ЖЭТФ, 2014, том 146, вып. 2 (8), стр. 368–372

# EFFECT OF COLD ELECTRON EMISSION ON DIFFUSION PLASMA PARAMETERS AND THE SHEATH STRUCTURE IN A DOUBLE PLASMA DEVICE

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Received December 24, 2013

It is observed experimentally that by injecting cold electrons in the discharge region of a double plasma device, the plasma parameters and sheath structure can be controlled in the other region, which is devoid of any electrical discharge. The main discharge region is separated from the region under investigation by a grounded mesh grid. Both cold and hot ionizing electrons are emitted from separate sets of filaments in the discharge region. With an increase in the cold electron emission current, the plasma parameters in the discharge region get changed, which in turn alter the plasma parameters in the other region. Two important effects caused by cold electrons in the diffusion region are the increase in the plasma density and decrease in the plasma potential. The increase in the plasma density and decrease in the sheath potential drop therefore cause the contraction of the sheath.

**DOI**: 10.7868/S0044451014080136

## 1. INTRODUCTION

The plasma produced by a dc discharge has wide applications in basic studies as well as in technology. Normally, the plasma parameters such as the electron temperature and the plasma potential determine the processing performance. The plasma potential determines the bombarding energy of plasma ions in film deposition on a substrate. The decrease in electron temperature is very important in the plasma etching process.

The study of sheath phenomena is very important in understanding the process between plasma and a solid surface because of its practical applications in material processing. The plasma sheath problem in a low-pressure discharge was first presented by Tonks and Langmuir [1]. The explicit formula and a clear interpretation of sheath formation is due to Bohm, who introduced the idea of a pre-sheath, a weak electric field that exists between plasma and the sheath edge [2]. The pre-sheath accelerates the ions to a sufficient velocity known as the Bohm velocity, such that the ion density exceeds the electron density everywhere within the sheath.

Actually, the thickness (width) of the sheath is a concept that can be either determined experimentally or defined theoretically. The thickness of an ion sheath formed at a wall depends on the sheath potential drop and the amount of the ion flux reaching it. The sheath potential drop is the difference between the plasma potential and the applied wall potential. Therefore, any change in plasma parameters such as the plasma potential and density plays a crucial role in the formation of the sheath structure.

The double plasma (DP) device, where weakly ionized plasma is produced by the filament discharge process, has often been used to study the effect of both ion and electron beams on plasma parameters and the sheath structure. An ion or an electron beam injected into the plasma is supposed to alter the electron energy probability function (EEPF) [3, 4].

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In a DP device, both ion and electron beams can be produced by creating a suitable potential difference between the two plasma regions, a source and a target. The effect of a low-energy electron beam on the plasma parameters and the sheath structure was observed in [3]. The authors of [3] observed a contraction of the ion sheath with an increase in the electron beam energy, and also observed that the ion sheath expands in the presence of an ion beam [4].

The changes in plasma parameters and sheath structure due to extraction of charged particles in a DP device were experimentally observed in [5].

In this paper, we inject cold electrons into the discharge region of a DP device to control the plasma parameters and sheath structure in the other region, which is devoid of any electrical discharge. The two regions are separated by a grounded mesh grid of high transparency. The injection voltage or bias voltage applied to the cold electrons is lower than the ionization potential of the gas used.

Previously, many researchers have used cold electrons for many purposes. In [6], the electron temperature was successfully decreased by replacing high-energy electrons with cold electrons emitted from an auxiliary hot electrode. On the other hand, in [7], the electron temperature was increased by injecting cold electrons in a multi-dipole plasma. Fast ions were confined by a negative electrostatic potential produced by cold electron injection in a multi-dipole plasma [8]. Recently, Mishra and Phukan controlled discharge plasma parameters by injecting cold electrons in the diffusion plasma region of a DP device [9].

Here, we successfully controlled the plasma potential and density in a region where no electrical discharge occurs. The cold electrons injected in the discharge region alter the plasma parameters, which in turn affects plasma parameters in the nearby region separated by a grounded mesh grid.

The change in the density and the plasma potential affects the collection current of the plate, and the sheath structure changes as a result. The technique adopted here is free from any geometrical perturbation or any perturbation caused by the external biasing.

## 2. EXPERIMENTAL SETUP

The experiment is carried out in a DP device consisting of two identical cylindrical multi-dipole cage structures 35 cm in length and 25 cm in diameter. These two cages, the source and the target, are electrically isolated from each other. A stainless steel mesh grid 24 cm in diameter is placed between the two cages. To place the grid, magnetic rows are removed from one end of each magnetic cage. Charged particles can move from one plasma region to the other through this grid.

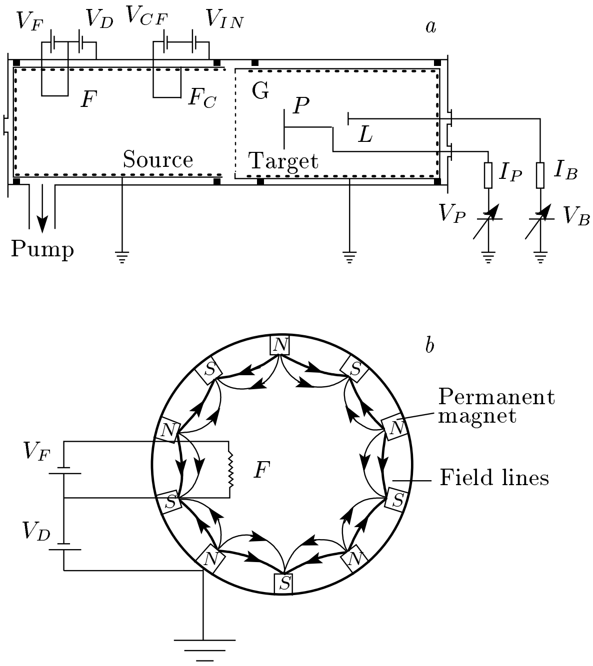

**Fig. 1.** *a*) A sketch of the experimental setup. G is the mesh grid between the source and the target section: $F$ is the filament used for emission of ionizing electrons in the source section and $F_C$ is the filament used for the cold electron injection, $V_F$ and $V_D$ are the ionizing electron emitting filament voltage and the discharge voltage in the source, $V_{CF}$ and $V_{IN}$ are the cold electron emitting filament voltage and the cold electron injection voltage, $L$ is the Langmuir probe, $V_B$ is the probe biasing voltage, $P$ is the stainless steel plate, and $V_P$ is the plate biasing voltage. *b*) The schematic diagram of the surface magnetic cusp field produced by multi-dipole magnets and the location of the filaments inside the magnetic cage

The magnetic cages of both the source and the target are grounded. The separation grid of the device is also grounded because the negative floating potential of the grid would provide a potential barrier to electrons, which may reduce the flow of electrons from the source to the target region. The wires of the grid collect some of the electrons, but due to the high transparency (20 lines per cm) of the grid used in the experiment, most electrons are able to escape through the spacing between the grid wires.

The schematic diagram of the experimental setup is shown in Fig. 1*a*.

A multi-dipole cage is a set of alternating rows of north and south pole permanent magnets placed around the discharge surface in a cylindrical shape. The alternating rows of magnets generate a line cusp magnetic configuration in which the magnetic field strength is maximum near the magnets and decays with the distance to the chamber. Hence, the bulk plasma volume is virtually free of the magnetic field, but a strong field of about 1 kG exists near the chamber wall, inhibiting plasma loss and leading to an increase in plasma density and uniformity. The schematic diagram of the surface magnetic field produced by the multi-dipole magnets and the location of the filaments inside the cage are shown in Fig. 1*b*.

The base pressure of the chamber is $4 \cdot 10^{-6}$ mbar. Plasma is solely produced in the source region by electron bombardment of a neutral Ar gas at $5 \cdot 10^{-4}$ mbar by applying a dc voltage between the hot filament (cathode) and the magnetic cage (anode). There are four filaments ($F$) that emit ionizing electrons and three other filaments ($F_C$) that emits cold electrons in the source region of the device. The electrons emitted from the hot filaments (cathode) ionize the background gas on their way to the anode (magnetic cage).

A negative voltage ($V_{IN} = -12$ V) is applied to the filaments in order to inject cold electrons to the plasma. The applied injection voltage is less than the ionization potential of the gas used (15.8 eV for an argon atom). The emission of cold electron can be increased by increasing the injection current $I_C$. The cold electron emission current $I_C$ is controlled by changing the filament heating voltage $V_{CF}$.

In the source region, the discharge voltage ($V_D$) and the discharge current ($I_D$) are respectively fixed at 50 V and 60 mA.

A plane Langmuir probe $L$ of diameter 4 mm is used to measure the plasma parameters in the target region. The plasma potential is determined as the probe voltage at which the first derivative of the probe characteristics has a maximum [10].

In order to measure the thickness of the ion sheath, a stainless steel plate 5 cm in diameter is inserted in the target region. The plate is placed at the distance of 10 cm from the separation grid. The backside of the plate is covered by an insulating material, such that plate collects charged particles only from the front side. The plate is biased at $V_P = -60$ V to produce an ion sheath, such that even hot electrons having the maximum energy ($E \approx eV_D$) of 50 eV cannot contribute to plate current $I_P$. The thickness of the sheath can be obtained from the Child's law,

$$I_P = \frac{4}{9}\varepsilon_0 A \left(\frac{2e}{m_i}\right)^{1/2} V_P^{3/2} d^{-2}, \qquad (1)$$

where $e$ is the elementary charge, $m_i$ is the ion mass, $\varepsilon_0$ is permittivity of free space, $A$ is the surface area of the plate, $V_P$ is the plate bias voltage, $I_P$ is the plate current, and $d$ is the sheath thickness. The plate current $I_P$ is monitored across a resistance of 1 k$\Omega$.

For measuring the sheath thickness, we have incorporated a change in the plasma potential in Eq. (1). Therefore, considering the sheath potential drop ($V_{TP} - V_P$) in Eq. (1), we can write

$$I_P = \frac{4}{9}\varepsilon_0 A \left(\frac{2e}{m_i}\right)^{1/2} (V_{TP} - V_P)^{3/2} d^{-2}, \qquad (2)$$

where $V_{TP}$ is the plasma potential in the target region.

## 3. RESULTS AND DISCUSSION

Cold electrons are first emitted into the source region and Langmuir probe characterictics are recorded in the target plasma region. The cold electron emission current $I_C$ is increased up to 10 A by increasing the filament heating voltage $V_{CF}$. The cold electron bias voltage is kept fixed at $-12$ V.

It is observed that the target plasma potential ($V_{TP}$) becomes less positive with the increase in $I_C$. The plasma potential is obtained from the first derivative of the probe characteristics. The plasma potential in the target region ($V_{TP}$) is found to decrease from around 4 V to 1 V with the increase in the cold electron emission current $I_C$.

A decrease in the plasma potential due to the injection of cold electrons into the discharge region a multidipole plasma was previously observed [7, 8]. This decrease in the plasma potential serves two purposes: it increases the loss rate of electrons and provides electrostatic confinement to the ions. Because of the decrease in the plasma potential in the source region, some electrons can escape through the spacing of the grounded mesh grid to the target region. Due to the high transparency of the grid (20 lines/cm), most of them enter the target region and some can be collected by grid wires. On entering the target region, these electrons lower the target plasma potential $V_{TP}$.

It is observed that the plasma density in the target region increases with the increase in $I_C$. The observed increase in plasma density in the target can be attributed to the increase in plasma density in the source region. The plasma diffuses from the higher-density region to the lower-density region.

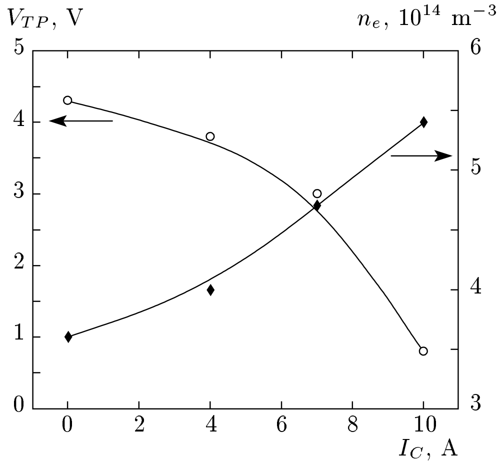

**Fig. 2.** Variation of the plasma density $n_e$ and the plasma potential $V_{TP}$ in the target region with an increase in $I_C$

In the source region, the plasma density increases due to the reduction in ion loss through the magnetic cusp [7, 8] or, in other words, for better ion confinement provided by the negative potential well [8]. Initially, the target region has a very low electron density (being devoid of any discharge). With the increase in the source plasma density, the plasma easily leaks through the mesh grid and enhances the target plasma density.

The increase in plasma density and decrease in plasma potential in the target region with the increase in the cold electron injection current are shown in Fig. 2.

In general, the plasma density is determined by a balance between plasma production and diffusion loss in a low-density plasma as in the target region [11]. Since the diffusion coefficient decreases with the electron temperature, the density is enhanced by the decrease in the electron temperature in the target region.

The decrease in the plasma electron temperature is indicated by the electron energy probability function obtained from the probe characteristics. The second derivative of the probe characteristics ($d^2I/dV^2$), which is proportional to the EEPFs [12, 13], is shown in Fig. 3 for three different values of $I_C$. Along the $x$ axis, the difference between the target plasma potential $V_{TP}$ and the probe bias voltage $V_B$ is plotted, which is again proportional to the electron energy ($T_e$) in the retarding field region of the probe characteristics. The distributions shift toward the left (lower-energy side), indicating the decrease in the plasma electron temperature as the cold electron emission current is increased. The variation of the plasma electron temperature obtained from the probe characteristics for three different

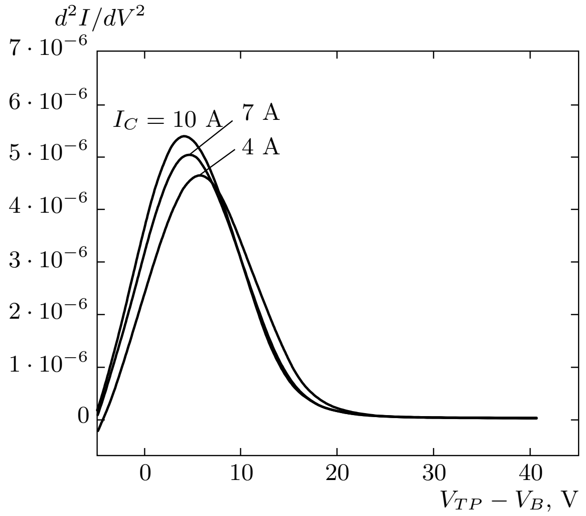

**Fig. 3.** The second derivative of the probe characteristics (EEPF) recorded in the target region for different $I_C$

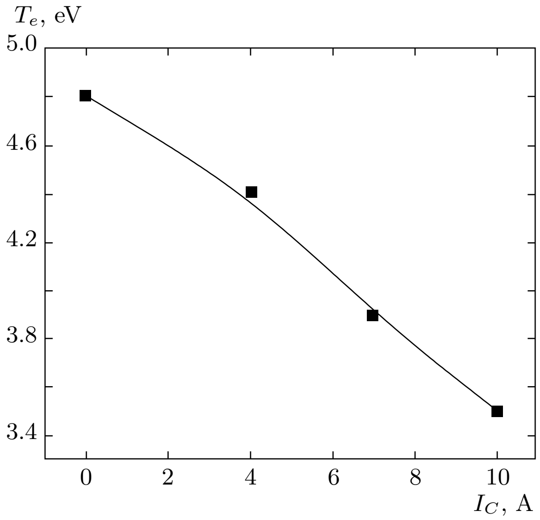

**Fig. 4.** Variation of the plasma electron temperature $T_e$ for different $I_C$ in the target plasma region

values of $I_C$ is shown in Fig. 4. It is seen that except for the electron temperature, other plasma parameters such as density and plasma potential in the diffusion region vary in a way similar to their variation in the discharge region, as reported in [7, 8].

Figure 5 shows the variation of the plate current ($I_P$) with $I_C$. The plate current increases with the increase in $I_C$. The observed increase in the plate current and the corresponding decrease in the sheath thickness can be attributed to the increase in the plasma density.

But at the same time, the effect of the plasma potential on the sheath structure has to be taken into

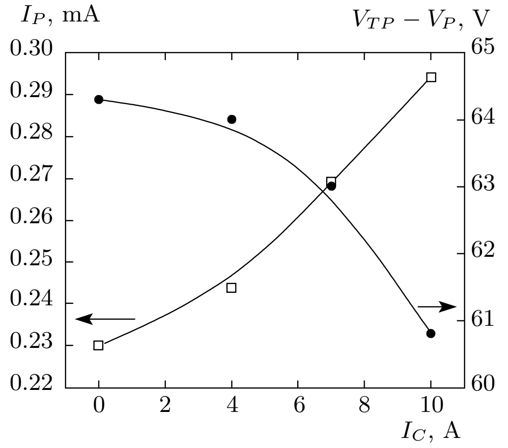

**Fig. 5.** Variation of the plate current $I_P$ and the sheath potential drop $V_{TP} - V_P$ for different $I_C$

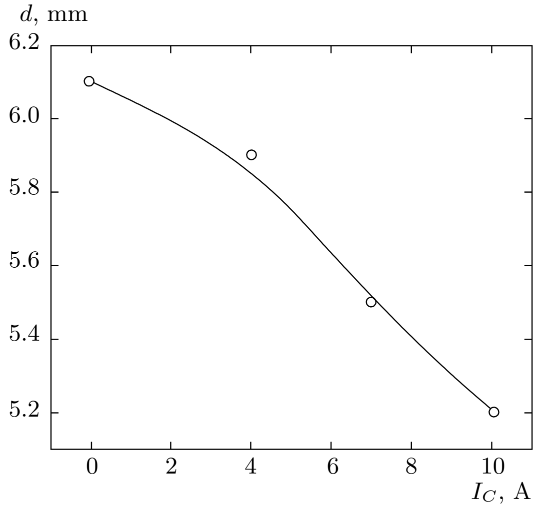

**Fig. 6.** Variation of the estimated sheath thickness $d$ for different $I_C$

account. Due to the decrease in the plasma potential, the sheath potential drop, which is the difference between the plasma potential and the applied plate bias voltage ($V_{TP} - V_P$), also decreases. This decrease in the sheath potential drop leads to the contraction of the sheath. The variation of the sheath potential drop ($V_{TP} - V_P$) is plotted with $I_C$ in Fig. 5.

Therefore, both the increase in plasma density and the decrease in sheath potential drop lead to a contraction of the ion sheath. The variation of the estimated sheath thickness $d$ using relation (2) is plotted for $I_C$ in Fig. 6.

## 4. CONCLUSIONS

The important plasma parameters such as the density and plasma potential are successfully controlled in a region separated from the discharge region by cold electron emission. The cold electrons first change the discharge plasma parameters, which in turn alters the plasma parameters in the diffusion region. The increase in plasma density and the decrease in the sheath potential drop lead to a decrease in the sheath size. All the plasma parameters that have been controlled here are important from the standpoint of different application. Control of the plasma potential and sheath thickness are very important for material processing assisted by plasma such as thin film deposition. The bombarding energy of ions on a substrate depends on both the plasma potential and the positive space charge layer formed in front of the substrate. Our present technique may be helpful in controlling these parameters in weakly ionized plasmas.

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