna conductor.

In this system the plasma source could be operated stably by the double half-loop antenna to attain densities approaching as high as $\sim10^{12}$ $cm^{-3}$. Furthermore, the dielectric insulation at higher

RF power operation exhibited a significant effect on the suppression of the electrostatic coupling with simultaneous achievement of plasma densities as high as $5x10^{11}$ $cm^{-3}$.

The azimuthal distribution of the plasma density showed the nonuniformity with the principal mode of m=2, which was found to be controlled by the RF voltage distribution along the antenna and the gas pressure.

REFERENCES

[1] K. Suzuki, H. Ohkubo, Y. Kuwashita, K. Nakamura, T. Kuroda and H. Sugai: Proc. 13th Symp. Plasma Processing (Tokyo, 1996) 93.

[2] Y. Setsuhara, M. Kawai, S. Miyake and J. Musil: Jpn. J. Appl. Phys. 36 (1997) 4568.

[3] M. Yamashita, Y. Setsuhara, S. Miayke, M. Kuamgai, T. Shoji and J. Musil: Jpn. J. Appl. Phys. 38 (1999) 4291.

[4] Y. Setsuhara, S. Miyake, Y. Sakawa and T. Shoji: Jpn. J. Appl. Phys. 38 (1999) 4263.

[5] S. Miyake, Y. Setsuhara, Y. Sakawa and T. Shoji: to be published in Vacuum (1999).

(Received February 7, 2000; accepted March 8, 2000)