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Sheath characteristics in multi-component plasma with negative ions*

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Abstract. Properties of steady state ion sheath formed in front of a negatively biased metal plate under the influence of negative ions have been investigated in collisionless argon/SF_6 plasma. This experiment is carried out at a fixed discharge voltage and fixed filament heating power. In this experiment, the decrement in plasma pre-sheath potential drop as well as positive ion drift velocity toward the plate is experimentally recorded in the presence of negative ions. It is also found that the plasma positive ion density and plasma electron temperature decrease in the presence of negative ions. These factors attribute to the decrease of ion current toward the plate. Hence the usual ion sheath expands.

Keywords. Ion sheath; Bohm sheath criteria; negative ions; drift velocity.

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1. Introduction

Involvement of negative ion plasma in plasma-based technologies is now a days widespread. In plasma processing, a good understanding of the characteristic properties of plasma sheath formed near a physical boundary is required to have a proper control over the parameters governing the plasma processes. The explicit formulation and clear interpretation of the sheath formation in plasmas is due to Bohm [1], who introduced the idea of pre-sheath which accelerates ions to a sufficient velocity for the ion density to exceed the electron density everywhere within the sheath. The modified Bohm sheath criterion derived for thermal electron–thermal negative ion–cold positive ion model predicts the decrease of positive ion drift speed toward the sheath than that of the usual electron–ion plasma [2,3]. In laboratories, new

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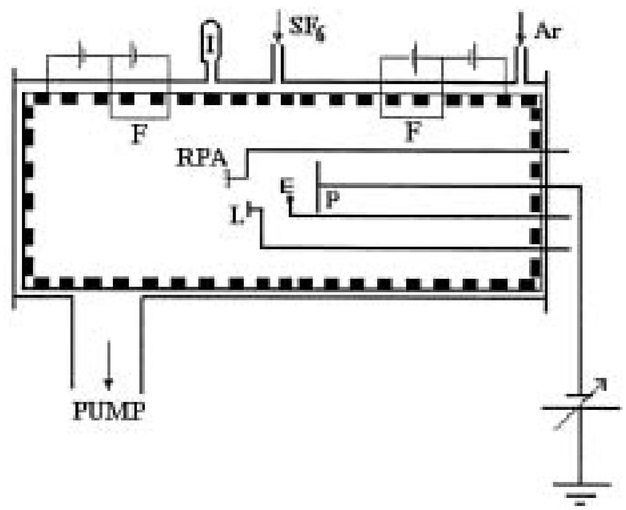

Figure 1. Schematic diagram of the experimental set-up. F – filament, L – Langmuir probe, E – emissive probe, P – metal plate, I – ionisation gauge.

diagnostic methods for negative ion plasmas have been introduced [4,5]. This paper presents the experimental study of steady state ion-rich plasma sheath in front of a negatively biased plate in multicomponent plasma with negative ions. The negative ion plasma is produced by introducing SF_6 gas into the argon plasma. The decrement in plasma pre-sheath potential drop and drift velocity of positive ions toward the sheath is observed in this experiment. The effect of negative ions on plasma parameters, e.g., electron temperature, ion density, electron density, etc. is also investigated.

2. Experimental set-up and measurement techniques

The experiment is carried out in a plasma device equipped with multi-dipole magnets for surface plasma confinement [6]. The device is a stainless steel chamber of 120 cm length and 30 cm diameter. A cylindrical magnetic cage made up of stainless steel bars of 80 cm length and filled with permanent bar magnets is kept inside the chamber. A schematic diagram of the device is shown in figure 1. The base pressure of the chamber is 2×10^{-6} Torr. Argon plasma is produced at a partial pressure 2×10^{-4} Torr by DC discharge between the tungsten filaments of 0.01 cm diameter as cathode and the magnetic cage as anode. The tungsten filaments are heated for thermo-ionic emission of electrons. The heating power is kept fixed throughout the experiment. The discharge voltage is 60 V and the discharge current is 100 mA in argon plasma and it decreases up to 50 mA when SF_6 is introduced up to a partial SF_6 pressure 1.4×10^{-4} Torr. Typical plasma parameters measured by a 6 mm diameter one-sided plane (disc type) Langmuir probe are: electron density 10^8–10^9 cm^{-3} and electron temperature $T_e = 1$–3 eV. The ion temperature in this device is $T_+ = T_e/15$–$T_e/10$. The RPA consists of two fine copper mesh grids and a stainless steel collector plate housed in a ceramic cup of 2.6 cm diameter and 0.4 cm depth. The first grid of RPA is left floating while the second grid bias is varied. The collector is biased at −90 V and its current is recorded against the second grid bias variation to obtain the I–V characteristics.

SF_6 gas is separately injected into the argon plasma at partial pressure in the range 0–1.4×10^{-4} Torr. Under the present discharge condition, the introduction of SF_6 leads to the formation of several species of positive and negative ions such as SF_5^+, SF_3^+, F^-, SF_5^- and SF_6^-. The dominant negative ion formation process under this condition is known as the dissociative attachment process, which reduces the electron population in the plasma. For the quasi-neutral bulk plasma, $n_{0+} = n_{0\mathrm{e}} + n_{0-}$, where n_{0+}, $n_{0\mathrm{e}}$ and n_{0-} are positive ion density, electron density and negative ion density respectively. The negative ion concentration in the bulk plasma, r_b is defined as the ratio of negative ion to positive ion density, i.e. $r_\mathrm{b} = n_{0-}/n_{0+} = 1 - n_{0\mathrm{e}}/n_{0+}$. In this experiment r_b is estimated by using the relation [7]

$$r_b = 1 - \frac{I_+(\mathrm{Ar})}{I_+(\mathrm{SF_6})}\frac{I_\mathrm{es}(\mathrm{SF_6})}{I_\mathrm{es}(\mathrm{Ar})}\sqrt{\frac{m_+(\mathrm{Ar})}{m_+(\mathrm{SF_6})}}\Omega(\mathrm{SF_6}), \tag{1}$$

where $I_\mathrm{es}(\mathrm{Ar})$ and $I_\mathrm{es}(\mathrm{SF_6})$ are electron saturation currents measured by the Langmuir probe in argon plasma and $\mathrm{Ar/SF_6}$ plasma respectively. I_es is found to decrease with increasing SF_6 partial pressure. The corresponding ion saturation currents $I_+(\mathrm{Ar})$ and $I_+(\mathrm{SF_6})$ are measured with the Langmuir probe. In eq. (1), $m_+(\mathrm{Ar})$ and $m_+(\mathrm{SF_6})$ denote the positive ion effective masses in argon plasma and $\mathrm{Ar/SF_6}$ plasma respectively. The factor $[m_+(\mathrm{Ar})/m_+(\mathrm{SF_6})]$ is equal to unity for lower concentrations of negative ions ($r_b \leq 0.5$) [7]. The sheath factor $\Omega(\mathrm{SF_6})$ is a complicated function of positive ion temperature (T_+), negative ion temperature (T_-) and pre-sheath potential drop (ϕ_pre). Since the negative to positive ion density ratio in our experiment is less than 0.4, the sheath factor is safely considered to be equal to 1.

An ion-rich sheath is produced in front of a stainless steel plate of 8 cm diameter by biasing it to negative potential of −100 V. The plate is placed at the middle of the anode cage and ceramic paste covers its back. The structure of the ion sheath in front of the negatively biased plate is determined by measuring the axial plasma potential using an emissive probe [8,9]. The emissive probe is made of 1% thoriated tungsten wire of 0.005 cm diameter and 0.4 cm length. The two ends of the tungsten wire are spot-welded to two stainless steel supporting rods (0.025 cm in diameter) which are covered by ceramic tubes. The probe is heated by a half-wave rectified DC voltage source (0–4 V). The procedure for interpretation of emissive probe is based on the fact that electron emission can take place when the probe bias is more negative than the local plasma potential [10]. The inflection point technique [8] has been employed to measure the plasma potential at 1 mm interval of axial distance using a motor driving system attached to the probe shaft. An ammeter is used in series with the plate to measure the plate current at different plate biasing voltages.

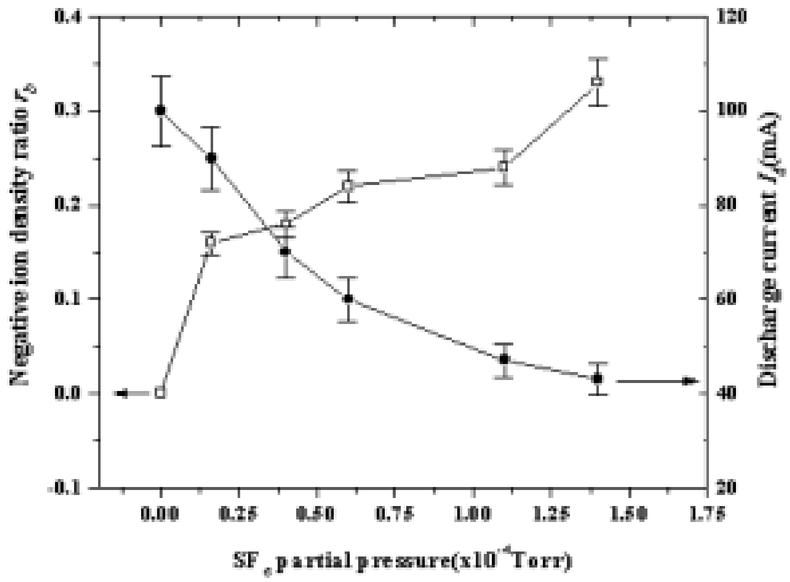

Figure 2. Variation of discharge current I_d and negative ion density ratio in the bulk plasma r_b with SF_6 partial pressure. Argon working pressure is fixed at 2×10^{-4} Torr.

3. Results and discussion

The electron saturation current (I_{es}) and the ion saturation current (I_+) in pure argon plasma as well as Ar/SF_6 plasma are measured from the I–V characteristics of the plane Langmuir probe. From the measured values of $I_{es}(Ar)/I_{es}(SF_6)$ and $I_+(Ar)/I_+(SF_6)$, the negative ion density ratio is obtained using eq. (1). With the increase of SF_6 partial pressure both the electron saturation current and ion saturation current are found to decrease. For measurement of positive ion density n_{0+} in pure Ar plasma, at first the electron density n_{0e} is measured from Langmuir probe I–V characteristics and n_{0+} is set equal to n_{0e}. Then the positive ion density in the presence of SF_6 is calculated using the relation $n_{0+}(SF_6) = n_{0+}(Ar)[I_+(SF_6)/I_+(Ar)][T_e(Ar)/T_e(SF_6)]^{1/2}$. The measured values of negative ion density ratio r_b in the bulk plasma at different SF_6 partial pressure are shown in figure 2. The argon discharge condition in the system is kept unaltered except the increase of SF_6 partial pressure ($0–1.4\times10^{-4}$) Torr which in turn increases the total pressure of the system. However, our investigation on the increase of Ar total pressure up to 3.4×10^{-4} Torr from 2×10^{-4} Torr shows slight increase in the plasma density and discharge current ($\sim 5\%$) and no significant change in the other plasma parameters such as electron temperature and plasma potential. It is found that discharge current decreases with increasing SF_6 partial pressure as shown in figure 2. This is caused by the modification of discharge mechanism in the presence of SF_6 leading to the formation of negative ions at the expense of plasma electrons and reduction of electron temperature and plasma density. The measured densities of different charge species with increasing r_b are

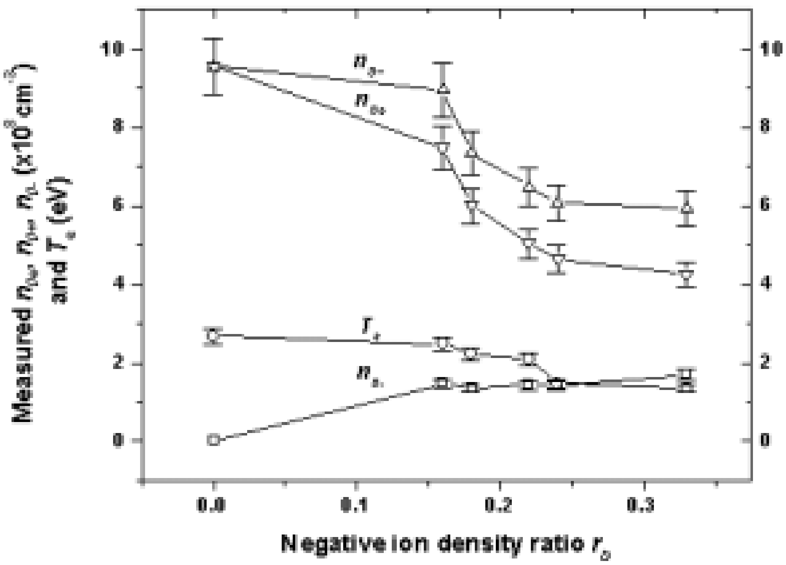

Figure 3. Variation of electron temperature T_e and densities of different charged species (n_{0+} – positive ions, n_{0e} – electrons, n_{0-} – negative ions) with increasing negative ion density ratio r_b.

plotted in figure 3. The electrons are replaced by the negative ions and therefore the electron density in the plasma decreases considerably. The measured electron density shows a decrement in the range 9.5×10^8 cm^{-3} to 4.2×10^8 cm^{-3} when r_b is varied in the range 0–0.33. It is interesting to note that the positive ion density n_{0+} also decreases with increasing SF_6 partial pressure. It is particularly important because n_{0+} determines the value of negative ion concentration r_b. In this experiment, positive ion density decreases from 9.5×10^8 cm^{-3} (at $r_b = 0$) to 6×10^8 cm^{-3} (at $r_b = 0.33$). The measured negative ion density slowly increases from 0 to 1.8×10^8 cm^{-3} in the same range of r_b. The electron temperature T_e measured from the I–V characteristics of the Langmuir probe is plotted for different r_b values and it is found that T_e decreases with increasing r_b.

Figure 4 shows the measured axial plasma potential profiles in front of the metal plate at different negative ion density ratios for $V_p = -100$ V. It is seen that the plasma potential in the bulk plasma increases with increasing r_b. The pre-sheath potential drop and sheath thickness are measured from the potential profile curves, which show a gradual pre-sheath potential drop up to the sheath edge and a sharp fall of potential drop from the sheath edge to the plate surface. The sheath edge is obtained from the semi-logarithmic plot of each axial potential profile curves from the intersection of the tangents drawn in the region of sharp fall of potential. The location of the sheath edge in potential profile curve for argon plasma is marked by an arrow in figure 4. The axial distance from the plate to the sheath edge gives the sheath thickness. The difference of plasma potential between bulk plasma and sheath pre-sheath edge gives the pre-sheath potential drop (ϕ_{pre}). The drift velocity of the positive ion u_d can be estimated from the

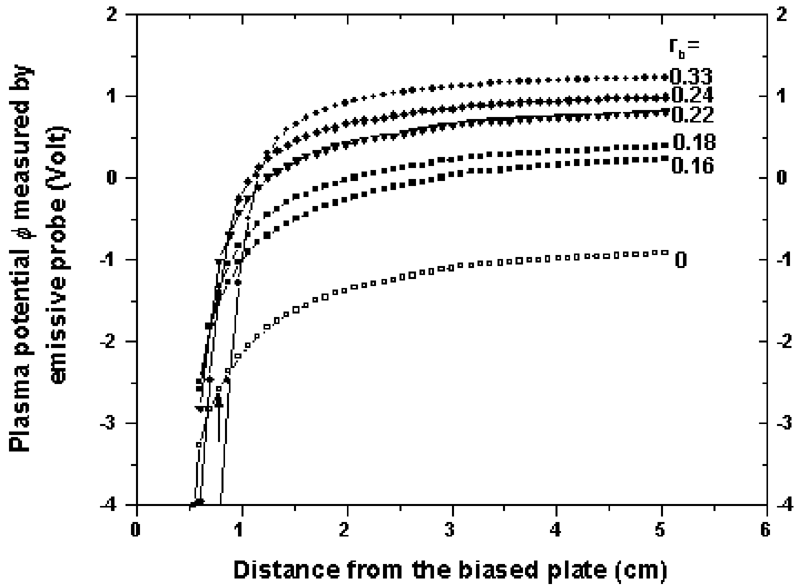

Figure 4. Measured axial plasma potential profiles (by emissive probe E) in front of the metal plate for different negative ion density ratio r_b. The plate biasing voltage V_p is −100 V.

relation $u_d = (2e(\phi_{pre} + T_+)/m_+)^{1/2}$, where m_+ is the mass of the positive ion. In this experiment we set $T_+ = 0.1$ eV and $m_+ = 40$ amu (for argon).

Figure 5 shows the current–voltage characteristics at the plate when the plate biasing voltage is varied below the floating potential for different negative ion density ratio. The plate current takes more negative value when the biasing voltage is more negative. This is due to the expansion of the sheath area which increases the effective ion collection area of the sheath. Therefore, the ion saturation current (I_{is}) at the plate is measured at that point of the current–voltage curve where its slope tends to saturate (as shown in figure 5 by the arrow mark for the curve at $r_b = 0$). The ion saturation current (I_{is}) at the plate is due to the positive ions only and it can be expressed as $I_{is} = (1/4)n_{0+}eu_dS$, where S is the plate area.

Figure 6 shows the measured pre-sheath potential drop (ϕ_{pre}) and sheath thickness (d) (when the plate is biased at $V_p = -100$ V) from the potential profile curve for different negative ion density ratio r_b. The variation of measured ion saturation current at the plate (I_{is}) and positive ion drift velocity (u_d) (calculated from ϕ_{pre}) with r_b are also shown in this figure. The pre-sheath potential drop decreases with negative ion concentration from its maximum value of 1.68 V (at $r_b = 0$) to 0.72 V (at $r_b = 0.33$). In plasma containing negative ions, the effective temperature of the negative charge components will be less than that of the simple two-component plasma. This is due to the fact that the faster electrons are to be replaced by the massive negative ions. From figure 2, it is found that the electron temperature also decreases with negative ion concentration. The required pre-sheath potential drop to form a stable positive ion sheath, decreases when the effective temperature of

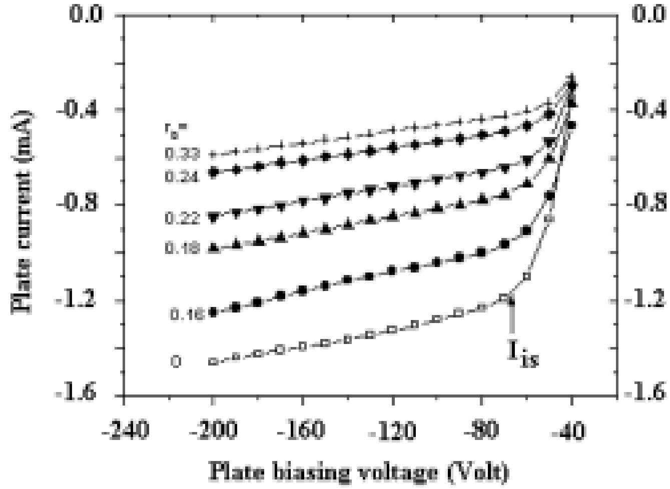

Figure 5. Current–voltage relation at the plate for different negative ion density ratio r_{b}.

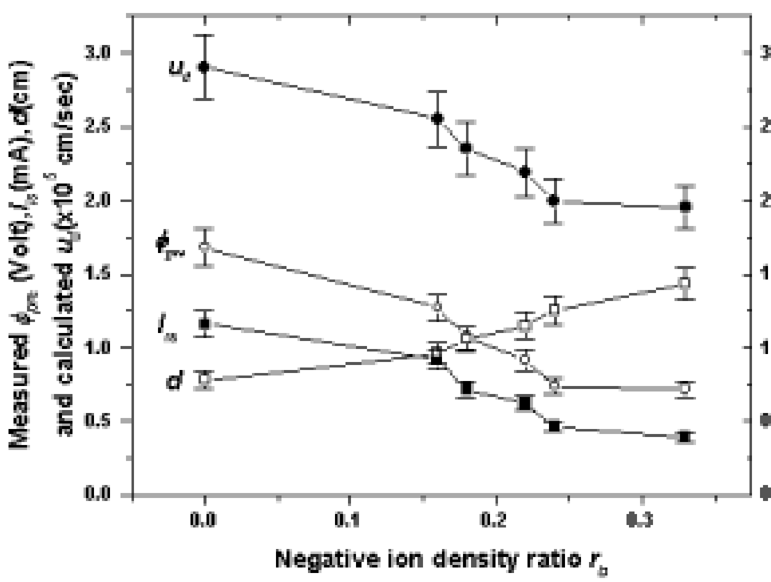

Figure 6. Measured pre-sheath potential drop (ϕ_{pre}), ion saturation current at the plate I_{is}, sheath thickness (d) when the plate is biased at -100 V and positive ion drift velocity (u_{d}) calculated from ϕ_{pre} for different r_{b}.

the negative charge components in plasma is reduced. This is the reason behind the decrement of ϕ_{pre} with r_{b}. The positive ion drift velocity decreases with negative ion concentration as found in figure 6. Since the accelerating potential (ϕ_{pre}) for the positive ions to the sheath decreases with r_{b}, the drift velocity of positive ions

(u_d) decreases. The ion saturation current at the plate (I_{is}) also decreases with r_b. The decrease of u_d and n_{0+} with negative ion concentration results in the decrease of I_{is} with r_b. The measured sheath thickness d is plotted against the negative ion concentration r_b in figure 6. The sheath thickness increases with the increase of negative ion density in the plasma. The increase of sheath thickness d with increasing r_b is due to the decrease of ion flux to the biased plate. Since the positive ion flux to the plate decreases, the space charge density inside the sheath region is also reduced. A higher volume of positive space charge will be required to shield the negative potential of the biased plate from the bulk plasma when the space charge density reduces. So the sheath expands, i.e. d increases with increasing r_b. The increase in sheath thickness d and decrease in positive ion saturation current I_{is} at the plate with negative ion concentration, support the decrease in positive ion drift velocity as well as presheath potential drop.

4. Conclusions

The characteristics of ion sheath under the influence of negative ions have been investigated. With the increase of negative ion concentration, the electron temperature is reduced and the plasma density is found to decrease. As predicted by the theory [2,3], the positive ion drift speed toward the sheath estimated from the experimentally measured pre-sheath potential is found to decrease with increasing negative ion concentration. Decrease in drift velocity and plasma density causes the reduction of ion flux into the sheath. As a result, the space charge density inside the sheath decreases and the sheath expands.

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