Volume 7, Number 11 ACTA PHYSICA SINICA November, 1998
1004-423X/98/07110823-09 (Overseas Edition) © 1998 Chin. Phys. Soc.

BEHAVIOR OF PLASMA FORMED IN A PAGODA-SHAPED RADIO FREQUENCY PLASMA SOURCE

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(Received 9 March 1998; revised manuscript received 20 May 1998)

A large volume, high density, and pagoda-shaped radio frequency (rf) plasma source has been developed for use in large scale plasma processing. The inductively coupled plasma (ICP) is created by a pagoda-shaped 13.65 MHz antenna to improve the plasma uniformity on substrate. Plasma densities and electron temperatures are measured by using a Langmuir probe and their radial and axial profiles are attained. Electron density of $> 1 \times 10^{11}\,\mathrm{cm}^{-3}$ on the substrate and uniform to $\leq \pm 1.6\,\%$ over 16 cm diameter can be produced at argon pressure of 6.65×10^{-1} Pa and input rf power of 1 kW. ICP etching photoresist in O_2 plasma has been tested and the etching uniformity consists with that of the plasma density on the substrate. A large scale etched sample with the uniformity to $\leq \pm 1.1\,\%$ over 10 cm diameter or to $\leq \pm 2.2\,\%$ over 13 cm diameter has been obtained.

PACC: 5250; 5270

I. INTRODUCTION

Inductively coupled plasma (ICP) has been widely employed in the microelectronics processing such as plasma etching and deposition of thin films. Uniformity is obviously desirable, in general, as all parts of the sample should be etched or deposited at the same rate. Several methods using magnetic field have been investigated to improve the uniformity. Yamauchi *et al.*[1] added a magnetic line-cusp field on their radio frequency (rf) plasma device and a useful area of plasma with 10 % uniformity over a 30-cm-diam region can be attained. Boswell *et al.*[2] arranged the small magnets surrounding the outside of a reactor to produce the cusp fields at the walls. They obtained the ion current uniform to $\pm 1.5\,\%$ over 15 cm diameter in SF_6 plasma. Lieberman and Gottscho *et al.*[3] designed a new source in which the downstream magnetic field was established by permanent dipolar magnets to help confine the plasma and improve the radial uniformity.

For an ICP source in the absence of a magnetic field, using the antenna of the planar coil configuration at the top of the process chamber is convenient.[4] A plasma density region, $10^{10}\,\mathrm{cm}^{-3} \leq n_0 \leq 10^{13}\,\mathrm{cm}^{-3}$, for efficient inductive source operation, can be obtained, which is about 100 times higher than that for capacitively driven rf plasma. However, for the ICP source with the antenna in this shape, the density distribution is far from uniform, i. e., the radial profile of the plasma density on the downstream substrate is a saddle-shape, which means the density on the edge of the substrate is much larger than that of the center area.

In order to improve the density uniformity on the substrate, a dome-shaped antenna is used which can increase the density at the center of the substrate and the radial profile of density is more even.[5]

In this paper, we describe how a large volume of uniform plasma can be created by using a pagoda-shaped plasma chamber and a pagoga-shaped antenna at the top of plasma chamber operating at a frequency of 13.56 MHz with magnetic field free. This device is used to study etching. Electron density of $> 1 \times 10^{11}\ \mathrm{cm}^{-3}$ on the substrate and uniformity to $< \pm 1.6\ \%$ over 16 cm diameter can be produced. Etching photoresist in O_2 plasma, the etching uniformity on the sample consists with the uniformity of the plasma density on the substrate, and an etched sample with uniformity to $\leq \pm 1.1\ \%$ over 10 cm diameter or to $\leq \pm 2.2\ \%$ over 13 cm diameter has been attained.

II. EXPERIMENTAL APPARATUS

The schematic diagram of the pagoda-shaped rf plasma source is shown in Fig.1.

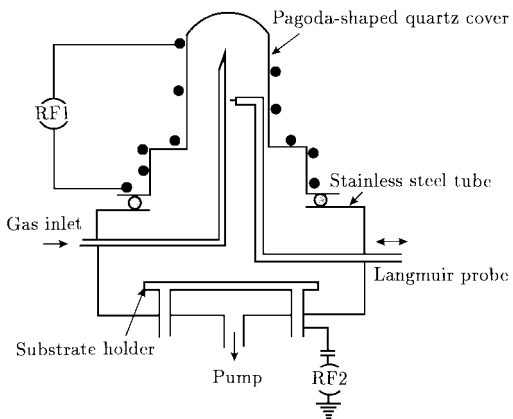

Fig.1. Schematic diagram of pagoda-shaped rf-plasma source.

This source is made by the Group 305 at Microelectronics R & D Center, Academia Sinica.[6] The vacuum chamber consists of a 22 cm bottom diameter, 18 cm high, pagoda-shaped quartz cover (plasma chamber) and a stainless steel tube (process chamber) with 32 cm in diameter and 14 cm in length. A pagoda-shaped antenna surrounds the outside of the plasma chamber and a rf power supply (RF 1 in Fig.1) at a frequency of 13.56 MHz is applied to it. The gas is filled at the top of the quartz cover, passing through a Pyrex glass tube from the base plate of the process chamber. Flow is controlled to within the range of 10–80 cm^3/min using a mass flow control system. For etching the sample a simple noncooled substrate holder is placed about 7 cm above the base plate in the process chamber. In order to control the bombardment energy of reactive ions and reduce the etching injure to the sample, the substrate holder can be independently biased by application of rf power using a separate generator, RF 2, at a frequency of 13.56 MHz.

The plasma densities and electron temperatures are estimated by using a Langmuir probe. A 1 mm diameter tungsten wire extending 3 mm from the ceramic insulator is used as a probe. The probe voltage V is swept from -90 to $+90$ V at a frequency about 1 kHz. In

the general case, the probe and probe cables will pickup the rf signals from rf power supply and the antenna. These rf signals will seriously affect the probe characteristic. Therefore, the rf power supplies, the plasma chamber, and the probe cables should be electrically shielded very carefully to reduced the rf interference signal to a minimum. At the same time, a resonant circuit including a low-pass (~1 kHz) filter and a resonator circuit (whose impedance is 2 orders larger than that of the probe for 13.56 MHz) is connected to the output of the probe.[7,8] And an additional Langmuir probe is placed outside of the vacuum chamber and a differential amplifier is used to eliminate the final noise.[9] A sharp probe current signal could then be obtained after these processes (Fig.2).

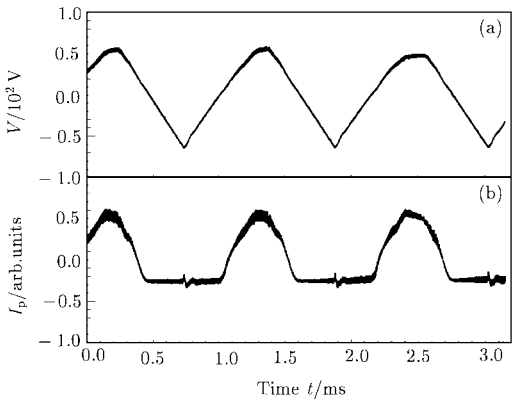

Fig.2. (a) Swept voltage signal applied to the probe and (b) typical Langmuir probe current signal.

Althrough the ICP plasma is not in thermo-equilibrium, i. e., the electron energy distribution function is not Maxwellian, Thomson scattering results indicate that the Maxwellian distribution can be a good approximation.[10] Hence, the electron temperature T_e is adopted in our experiment and can be determined by the slope of log I (I is the probe current) versus voltage V near the floating potential on the Langmuir probe.[9] The plasma density n_i can be calculated from the saturation ion current I_B of the probe[11]

$$I_B = 0.5 n_i e A (kT_e/m_i)^{1/2} ,$$

where A is the probe area, m_i is the ion mass, and e is the electron charge.

The probe is inserted radially into the system through five o-rings seal. Thus, it can be scanned radially. Changing the probe with different probe stem length along the symmetric axis of system, the data of the probe at different axial position z can be obtained. The position z=0 is on the substrate. Because the Pyrex tube filled with gas is located at the axis of system (r=0), the probes scan radially just from $r = 2$ cm except the probe at position $z = 0$.

Ⅲ. CHARACTERISTICS OF THE ARGON PLASMA SOURCE

Argon gas is used as a reference for describing the ICP source operation. The gas can suffer breakdown due to the induced rf electric field at an input rf power of P_i=300 W and a gas pressure of $P \leq 1.33 \times 10^{-1}$ Pa, and the plasma is in a stationary state after breakdown.

Figures 3(a) and (b) show the plasma densities n_i and electron temperatures T_e as functions of pressure P for different input powers P_i at z=17.5 cm and r=2 cm. The maximum plasma density is as high as 3×10^{12} cm^{-3} at P_i=1 kW and $P = 6.65$ Pa, which is two orders of magnitude higher than that of the rf diode plasma source. From Fig.3(a), the plasma density is increased as the pressure is increased because the collision mean free path becomes shorter when the pressure is increased. The collision mean free path for ionizing neutrals in argon plasma is given by

$$\lambda = v_{Ar}/n_e < \sigma v_e > ,$$

where v_{Ar} is the mean argon velocity at room temperature, v_e is the relative electron-argon velocity, and σ is the cross-section for ionization. Gorbatkin *et al.*[10] calculated $< \sigma v_e >$. In our experimental condition, $v_{Ar} = 4 \times 10^4$ cm/s, $T_e \approx 5$ eV, and mean density $n_e \approx 5 \times 10^{11}$ cm^{-3}. We can obtain a mean free path for ionization of 17 cm. Assuming the length of the plasma system in our device is 30 cm, we estimated that < 50 % of the injected argon atoms will be ionized.

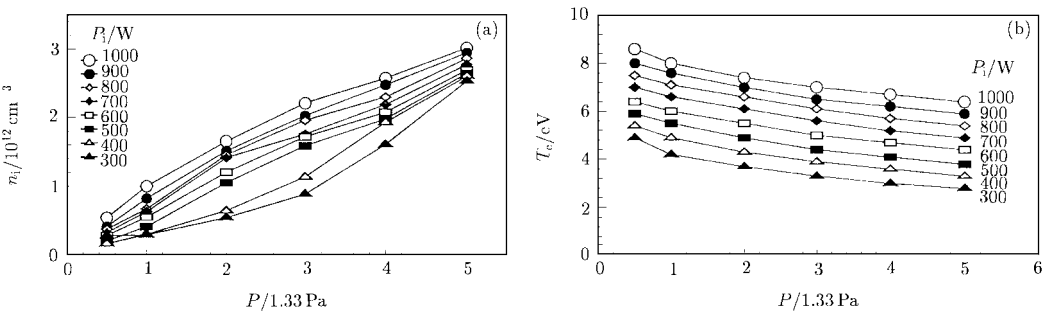

Fig.3. (a) Plasma densities n_i and (b) electron temperature T_i as functions of pressure P for different input rf power P_i at z = 17.5 cm (z=0 at substrate) and r = 2 cm.

Figure 4 shows the plasma densities n_i as a function of the input rf power P_i for different pressures P at the middle of the plasma chamber (z=13 cm, r=2 cm). This figure indicates that the densities are increased linearly with increasing input power, and the larger the pressure, the steeper the slope of the line. The results can be explained by ICP discharge

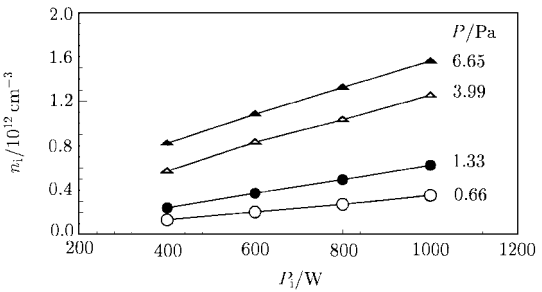

Fig.4. Plasma densities n_i as a function of input rf power P_i for different pressures P at the middle of the plasma chamber (z=13 cm and r =2 cm).

mechanism as follows.[3] Considering the power balance requirement, the plasma density should be proportional to the power absorbed by the plasma, $n_i \propto P_i$. According to equivalent transformer coupled circuit (ETCC) model of an ICP discharge[3], the slope of the density versus input power depends on the source current of ETCC, I_{rf}. By increasing the pressure, the ion density is increased and the impedance seen at the coil terminals in ETCC also increases. Hence, the slope of the density versus input power is steeper due to the decrease of the source current I_{rf}.

The plasma diffusion from source regime to process chamber has been studied and is shown in Fig.5 for different input powers. The diffusion rate clearly depends on the input power. The axial profiles of the plasma density for different pressures is shown in Fig.6. The higher the pressure, the larger the gradient of the ion density. And the gradient of the ion density is increased as the input power or the pressure is increased, which can be explained as follows. Consider the plasma diffusion is an ambipolar diffusion. If we consider a steady state plasma, i. e., analyze a steady discharge, the ion diffusion flux,

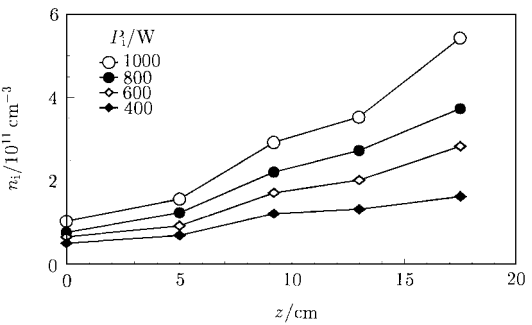

Fig.5. The axial profiles of the plasma density for different input power at r =2 cm and $P = 6.65 \times 10^{-1}$ Pa.

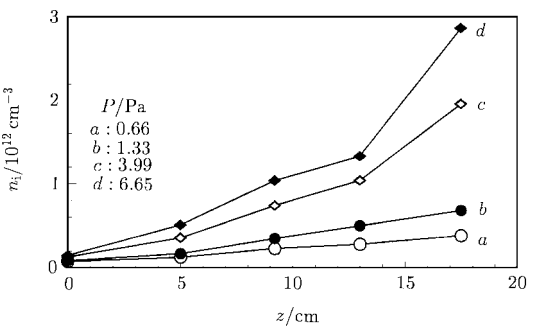

Fig.6. The axial profiles of the plasma density for different pressure at r = 2 cm and P_i=800 W.

$\Gamma_i = -D_a \nabla n_i$, is constant when assuming the ionization rate is zero in diffusion. D_a is the ambipolar diffusion coefficient $D_a \approx D_i T_e/T_i$, where D_i is the ion diffusion coefficient, T_e and T_i are the electron and ion temperatures, respectively. Hence the gradient of ion density is inversely proportional to the ambipolar coefficient, $\nabla n_i \propto -1/D_a$. D_i is given by $kT_i/m_i\nu_{in}$, where ν_{in} is the ion-neutral collision frequency which is proportional to the ion density[12], $\nu_{in} \propto n_i$. Therefore, the gradient of ion density in the diffusion is increased as

the ion density is increased. In the case of ionization-free or week ionization (i. e., in the case of low input power or low pressure in our experiment), the ion density in diffusion is decreased at a linear rate.

The spatial profiles of the plasma density and the electron temperature at the pressure $P = 6.65 \times 10^{-1}$ Pa. and the input power P_i=1 kW are shown in Figs. 7 and 8, respectively.

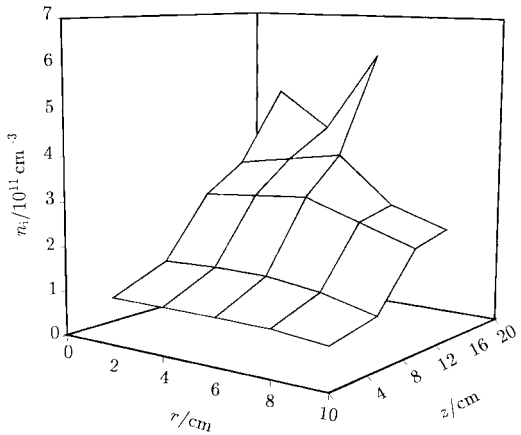

Fig.7. The spatial profile of the plasma density at $P = 6.65 \times 10^{-1}$ Pa and P_i=1 kW.

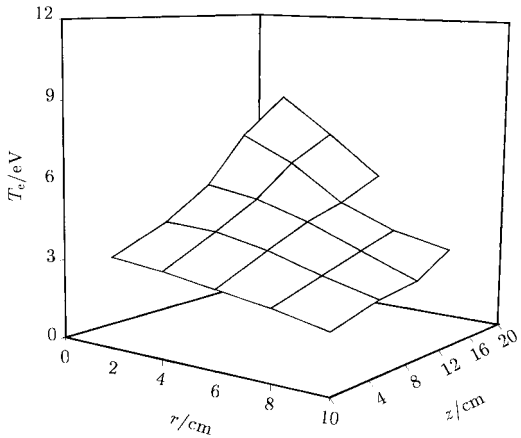

Fig.8. The spatial profile of the electron temperature at $P = 6.65 \times 10^{-1}$ Pa and P_i=1 kW.

Significant axial density gradients exist due to downward diffusion. The plasma density in the source is nearly one order of magnitude higher than that in the downstream. Note that the radial plasma density profile at the top is an obvious saddle-shape, but it becomes more uniform with the increase of distance from the source. The distribution of the electron temperature is non-uniform both axially and radially, as shown in Fig.8. The temperature in the source is about 2–3 times larger than that above the substrate. Different from the radial density profile (although the radial gradient of the electron temperature is also decreased along the axis), the temperature above the substrate still drops radially.

The plasma uniformities or the radial profiles for the different conditions are investigated. Figure 9(a) shows the radial distributions of the plasma density at the pressure $P = 6.65 \times 10^{-1}$ Pa and position $z = 5$ cm for different input rf powers. The uniformity is changed with input power from $\leq \pm 5.3\,\%$ at P_i=1 kW to $\leq \pm 4.5\,\%$ at P_i=400 W over 8 cm radius, or from $\leq \pm 12.7\,\%$ to $\leq \pm 11.3\,\%$ over 10 cm radius. Hence, the input rf power does not obviously affect the plasma density uniformity in the downstream regime. Figure 9(b) shows the radial profiles of the electron temperature under the same conditions. The figure indicates that T_e is decreased along the radial direction and the tendency seems to be independent of the input power.

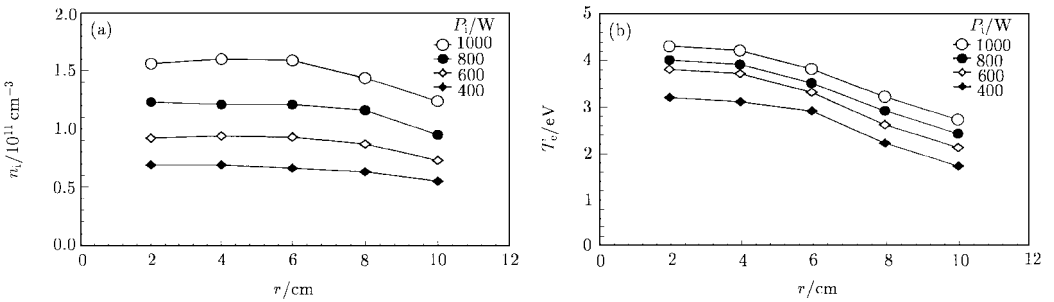

Fig.9. The radial distributions of the plasma density (a) and the electron temperature (b) for different input powers at z=5 cm and $P = 6.65 \times 10^{-1}$ Pa.

Figure 10 shows the radial profiles of the plasma density for different pressures at the power P_i=1 kW on the substrate (z=0). The uniformity is obviously improved from $\leq \pm 8.7\,\%$ at high pressure P =6.65 Pa to $\leq \pm 1.6\,\%$ at low pressure $P = 6.65 \times 10^{-1}$ Pa over 8 cm radius or from $\leq \pm 12.5\,\%$ to $\leq \pm 6.6\,\%$ over 10 cm radius. Obviously, the plasma uniformity on the substrate depends on the pressure rather than the rf power. At low pressure and high input rf power, we should obtain the plasma with high density and better uniformity. These results indicate that a large volume of uniform plasma can be created by using a pagoda-shaped plasma chamber and a pagoga-shaped antenna.

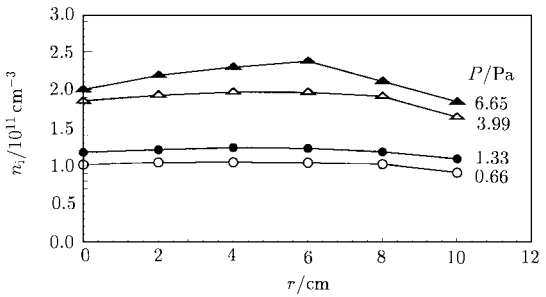

Fig.10. The radial profiles of the plasma density for different pressures at P_i=1 kW on the substrate (z=0).

IV. ETCH UNIFORMITY OF O_2 PLASMA

Etching photoresist in O_2 plasma is tested to check the above uniformity experiment. The photoresist (Model SPR6809 made by Shipley Corporation) with a thickness of 0.75 μm

is coated on a Si surface with a diameter of 15 cm. Etching in O_2 plasma is made for 2.6 min at the pressure of 6.65×10^{-1} Pa and power of 800 W. The photoresist with a thickness of 0.60 μm in the center regime of sample is etched. Hence, the etch rate R is about 0.23 μm/min. Figure 11 shows the radial profile of the etch rate. A uniform regime to $\leq \pm 1.1\,\%$ over 10 cm diameter or to $\leq \pm 2.2\,\%$ over 13 cm diameter is obtained. In order to compare the etching uniformity with that of the plasma density, the radial profile of the plasma density above the sample surface is also plotted in the same figure under same conditions. The plasma with the uniformity to $\leq \pm 1.7\,\%$ over 13 cm diameter is presented. These results imply that the etch uniformity should be in reasonable agreement with that of the plasma density.

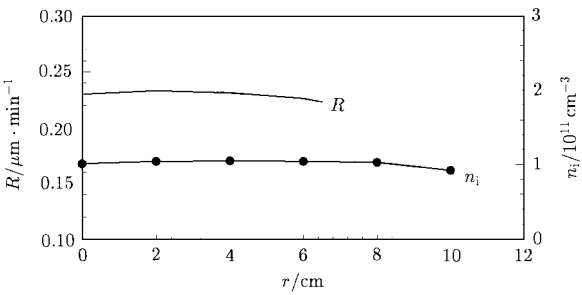

Fig.11. The radial profile of etch rate R for etching photoresist in O_2 plasma and the radial profile of the plasma density on sample surface at $P = 6.65 \times 10^{-1}$ Pa and P_i=800 W.

V. CONCLUSION

A large volume pagoda-shaped radio-frequency plasma source has been setup. The plasma density and electron temperature have been measured by using a Langmuir probe. Their spatial distributions are described and the plasma characteristics are investigated with variation of the pressure and the input rf power. The results indicate that this kind of plasma source has a good uniformity on the substrate. Uniformity to $\leq \pm 1.6\,\%$ over 16 cm diameter can be produced at an argon pressure of 6.65×10^{-1} Pa (at low pressure) and an input rf power of 1 kW (at high power). Comparing the uniformity of the plasma density with that of the etching photoresist, they are in reasonable agreement with each other. These results indicate that the pagoga-shaped antenna can obviously improve the plasma uniformity. The field strength at the top of antenna is stronger than that at the bottom of antenna due to the smaller diameter of the antenna coil. Higher ionization rate enhances the plasma density in the center region on the substrate and improves the plasma uniformity. We tend to believe that increasing step of the pagoga (in this paper, the step of the pagoda is 2), one can obtain a high density plasma with larger diameter (more than 18 cm) uniformity.

ACKNOWLEDGMENT

The authors wish to acknowledge Group 305 at Microelectronics R & D center, Academia Sinica, for their technical assistance.

REFERENCES

[1] K. Yamauchi, K. Takahashi and E. Yabe, *Rev. Sci. Instrum.*, **64**(1993), 2434.
[2] R. W. Boswell, A. J. Perry and M. Emami, *J. Vac. Sci. Technol.*, **A5**(1989), 3345.
[3] M. A. Lieberman and R. A. Gottscho, Design of High Density Plasma Sources for Materials Processing in Physics of Thin Films, ed. by M. Francombe and J. Vossen (Academic Press, New York, 1993), p.56.
[4] Lam Research Corporation, Technical Note TN-003(1992).
[5] H. M. Wu, M. Li, Y. M. Chen and C. K. Wu, *Chin. Phys. Lett.*, **12**(1995), 281.
[6] X. C. Liu, D. C. Ye, X. M. Li, X. W. Wang, H. Qian, W. J. Xu, Z. Y. Cao and X. Zhang, Chinese Patent No. ZL95 2 09870.9(11, May, 1995).
[7] R. R. J. Gagne and A. Cantin, *J. Appl. Phys.*, **43**(1972), 2639.
[8] D. Sudit and R. C. Woods, *Rev. Sci. Instrum.*, **64**(1993), 2440.
[9] F. F. Chen, in Plasma Diagnostic Techniques, edited by R. H. Huddlestone and S. L. Leonard (Academic Press, New York, 1965), Chap. 3.
[10] S. M. Gorbatkin, L. A. Berry and J. B. Roberto, *J. Vac. Sci. Technol.*, **A8**(1990), 2893.
[11] F. F. Chen, Introduction to Plasma Physics and Controlled Fusion Vol. 1: Plasma Physics (Plenum Press, New York, 1984), p.296.
[12] M. A. Liebermann and A. J. Lichtenberg, Principle of Plasma Discharges and Material Processing (Wiley Interscience Publication, New York, 1994), p.130.