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Analysis of Langmuir Probe Data in High Density Plasmas

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Abstract−Analysis of Langmuir probe data by using the parametrization of Laframboise's numerical results was performed to characterize high density plasmas (argon or deuterium discharges) in terms of plasma parameters such as plasma density and electron temperature. The use of parameterizing Laframboise's results was found to readily extract the plasma parameters for arbitrary ratios of probe radius to Debye length in high density plasmas. It was observed that the electron temperature increased with decreasing gas pressure, and was nearly constant with power in both argon and deuterium plasmas. The plasma density increased with both power and pressure in both argon and deuterium plasmas. Over the power and pressure ranges used in this work, the plasma density in deuterium plasmas was found to be an order of magnitude lower than that in argon plasmas. A simulation study showed good agreement of predicted electron temperature and plasma density with experimental results for argon plasmas.

Key words: Plasma, Langmuir Probe, Plasma Density, Electron Temperature, Parametrization

INTRODUCTION

Plasmas are widely used to etch and deposit thin solid films in the fabrication of various devices such as integrated circuits, microelectromechanical devices, and photonic devices [Hwang et al., 2003; Ryu et al., 2003; Chung et al., 2002; Cho et al., 2000]. Recently, high density plasmas have drawn much attention since they have many advantages over conventional low density plasmas, which are mostly generated in a capacitively coupled method. Major advantages of the use of the high density plasmas include (a) independent control of plasma density and ion bombardment energy, (b) collisionless sheath that promotes ion directionality due to high plasma density (small Debye length) and low gas pressure (long mean free path), and (c) better uniformity over large diameter substrates since low gas pressure facilitates diffusion [Economou, 2000].

In any plasma system, it is essential to know basic plasma parameters such as plasma density and electron temperature because these parameters directly affect the Debye length and corresponding sheath thickness. Especially, high density plasmas are expected to have high plasma density ($>10^{11}$ cm^{-3}) so that the sheath formed in the high density plasmas would be collisionless. Therefore, knowing plasma parameters such as plasma density and electron temperature is of primary importance in the characterization of high density plasmas.

Langmuir probe measurements are a powerful and experimentally simple way to characterize basic plasma parameters. A Langmuir probe is simply a small metallic wire in contact with a plasma which can be biased relative to the plasma. The current collected by the probe is measured as a function of the probe bias.

Langmuir probes have been the most widely used form of plasma diagnostic since they were introduced in the 1920s. Langmuir probe measurements are indirect in the sense that a theory is needed to obtain plasma parameters. Although the experimental determination of the probe characteristic is comparatively simple, there is no universal theory to analyze Langmuir probe measurements.

The most complete analysis of Langmuir probe data was conducted by Laframboise [1966]. He reported extensive numerical studies for different types of probes and various plasma conditions. Recently, Steinbruchel [1990] showed that Laframboise's numerical results could be parametrized for arbitrary ratios of probe radius to Debye length, and demonstrated the determination of plasma density and electron temperature in capacitively coupled plasmas (low density plasmas).

In this work, high density plasmas generated in an inductively coupled plasma source were characterized with Langmuir probe measurements. Langmuir probe data were analyzed by using the parametrization of Laframboise's results, following Steinbruchel, to extract basic plasma parameters such as plasma density and electron temperature in high density plasmas. It will be shown that the use of parametrization of Laframboise's results allows one to easily obtain plasma parameters for arbitrary ratios of probe radius to Debye length in high density plasmas. A simulation study was also conducted for comparison with experimental values.

EXPERIMENTAL

1. Plasma Source

An inductively coupled high-density plasma was used in this study based on an earlier design by Chen and Yang [1996]. Fig. 1 shows a schematic of a plasma source equipped with a Langmuir probe. The plasma was ignited in a ceramic tube (Al_2O_3) with 1.25 inch in inner diameter and 3.25 inch in length, by applying 13.56 MHz rf power (ENI Power Systems, OEM-6AM-1-B) to a three-turn coil through a matching network. The matching network consisted of two variable capacitors (5-500 pF) connected to the rf power supply in series and parallel, respectively. A 0.5 inch-diameter sapphire window was placed on the top of the plasma source to allow the visual inspection of the plasma. A stainless steel electrode was placed at the bottom of the source and kept grounded during the

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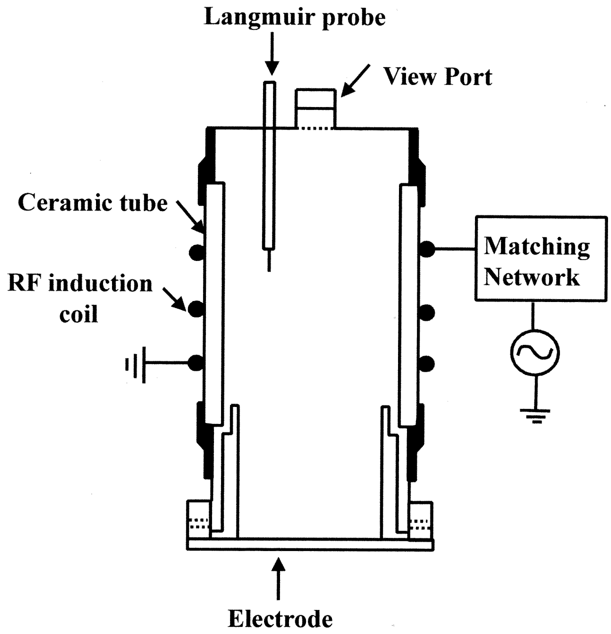

Fig. 1. Schematic of the plasma source equipped with the Langmuir probe.

experiments.

Argon and deuterium were used as discharge gases. Argon was selected since its simple plasma chemistry makes it an appropriate starting gas for Langmuir probe measurements. Deuterium was chosen because of its long mean free path which made the sheath collisionless. The power ranged 200-600 W both in argon and deuterium plasmas, while the pressure ranged 5-50 mtorr and 10-50 mtorr in argon and deuterium plasmas, respectively.

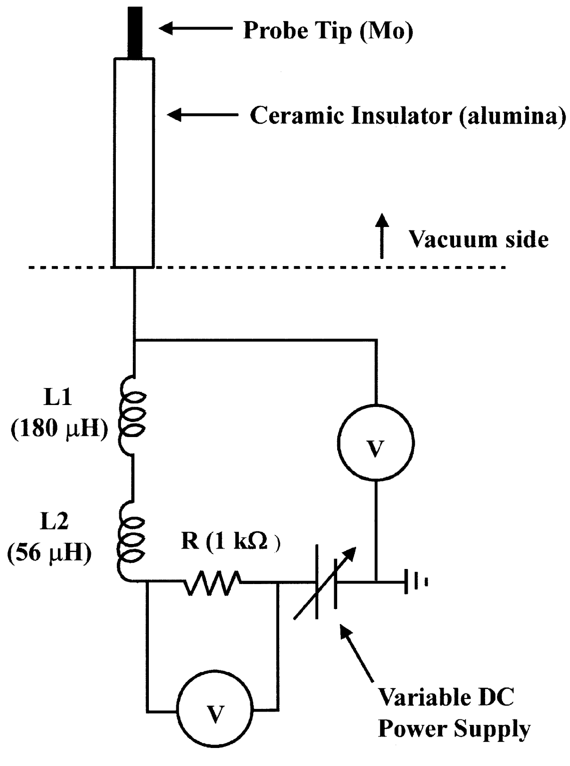

Fig. 2. Apparatus for Langmuir probe measurements. Probe wire was connected to inductors (L1 and L2) in order to choke the rf current of the probe. Current was measured by the voltage drop across the resistor, R.

2. Langmuir Probe

Fig. 2 shows the experimental arrangement used for Langmuir probe measurements. In this work, the single probe technique was used to measure plasma parameters such as electron temperature and plasma density. The Langmuir probe was a molybdenum wire 0.8 mm in diameter. The probe was encaged in a ceramic insulator tube (alumina, 11 mm in inner diameter) except for a 4 mm exposed tip of the probe. The gap between the Langmuir probe and the ceramic insulator was filled with epoxy to prevent plasma from leaking into the gap. Langmuir probes have to be compensated for rf fluctuations of the plasma potential to deliver reliable results [Godyak et al., 1992]. To suppress rf current through the probe, the probe wire was connected to two inductors (L1 and L2 in Fig. 2) in series, providing an impedance that minimize any rf-induced distortion of the probe characteristics [Paranjpe et al., 1990].

Langmuir probe measurements were conducted as follows. Prior to measurements, the probe was biased at a negative potential of about −80 V with respect to ground to clean the probe surface by ion bombardment. The ion saturation current was obtained by applying voltages down to −100 V on the probe with respect to ground. The electron saturation current, however, was not reached because the probe tip evaporated at large positive potentials with respect to ground. Thus, the voltage applied to the probe ranged from −100 to only +40 V with respect to ground at intervals of 1 V. In this voltage range, only the ion saturation region and the transition region were accessed.

The probe current as a function of the probe voltage was measured by the voltage drop across a 1 kΩ precision resistor (R in Fig. 2) by using a data acquisition system (National Instruments, 6071E). The voltage to the probe was swept with a Kepco DC power supply (BHK 500-0.4 MG). The data acquisition system and the Kepco DC power supply were controlled by a National Instruments PCI-GPIB using LabVIEW 5.1 for Windows.

During measurements, the probe tip was located at r=0.5 mm and z=11.3 mm, assuming that the center of the plasma source is at (r, z) = (0, 0) mm.

3. Data Analysis for Langmuir Probe Measurements

Langmuir probes are used in a wide variety of plasmas ranging from low density, low magnetic field space plasmas to those at the edge of fusion research devices [Lipschultz et al., 1986]. Although Langmuir probes are fairly straightforward to operate, analysis of Langmuir probe data is quite complicated because there is no universal method of interpretation.

Assuming a non-magnetized plasma, theories for the analysis of Langmuir probe data can be classified into three groups, according to the ratio of probe radius (r_p) to the Debye length (λ_D): i) planar sheath approximation when $r_p/\lambda_D >> 1$, ii) orbital motion limit (OML) theory when $r_p/\lambda_D \rightarrow 0$, and iii) Laframboise's theory for intermediate values of r_p/λ_D.

Using typical values of electron temperature (4 eV) and plasma density (10^{11} cm^{-3}) for the inductively coupled plasma used in this work, the Debye length can be estimated to be about 50 μm. Although the probe radius used in these experiments is 0.4 mm, so that r_p/λ_D is larger than 1, it is not safe to use the planar sheath approximation, because the sheath thickness can be much larger than λ_D.

Laframboise's theory was thus used to analyze the Langmuir probe data [Laframboise, 1966]. It is known that the electron current to the probe, I_e, in the transition region of the current-voltage (I−V) characteristics is proportional to exp X, if the electron distribution is Maxwellian [Clements, 1978], i.e.,

$$I_e = eN_e A_p (kT_e/2\pi m_e)^{1/2} \exp X. \quad (1)$$

In Eq. (1), e is the elementary charge, N_e is the electron density in the bulk plasma, A_p is the probe area, k is the Boltzmann constant, T_e is the electron temperature, m_e is the electron mass, and X is the dimensionless potential defined as

$$X = \frac{e(V_p - V_s)}{kT_e}, \quad (2)$$

where V_p and V_s are the probe and plasma potential, respectively. Laframboise represented the ion current to the probe, I_i, as

$$I_i = eN_i A_p (kT_e/2\pi m_i)^{1/2} i_i \quad (3)$$

in analogy to Eq. (1). In Eq. (3), N_i is the ion density in the bulk plasma, m_i is the ion mass, and i_i is a dimensionless correction factor depending on r_p/λ_D and dimensionless potential X. Fig. 3 shows Laframboise's original results for i_i as a function of X and r_p/λ_D, for $T_e \gg T_i$, where T_i is the ion temperature.

Steinbrüchel [1990] proposed a parameterization of Laframboise's results for arbitrary values of r_p/λ_D in the form

$$i_i(X) = a(-X)^b. \quad (4)$$

By fitting the data on a plot of ln i_i vs ln (−X), parameters a and b in Eq. (4) can be extracted as a function of r_p/λ_D, and are given in Fig. 4. Once a and b are obtained, the ion density N_i can be determined by combining Eqs. (3) and (4) as

$$N_i = (-\partial I_i^{1/b}/\partial V_p)^b (aA_p)^{-1} (2\pi m_i)^{1/2} e^{-b-1} (kT_e)^{b-1/2}. \quad (5)$$

Assuming that the number of negative ions in a plasma is negligible, the ion density is nearly equal to the plasma density. Therefore, it can be said that Eq. (5) directly determines the plasma density.

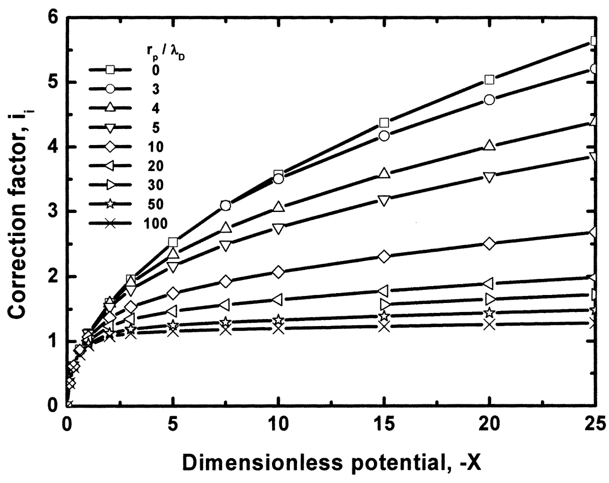

Fig. 3. Correction factor i_i as a function of dimensionless potential X at various r_p/λ_D with $T_e \gg T_i$. Data were taken from Laframboise's original results [Laframboise, 1966].

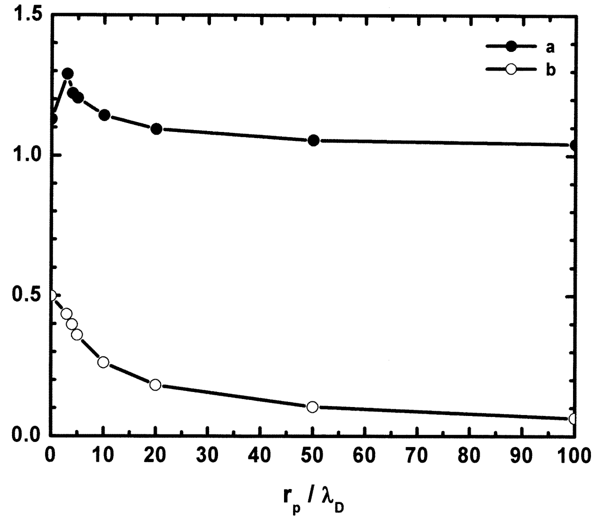

Fig. 4. Parameters a and b in Eq. (4) as a function of r_p/λ_D.

A simple iterative method was applied to obtain a and b in Eq. (5): i) guess λ_D, ii) extract parameters a and b from Fig. 4, iii) obtain the ion density (plasma density) from Eq. (5), iv) calculate a new λ_D with the new plasma density obtained from step iii), and v) iterate steps i) to iv) until λ_D converges. It was found that 4 to 5 iterations were sufficient to obtain a converged λ_D.

Eq. (5) shows that the electron temperature must be known to obtain the plasma density. The electron temperature was also measured by the Langmuir probe. Eq. (1) shows that a plot of ln I_e versus V_p gives the electron temperature as the inverse of the slope of the resulting straight line.

RESULTS AND DISCUSSION

1. Argon Plasma

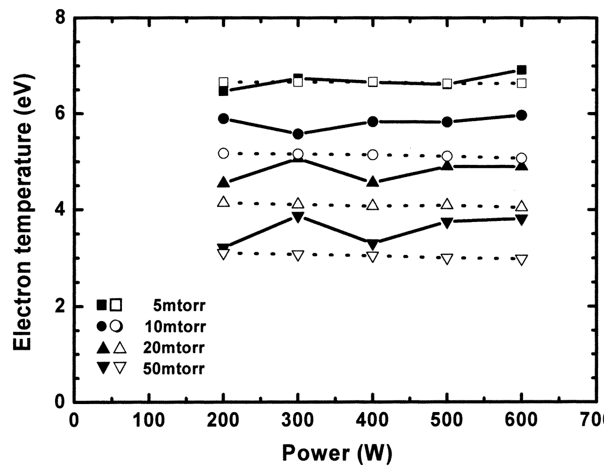

Fig. 5. Electron temperature in an argon plasma as a function of power at various discharge gas pressures. Filled and open symbols represent Langmuir probe measurements and MPRES simulations, respectively.

Fig. 5 shows the electron temperature in an argon plasma as a function of power at various discharge gas pressures. The electron temperature was extracted from Eqs. (1) and (2). A semi-logarithmic plot of electron current (I_e) versus probe potential (V_p) gives the electron temperature as the inverse of the slope of the resulting straight line. In Fig. 5, filled symbols represent the experimental results from Langmuir probe measurements and open symbols represent the simulated results using the MPRES code. MPRES (Modular Plasma REactor Simulator) is a rapid self-consistent simulation package that has been developed in the Plasma Processing Laboratory at the University of Houston [Wise et al., 1996]. The MPRES package allows one to simulate plasma transport and chemistry in arbitrary two-dimensional inductively coupled plasma reactors.

It can be seen from Fig. 5 that the electron temperature is nearly independent of power, and increases with decreasing gas pressure. These results are similar to other studies of argon discharges in either inductively coupled plasmas [Shatas et al., 1992; Miller et al., 1995; Hori et al., 1996] or capacitively coupled plasmas [Cox et al., 1987]. The increase of electron temperature with decreasing pressure is caused by the lower rate of electron-heavy particle collisions. An inverse dependence of the electron temperature on pressure was also predicted from a global model, with the electron temperature determined by the balance between ion creation and loss rate to the reactor walls [Lieberman and Lichtenberg, 1994].

Using the experimentally determined values of electron temperature, the ion density or plasma density was obtained by the iterative method described earlier in the previous section. Fig. 6 shows the plasma density in an argon plasma as a function of power at various discharge pressures. The experimental results (filled symbols) match the predictions of MPRES simulations (open symbols) over the entire range of power and pressure, assuming that only 20% of the applied power is dissipated in the plasma. Plasma densities increase both with power and pressure. This behavior also agrees with other studies of argon discharges in either inductively coupled plasmas [Shatas et al., 1992; Miller et al., 1995; Hori et al., 1996] or capacitively coupled plasmas [Cox et al., 1987]. It is expected that a higher pressure results in a lower ion diffusion loss rate. Under the present conditions, the plasma density is measured to be as high as 3.2×10^{12} cm^{-3}.

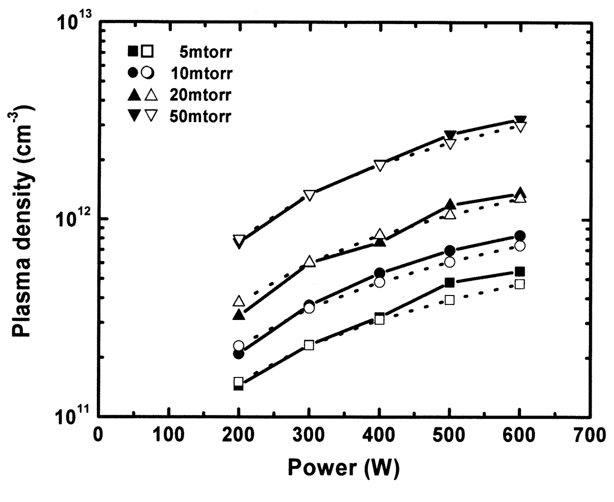

Fig. 6. Plasma density in an argon plasma as a function of power at various discharge gas pressures. Filled and open symbols represent Langmuir probe measurements and MPRES simulations, respectively.

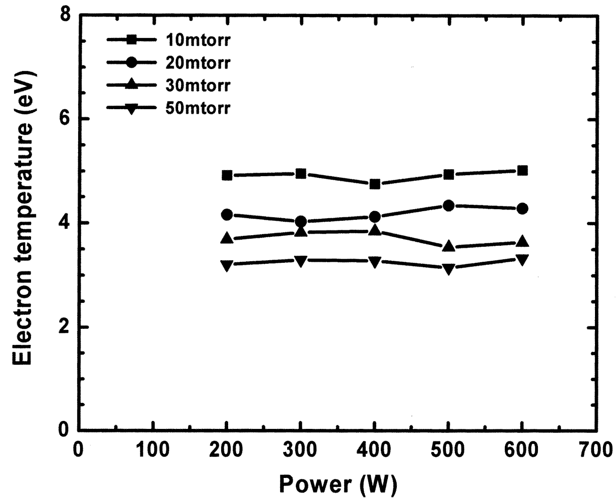

Fig. 7. Electron temperature in a deuterium plasma as a function of power at various discharge gas pressures.

2. Deuterium Plasma

Fig. 7 shows the electron temperature in a deuterium plasma as a function of power at various discharge gas pressures. The dependence of the electron temperature in the deuterium plasma on pressure and power reveals the same behavior as in argon plasmas: the electron temperature is nearly independent of power and increases with decreasing gas pressure. This behavior is found in other studies of deuterium plasma as well [Mullan and Graham, 1990].

It can be seen that the electron temperature in a deuterium plasma is about 0.3-0.9 eV lower than that in an argon plasma over the pressure range of 10-50 mtorr (see Fig. 5). This observation is contrary to the initial expectation of a higher electron temperature in a deuterium plasma than that in an argon plasma due to a higher diffusion loss in a deuterium plasma. Parameters controlling the electron temperature are complex, but one of the possible reasons for this effect may be the lower ionization potential of deuterium (15.4 eV) compared to that of argon (15.8 eV). Schwabedissen et al. [1997] measured electron temperatures in various gas discharges (Ar, Kr, Xe, Ne, O_2, and N_2) generated in an inductively coupled plasma source. They found that the lower the ionization potential of the gas, the lower the electron temperature in that gas.

Fig. 8 shows the plasma density in a deuterium plasma as a function of power at various discharge pressures. Plasma densities in deuterium plasma increase both with power and pressure as in the case of argon plasma. Other studies of deuterium plasma also show this behavior [Mullan and Graham, 1990]. Over the power and pressure ranges employed in this work, a plasma density as high as 3×10^{11} cm^{-3} is obtained in a deuterium plasma.

Comparing the plasma density in a deuterium plasma (Fig. 8) to that in an argon plasma (see Fig. 6), it can be seen that the plasma density in an argon plasma is higher (about 8-10 times) than that in a deuterium plasma. This is expected since deuterium has a lower electron impact ionization cross section [McDaniel, 1989] and ion losses are higher in a deuterium plasma. Anderson et al. [1990] mea-

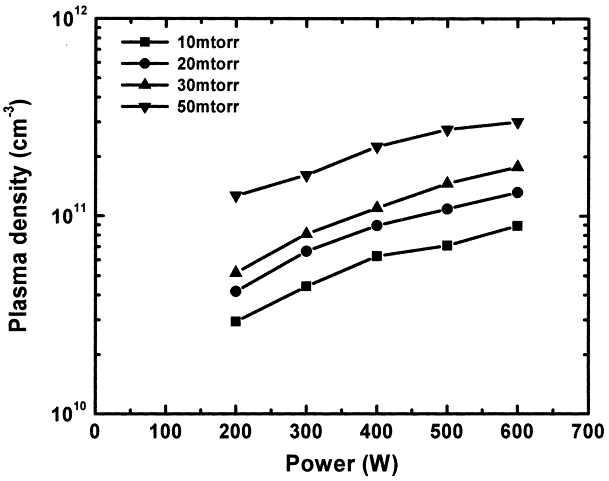

Fig. 8. Plasma density in a deuterium plasma as a function of power at various discharge gas pressures.

sured the plasma density in deuterium and argon plasmas in a capacitively coupled discharge and they found a higher plasma density in argon plasma.

CONCLUSIONS

High density plasmas have been characterized with Langmuir probe measurements. An inductively coupled plasma source generated a high density argon or deuterium plasma using rf power at 13.56 MHz. Basic plasma parameters such as plasma density and electron temperature were extracted from the parametrization of Laframboise's results.

The electron temperature increased with decreasing gas pressure (5-50 mtorr for argon and 10-50 mtorr for deuterium), and was nearly constant with power (200-600 W) in both argon and deuterium plasmas. The increase of electron temperature with decreasing gas pressure was caused by the lower rate of electron-heavy particle collisions enhancing electron losses to the wall. The plasma density increased with both power and pressure in both argon and deuterium plasmas. The increase of plasma density with higher gas pressure resulted from the higher rate of electron impact ionization and the lower rate of ion diffusion to the reactor wall. Over the power and pressure ranges employed in this work, the bulk plasma density was as high as 3.2×10^{12} cm^{-3} and 3.0×10^{11} cm^{-3} in argon and deuterium plasmas, respectively. The lower plasma density in deuterium plasmas resulted from the lower electron impact ionization cross section and the higher ion loss rate in deuterium plasmas compared to argon plasmas. MPRES (Modular Plasma REactor Simulator) simulation showed good agreement of predicted electron temperature and plasma density with experimental results for argon plasmas.

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NOMENCLATURE

a : constant
A_p : probe area
b : constant
e : elementary charge
I_e : electron current to the probe
i_i : dimensionless correction factor
k : Boltzmann constant
m_e : electron mass
m_i : ion mass
N_e : electron density in the bulk plasma
N_i : ion density in the bulk plasma
r_p : probe radius
T_e : electron temperature
T_i : ion temperature
V_p : probe potential
V_s : plasma potential
X : dimensionless potential

Greek Letter

λ_D : Debye length

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