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Improved double planar probe data analysis technique

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Plasma electron number density and ion number density in a dc multidipole weakly collisional Ar plasma are measured with a single planar Langmuir probe and a double planar probe, respectively. A factor of two discrepancy between the two density measurements is resolved by applying Sheridan's empirical formula [T. E. Sheridan, Phys. Plasmas **7**, 3084 (2000)] for sheath expansion to the double probe data. © *2009 American Institute of Physics.* [DOI: 10.1063/1.3089811]

I. INTRODUCTION

Two types of planar electrostatic probes, a single probe (SP, i.e., Langmuir probe) and a double probe (DP), can be used to diagnose plasma characteristics. A SP provides electron and ion number density, the electron energy distribution function, and the floating and plasma potential, while a DP provides ion number density and electron temperature at the floating potential.[1] Nevertheless, a DP is convenient to use in plasma with fluctuating plasma potential because it is electrically floating.[2] Unfortunately, many investigators have found that DPs overestimate the ion number density by factors of 2 or more.[3–7] Reifman and Dow[8] were the first to make use of a double probe. They measured plasma density in the ionosphere. Johnson and Malter[2] recognized that the ion saturation current varied with the applied bias voltage on the probe. They tried to resolve the problem by assuming that ion saturation current was linearly proportional to the applied bias voltage. Yamamoto and Okuda[9] treated the problem more carefully and provided an expression in which the ion saturation currents were not only dependent on the applied bias voltage but also on the electron temperature. Both papers argued that the ion saturation currents varied due to the sheath expansion around the probe tips. This problem is also apparent in the comparison of electron density and ion density for a SP. Sudit and Woods[3] explored apparent differences of a factor of 10 in ion and electron densities determined by a cylindrical probe. Recently, Jauberteau and Jauberteau[4,5] reported a way to determine the electron number density from ion saturation currents of a cylindrical single probe and a cylindrical double probe with consideration of sheath expansion and the collisions in the sheath. Their results still had discrepancies of about a factor of 2.

One of the assumptions for analyzing *I-V* curves obtained from a planar probe is that the radius of the probe is significantly greater than the sheath dimension. This assumption validates the usage of the physical probe surface area for the probe collection area S. On the other hand, Sheridan[10] used a particle-in-cell (PIC) code to show that the sheath expansion for planar probes biased negatively with respect to the plasma potential could not be ignored. He provided an empirical formula giving the effective probe area due to sheath expansion. This allows one to use the effective probe area (S_{eff}) rather than the physical probe area (S_{phy}) for S. Lee and Hershkowitz[11] experimentally verified that Sheridan's model properly described sheath expansion around the SP, and electron and ion number densities were found to agree within the experimental uncertainties of ±10%.

In a weakly collisional single-ion plasma where the mean free path for ion-neutral collisions (λ_{in}) is considerably longer than the Debye length (λ_D), the ion number density can be found using a SP or a DP from[1]

$$I_i^* = \kappa e n_i S c_S, \tag{1}$$

where I_i^* is the ion saturation current from the probe, e is an electron charge, n_i is the ion number density in the bulk plasmas, and $c_S = \sqrt{T_e/m_i}$ is the Bohm velocity with $T_i \ll T_e$. Here T_i and T_e are the ion and electron temperatures measured in eV, respectively, and m_i is the ion mass. In a collisionless plasma assuming energy conservation κ is $e^{-1/2}$, which is approximately 0.6.[1] However, the value of κ becomes lower as the λ_{in} gets smaller (i.e., energy conservation from the bulk plasmas to the sheath edge is not valid). If λ_{in} is comparable to or smaller than λ_D, then Eq. (1) cannot be used because Eq. (1) is derived by assuming ion flux conservation inside the sheath.

In this paper, electron number density is found for a SP from the electron saturation current, and ion number density is found for a DP from the ion saturation current using Sheridan's model. These two values are compared and the discrepancies are shown to be within 5% at pressures lower than 0.60 mTorr and get bigger (up to 20%) as the neutral pressure increases to 2.00 mTorr. In Sec. II, the experimental setup is described. Description of using Sheridan's model to DP *I-V* curves is in Sec. III, followed by experimental results and discussion in Sec. IV. The paper concludes with a summary in Sec. V. To the best of authors' knowledge, this is the first report using Sheridan's model to a DP and of resolving overestimation of ion number density from a DP.

II. EXPERIMENTAL SETUP

The plasma for this study was generated in a dc multidipole cylindrical chamber 70 cm in length and 60 cm in diameter (interior dimensions). Figure 1 shows the schematic

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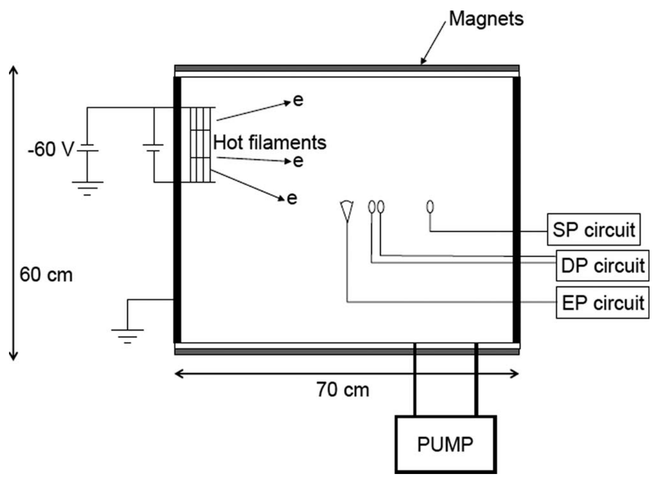

FIG. 1. Schematic of the dc multidipole chamber and probe circuitry for the SP (single planar probe), the DP (double planar probe) and the EP (emissive probe).

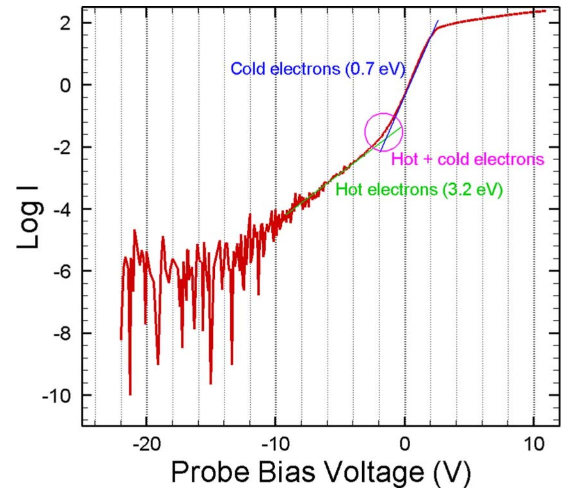

FIG. 2. (Color online) Semilog plot of the *I*-*V* curve from the SP for 0.60 mTorr neutral Ar. Hot electrons are mostly collected for $V_{bg} < -2$ V, both hot and cold electrons for $-2\ V < V_{bg} < -1$ V, and cold electrons for $V_{bg} > -1$ V. Here V_{bg} is the bias voltage on the probe with respect to the ground.

of the chamber. Alternating permanent magnets surrounding the cylindrical surface of the chamber provide better plasma confinement[12] without magnetizing electrons and ions in the center of the chamber. Thoriated hot tungsten filaments biased at −60 V with discharge current of 0.8 A emitted primary electrons that produced the plasma. Detailed descriptions of the chamber can be found elsewhere.[13] The base pressure of the chamber was kept at 1×10^{-6} Torr using a turbomolecular pump backed by a mechanical pump. Ar was used as the working gas with neutral Ar pressures ranging from 0.20 to 2.00 mTorr. Three types of probes, an emissive probe (EP), a SP and a DP, were employed for this study. Each probe can be moved axially and rotated azimuthally. When one probe was working, the other two probes were rotated toward the wall of the chamber to minimize influences of the other two on the working one. All the data were taken in the center of the plasma radially and axially.

Plasma potential was found using the EP. The inflection point method in the limit of zero emission[14] avoids space charge effects, which result in underestimation of the plasma potential. Extrapolating the inflection point of the EP *I*-*V* curves to zero emission provides a good estimate of the plasma potential.[14]

The SP is used to find electron temperature and electron number density. The probe tip is a tungsten disk with a radius of 4.0 mm and a thickness of 0.05 mm. SP *I*-*V* curves in this study showed that there were hot and cold electrons. Figure 2 is an example of the SP *I*-*V* curve obtained during this study for a neutral Ar pressure of 0.60 mTorr. To find the Bohm velocity c_S, the effective electron temperature must be calculated. It is calculated by a density weighted harmonic average of hot and cold electron temperature,[15]

$$\frac{1}{T_e} = \left(\frac{n_c}{n_e}\right)\frac{1}{T_c} + \left(\frac{n_h}{n_e}\right)\frac{1}{T_h}. \tag{2}$$

Here, subscripts h and c denote hot and cold electrons, respectively. n denotes number density, n_e for total electron number density, and T_e for effective electron temperature in eV. The temperatures of hot and cold electrons are found by fitting linear lines to a semilog *I*-*V* curve as seen in Fig. 2. Hot and cold electron number densities are found from the hot and cold electron saturation currents ($I^*_{h,c}$) of the SP using

$$I^*_{h,c} = \frac{1}{4} e n_{h,c} S \sqrt{\frac{8T_{h,c}}{\pi m_e}}, \tag{3}$$

where m_e is the electron mass. Hot electron saturation current is found by extrapolating the linear line corresponding to hot electron temperature to the plasma potential in a semilog *I*-*V* curve. Then, the hot electron contribution to the curve is subtracted from the curve and the resulting current is graphed as a semilog *I*-*V* curve. The cold electron saturation current is found by extrapolating the linear line corresponding to the cold electron temperature to the plasma potential. The total electron number density n_e is found by adding hot and cold electron number densities. The electron collecting area is equal to the physical probe surface area S_{phy} because I^*_e is measured at the plasma potential.

The DP was used to find ion number density. Probe tips are tungsten disks with radii of 4.0 mm and a thickness of 0.05 mm. The DP circuitry is electrically floating, and the voltage is applied between the two probe tips rather than with respect to the grounded chamber. In this report, V_{bg} denotes the bias voltage on the probe with respect to the ground, and V_{bp} denotes the bias voltage between the probe tips for the DP. For this study, V_{bp} was swept from −40 V to +40 V. Figure 3(a) shows a cartoon picture of potentials on each probe with respect to the grounded chamber. When the DP Tip #1 has a relative negative bias, it collects ion saturation current. The DP Tip #2 with a relative positive bias sets its potential $\sim T_e/e$ greater than the floating potential to collect excessive electrons, which compensates the ion saturation current on the DP Tip #1. At any time, the DP circuitry is floating. Figure 3(b) shows an example of an actual DP *I*-*V* curve. In Fig. 3, from A to B and from C to D are ion collection regions, whereas in the region from B to C both electrons and ions are collected by the DP. Note that the letters A, B, C, D, and O from Figs. 3(a) and 3(b) correspond

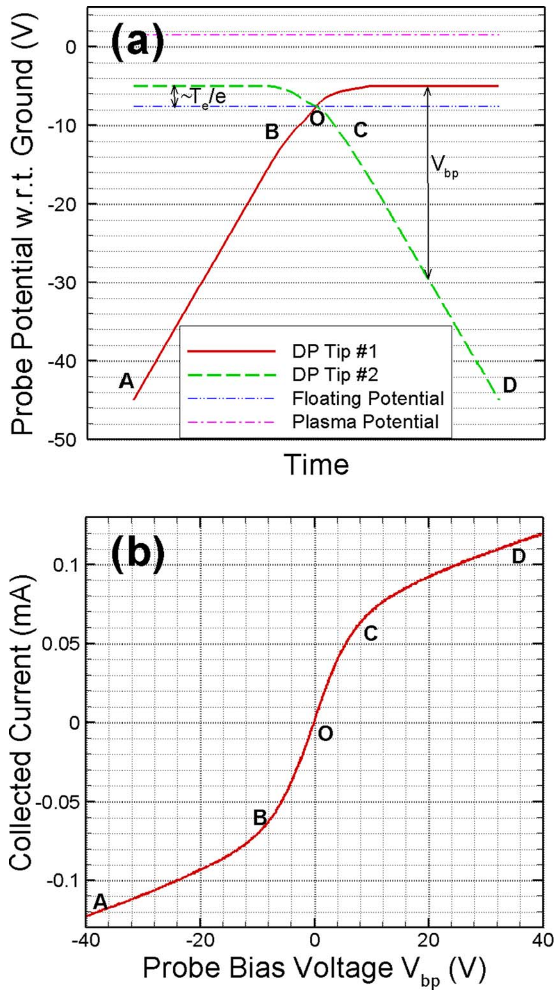

FIG. 3. (Color online) (a) A cartoon picture of potential on the probe tips with respect to the ground. (b) An example of the DP *I-V* curve for 0.6 mTorr neutral Ar.

to each other. Because electrons are collected in the region of BC, one also can find the corresponding T_e from the DP. However, because the potential on the probe tips with respect to the ground are approximately the floating potential (≈ -5 V) in this region of BC, the measured T_e corresponds to the hot electron temperature (see Table I). Electron temperatures from the DP are lower than the hot electron temperature from the SP as the neutral pressure becomes higher (see Sec. IV). Therefore, T_e's from the DP were not used in this study.

The DP *I-V* curve is fit by

TABLE I. Measured electron temperatures from the LP and the DP.

Ar pressure (mTorr)	From LP T_e (eV)	T_h (eV)	T_c (eV)	From DP T_e (eV)	V_f (V)
0.2	0.89	3.28	0.82	3.4	−5.9
0.4	0.82	3.09	0.78	3	−5.1
0.6	0.77	3.17	0.74	2.7	−4.6
0.8	0.79	2.98	0.76	2.4	−4.2
1.0	0.79	2.66	0.76	2.3	−4.1
1.5	0.76	2.85	0.74	1.9	−3.8
2.0	0.77	2.53	0.75	1.7	−3.7

$$I = I_i^* \tanh\left(\frac{eV_{bp}}{2T_e}\right) + \frac{V_{bp}}{R}, \quad (4)$$

where I_i^*, R, and T_e are the fitting parameters. The last term in Eq. (4) is a first order correction introduced to take into account the sheath expansion.[2]

III. APPLYING SHERIDAN'S EMPIRICAL FORMULA

Sheridan derived an empirical formula for the effective surface area, S_{eff}, of a planar probe with a physical surface area, S_{phy},[10]

$$S_{eff} = S_{phy}(1 + a\eta^b), \quad (5)$$

where a and b are fitting parameters, and η is $-e(V_{bg} - V_p)/T_e$ with V_p being the plasma potential found from the EP. The fitting parameters, a and b, are

$$a = 2.28\left(\frac{r_p}{\lambda_D}\right)^{-0.749}, \quad b = 0.806\left(\frac{r_p}{\lambda_D}\right)^{-0.0692}, \quad (6)$$

where r_p is the probe radius. In Sheridan's model, the thickness of the planar probe is ignored. The fitting parameters were found for following conditions:

$$10 < \frac{r_p}{\lambda_D} < 45, \quad 5 < \eta < 30. \quad (7)$$

The actual V_{bg}, which is required information to use Eq. (5), is not known precisely. However, it can be estimated by knowing the floating potential (V_f) and V_{bp}. The V_f on the probe tip can be measured with a volt meter, and V_{bg} is estimated to be $-|V_{bp}| + V_f$ [cf. Figure 3(a)]. Note that measuring the actual V_{bg} while the V_{bp} is being swept requires an external circuitry connected to the ground, which may result in a nonfloating DP circuitry.

With Eq. (5), the measured currents, $I_{i,mea}$, can be converted into[11]

$$I_{i,Sheridan} = \frac{I_{i,mea}}{1 + a\eta^b}, \quad (8)$$

where $I_{i,Sheridan}$ is the collected current after removing the effects of sheath expansion. Combining Eq. (4) and Eq. (8),

$$I_{i,Sheridan} = I_i^* \tanh\left(\frac{eV_{bp}}{2T_e}\right) + \frac{V_{bp}}{R}. \quad (9)$$

Once I_i^* is found from Eq. (9), Eq. (1) is used to find n_i with $S = S_{phy}$, and $\kappa = 0.6$. With $-40\ \text{V} < V_{bp} < +40\ \text{V}$, η may be out of the range specified in Eq. (7). Then, the out-of-range data are ignored to find I_i^* because validity of the fitting parameters, a and b, for out-of-range data is not specified.[10] Figure 4 shows the DP *I-V* curves with and without Sheridan's model for 0.20 and 1.00 mTorr neutral Ar pressures.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

Neutral Ar pressure was varied from 0.20 to 2.00 mTorr. In this range, effective hot and cold electron temperatures were 0.89–0.77, 3.28–2.53, and 0.82–0.75 eV, respectively. The values of n_h/n_c varied from 0.11 to 0.05 as the neutral Ar pressure changed. Figure 5 shows n_e and n_i as a function of pressure. It is clear that the n_e and n_i are in good agree-

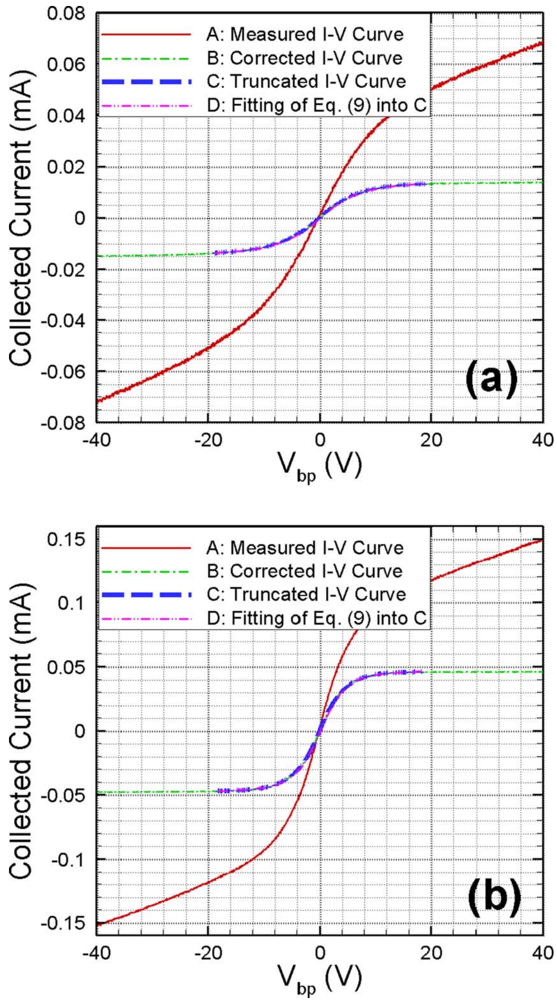

FIG. 4. (Color online) The DP *I-V* curves (a) 0.20 mTorr neutral Ar. ($I_i^*=11.3$ μA, $T_e=3.4$ eV, $R=8000$) (b) 1.00 mTorr neutral Ar. ($I_i^*=42.2$ μA, $T_e=2.3$ eV, $R=4600$). A: Measured *I-V* curve. B: Corrected *I-V* curve using Eq. (8). C: Truncated *I-V* curve to make sure $5<\eta<30$. D: Fit of Eq. (9) into C.

ment if the DP *I-V* curves are treated with Sheridan's model for the investigated conditions of neutral Ar pressure. The agreements are within the experimental uncertainties up to 1.00 mTorr. One of the experimental uncertainties for n_i comes from the estimating $V_{\rm bg}$ on the DP tips using $V_{\rm bp}$ and V_f described in Sec. III. n_i starts overestimating n_e as the pressure goes higher than 1.00 mTorr. This may be due to the fact that Sheridan's model assumes collisionless plasma. The underestimation of electron temperature from the DP in Table I may be due to this assumption as well as the decreasing (in magnitude) floating potential as the neutral pressure becomes higher. It is worthwhile to mention that other authors reported overestimation of n_e about a factor of 2 when ion saturation currents were used.[5,7] Figure 5 shows that without Sheridan's model correction, n_i is about a factor of 2 larger than n_e.

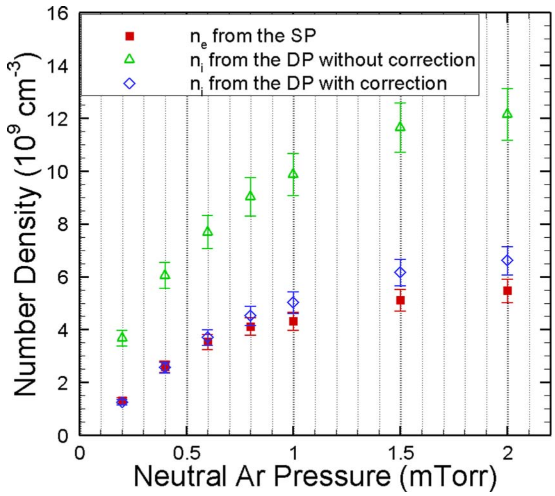

FIG. 5. (Color online) n_e and n_i (with and without Sheridan's correction) vs pressure.

V. SUMMARY

Since correction of Johnson and Malter[2] on the ion saturation currents of a DP in 1951, sheath expansion around the negatively biased probe has usually been approximated by assuming that the ion saturation current is linearly proportional to the bias voltage of the probe. However, this first order correction has not provided quantitative agreements between n_i and n_e. A combination of the linear model and the power-dependent model given by Sheridan[10] has been applied to DP data. Quantitative agreements of n_e obtained from SP electron saturation current and n_i from DP has been achieved for planar probes measuring weakly collisional Ar plasma with neutral pressure ranging from 0.20 mTorr to 2.00 mTorr and plasma number density of $1-5\times10^9$ cm^{-3}.

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