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Variation of plasma parameters in a modified mode of plasma production in a double plasma device

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Abstract. A modified mode of plasma production in a double plasma device is presented and plasma parameters are controlled in this configuration. Here plasma is produced by applying a discharge voltage between the hot filaments in the source (cathode) and the target magnetic cage (anode) of the device. In this configuration, the hot electron emitting filaments are present only in the source and the magnetic cage of this is kept at a negative bias such that due to the repulsion of the cage bias, the primary electrons can go to the grounded target and produce plasma there. The plasma parameters can be controlled by varying the voltages applied to the source magnetic cage and the separation grid of the device.

Keywords. Plasma parameters; double plasma device; filament discharge; multidipole magnetic cage.

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1. Introduction

DC discharges have been widely used in basic plasma studies as well as in material processing applications. In a double plasma (DP) device, a quiescent and unmagnetized DC plasma can be produced using the multidipole principle [1]. Multidipole devices can be operated at neutral pressures that are several orders of magnitude lower than in conventional discharge devices. Source characteristics such as parametric dependencies of plasma parameters like density, electron temperature, neutral pressure, cusp magnetic field geometry, plasma potential etc. have been the subjects of many investigations [2]. A DP device consists of a source and a target which are separated by a mesh grid. Primary electrons are the chief source of plasma generation in these types of devices. The primary electrons are emitted by the hot filaments (cathode) and on their way to the cage (anode), they ionize the background gas.

In this paper, we have used a modified configuration for plasma production in a DP device, where the plasma parameters are varied by changing source magnetic cage bias voltage and separation grid bias. Here the hot filaments are placed only in the source and there are no filaments in the target. Plasma is produced by applying a discharge voltage between the electron-emitting filaments in the source (source side filaments) and the grounded target magnetic cage, while keeping the source magnetic cage at a negative potential relative to the target chamber. Due to the negative potential of the source magnetic cage, the highly energetic primary electrons of the source are directed towards the target after penetrating the grid and cause ionization of the gas molecules. This mode of plasma production is similar to the plasma produced by an electron beam. Studies on electron-beam-excited plasma discharges also reveal that the thermal beam component has a significant role in determining process conditions [3–5]. Normally, the plasma parameters determine the processing performance; hence the control of the parameters is essential to have an optimum result. The control of plasma potential and electron temperature in weakly ionized plasma is of much importance in many plasma-based applications such as plasma etching [6]. Also the plasma parameters like electron temperature and density are essential to study dependencies of different particle elementary processes and plasma collective phenomena in weakly ionized plasmas [7]. Different techniques have been employed to control plasma potentials and plasma electron temperature.

Biased grids are most commonly used in controlling plasma parameters. Kato *et al* [7,8] performed experiments on controlling the electron temperature on plasmas passing through a mesh grid from a discharge region. Recently, they have showed that the grid bias method can be used for temperature control, even if the conductivity of the grid is reduced by the deposition of a dielectric diamond-like carbon film [9]. Bai *et al* also used mesh grid to control the electron temperature in the diffuse region of an inductively coupled plasma [10–12]. Recently, we have used a negatively biased grid to control the energy of both high and low energy electron species in the diffuse plasma region of a double plasma device [13]. Hershkowitz *et al* [14] adopted a mechanical method to vary the plasma potential and electron temperature in an RF glow discharge plasma. Phukan *et al* also applied a similar technique to control plasma parameters in a region separated from the main discharge region that is in the diffused plasma region, where plasma is produced by hot filament discharge and confined by a multidipole magnetic cage system [15]. In the present work, we have applied variable negative potentials to the source magnetic cage and positive biases to the separation grid in order to vary the plasma parameters in the target of the device.

The primary electron flux coming from the source to the target can be increased by applying more negative potential to the source magnetic cage, to increase the plasma density in the target of the device. Consequently, other plasma parameters like electron temperature and plasma potential will also be varied as they strongly depend on plasma density.

To get an opposite trend of plasma parameter variations under such a configuration, we have applied low positive voltages to the separation grid. The use of a highly positive biased grid as a second anode for an enhancement in electron temperature and plasma potential was used earlier by MacKenzie *et al* [16] in a different configuration of the DP device. In our case, the observed changes in the plasma parameters are occurred due to the increase in the electron diffusion loss to the positively biased separation grid.

In this scheme of plasma production, the plasma is not a diffused one. Here the plasma is produced in the target by extracting high energy electrons from the source side filaments to the grounded target magnetic cage by applying a retarding potential (to the electrons) to the source magnetic cage. So the plasma parameters are controlled in a region which has one order more plasma density than that of the diffused plasma region.

2. Experimental configuration

The experiment is carried out in a DP-device consisting of two identical cylindrical cage structures of 35 cm length and 25 cm diameter, which are made up of vacuum-sealed rectangular tubes containing small permanent magnets for surface plasma confinement. The two cage structures are electrically isolated from each other. A stainless steel grid of 80% transparency separates the device into two regions. A schematic diagram of the experimental set-up is shown in figure 1a. The schematic diagram of the surface magnetic cusp field produced by multidipole magnets and the location of the filaments inside the source magnetic cage are shown in figure 1b.

The base pressure of the chamber is 4×10^{-6} mbar. Hot electron-emitting filaments (cathode) are placed inside the source magnetic cage. No filaments are placed in the target region. The plasma is produced by electron bombardment of neutral argon gas at 5×10^{-4} mbar pressure by applying a DC voltage between the hot filament (cathode) and target magnetic cage (anode) while keeping the source magnetic cage bias at a negative potential below its floating potential. Electrons emitted from the hot filaments (cathode) in the source ionize the background gas on their way to the anode (target magnetic cage). The discharge voltage (V_{D}) and the discharge current (I_{D}) are fixed at 60 V and 80 mA respectively. A plane Langmuir probe (4 mm in diameter) is placed in the magnetic field-free central region of the target chamber to measure the plasma parameters. The measured electron plasma density is around 10^{16} m^{-3}. The plasma potential is measured from the maximum in the first derivative of the probe characteristics [15,17–19].

3. Results and discussions

3.1 *Effect of source magnetic cage bias* (V_{S})

At first a negative potential (V_{S}) less than the floating potential (≈ -35 V) of the source magnetic cage is applied to the source magnetic cage by keeping the separation grid floating. It is observed that the target plasma density increases with a fall in plasma electron temperature when V_{S} is decreased towards negative. This is shown in figure 2. The electrons emitted from the source side filaments may be lost in the magnetic cusps and into the grid (mainly the low energy electrons) and the high energy electrons will be accelerated to the target through the separation grid. Due to the application of a negative bias to the source magnetic cage, the effective discharge voltage in the source decreases and hence the plasma is appeared mainly

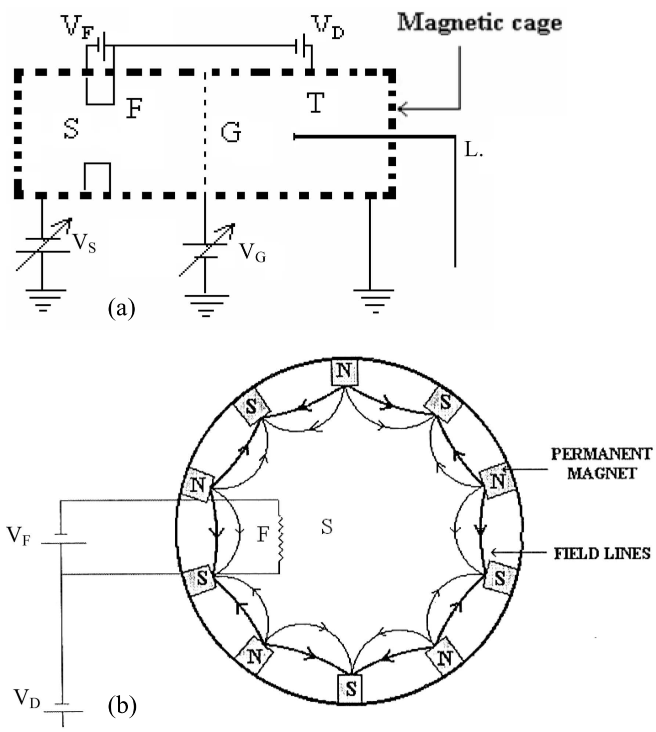

Figure 1. (**a**) Schematic diagram of the experimental set-up, where S and T represent the source and the target of the device. V_{F}, V_{D} and F represent the filament voltage, the discharge voltage and the filament respectively. V_{S} and V_{G} represent the source cage bias and the grid bias respectively. L is the Langmuir probe and G is the separation grid of the device. (**b**) The schematic diagram of the surface magnetic cusp field produced by the multi-dipole magnets and the location of the filaments inside the source magnetic cage.

in the grounded target. Also applying a voltage more negative than the floating potential of the source magnetic cage will reduce the loss of electrons to the surface of the cage; as a result electron flux from the source to the target will increase. The enhanced electron flux in the target will cause more ionizing collisions and as a result plasma density increases in the target.

The decrease in plasma electron temperature in the target may be due to the decrease in the plasma potential (as shown in figure 3) of the target when more high-energy electron flux enters the target or due to the decrease in the electron diffusion from the target region because of the increase in plasma density. That is, the electron diffusion from the target to the source will become lower because of the repulsive potential applied to the source magnetic cage. The rate of plasma diffusion is proportional to the square root of the electron temperature [7,15]. Thus, the observed lowering of plasma electron temperature may be attributed to the decrease in the plasma diffusion from the target.

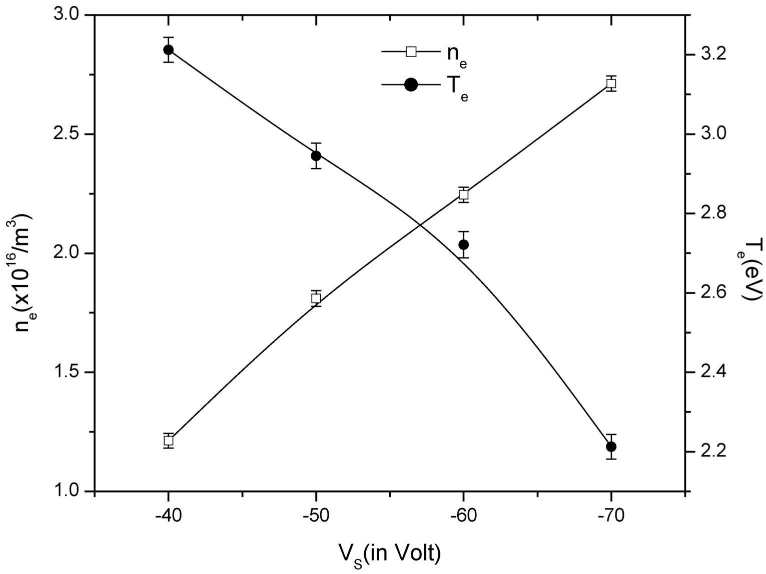

Figure 2. Variation in the plasma density (n_e) and the electron temperature (T_e) with the source anode cage bias (V_S).

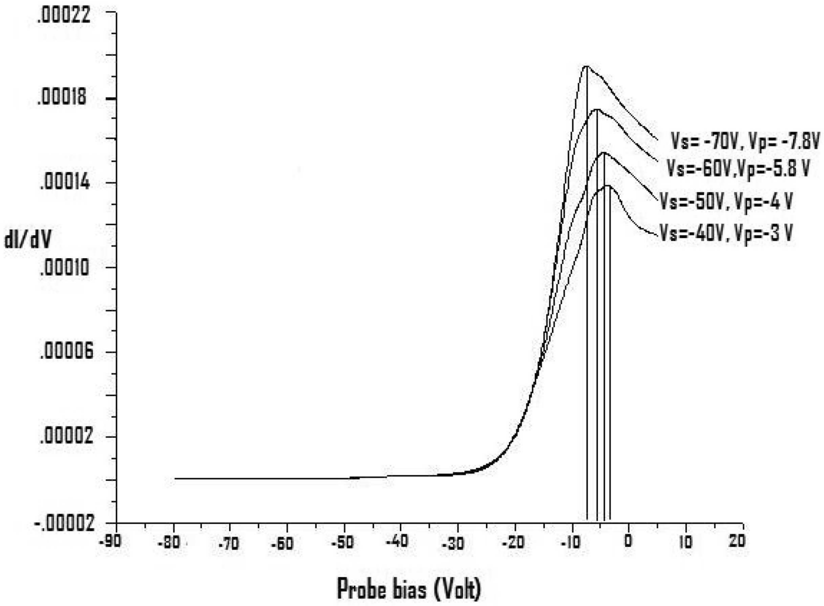

Figure 3. First derivative of the probe characteristics showing variation in the target plasma potential (V_P) as a function of source anode cage bias (V_S). The maxima in these curves give the plasma potential.

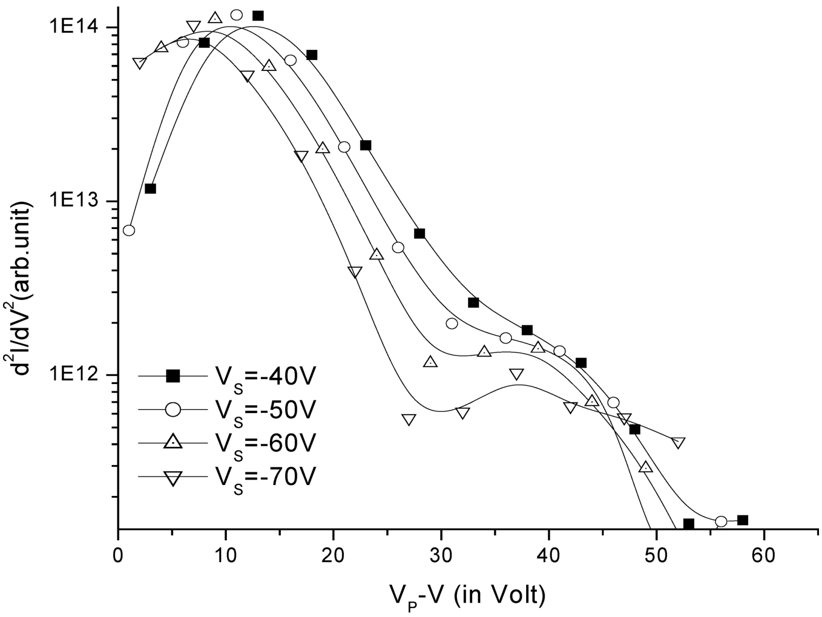

Figure 4. The double derivative of the probe characteristics (which is proportional to the EEPF) is plotted for different V_S. Along x-axis, $V_P - V$ (which is proportional to the electron energy in the retarding portion of the probe characteristics) is plotted.

Figure 3 shows the variations of the plasma potential as obtained from the maximum of the first derivative of Langmuir probe characteristics. It is observed that the plasma potential of the target decreases to a more negative value with the increase in the negative bias (V_S) applied to the source magnetic cage. As the electron flux from the source to the target increases, the bulk plasma region in the target becomes electron-rich and hence the plasma potential becomes more negative. The negative plasma potential repels (retard) the plasma electrons towards the bulk plasma region and accelerate the ions, hence the electrons loss their energy and the plasma electron temperature decreases. Pal *et al* [20] have shown that the plasma potential decreases to a more negative value when an electron beam is injected into the target by applying a negative bias to the source magnetic cage.

The double derivative of the Langmuir probe characteristics ($\mathrm{d}^2I/\mathrm{d}V^2$), which is proportional to the electron energy probability function (EEPF) [19,21] is shown in figure 4 for different V_S. Along the x-axis, the difference between the plasma potential (V_P) and the corresponding probe bias (V) is plotted, which is also proportional to the electron energy in the retarding field region of the probe characteristics. In our working pressure range of $\approx 10^{-4}$ mbar, the primary and the plasma electrons exhibit Maxwellian distribution [22] as shown by these EEPFs, but a bump-like structure appears in the high energy tail of the distribution. This bump-like structure is a clear deviation from the Maxwellian nature and is an indication of a high energy electron beam formed in the system. Bai *et al* [12] have also observed a similar kind of bump structure in the high energy range of the EEPF at a working

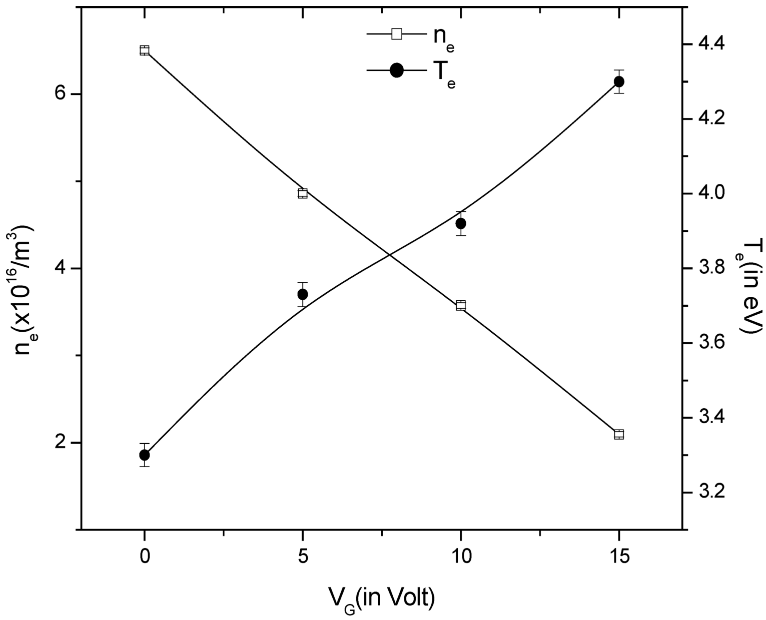

Figure 5. Variation in the plasma density (n_{e}) and the electron temperature (T_{e}) with the separation grid bias (V_{G}).

pressure of 0.67 Pa (5×10^{-3} mbar) and they put forward an argument in support of the observed 'bump' structures on the basis of electron–electron collision frequencies.

3.2 *Effect of the grid bias* (V_{G})

To have an inverse effect on the plasma parameters, the grid is biased positively by keeping the source magnetic cage fixed at −40 V. Initially the grid is kept at the ground potential and then the grid bias (V_{G}) is slowly varied positively. The variation of the plasma electron density and temperature with the positive grid bias is shown in figure 5. The grid absorbs some of the low energy primary electrons coming from the source and as a result the electron flux in the target decreases when the grid bias increases. Still, some high-energy primary electrons from the source are able to pass to the target and these electrons can make ionizing collisions in the target and produces a plasma there.

The observed decrease of the target plasma density with V_{G} is mainly due to the increase in the loss rate of electrons to the positively biased grid. In other words, the plasma electron diffusion increases when the grid bias increases. The increase in the plasma electron temperature may be either due to the increase in the plasma potential or due to more electron diffusion from the bulk plasma region. The plasma electrons are accelerated towards the grid because of the positive potential applied to the grid. So the effective plasma electron temperature increases as they

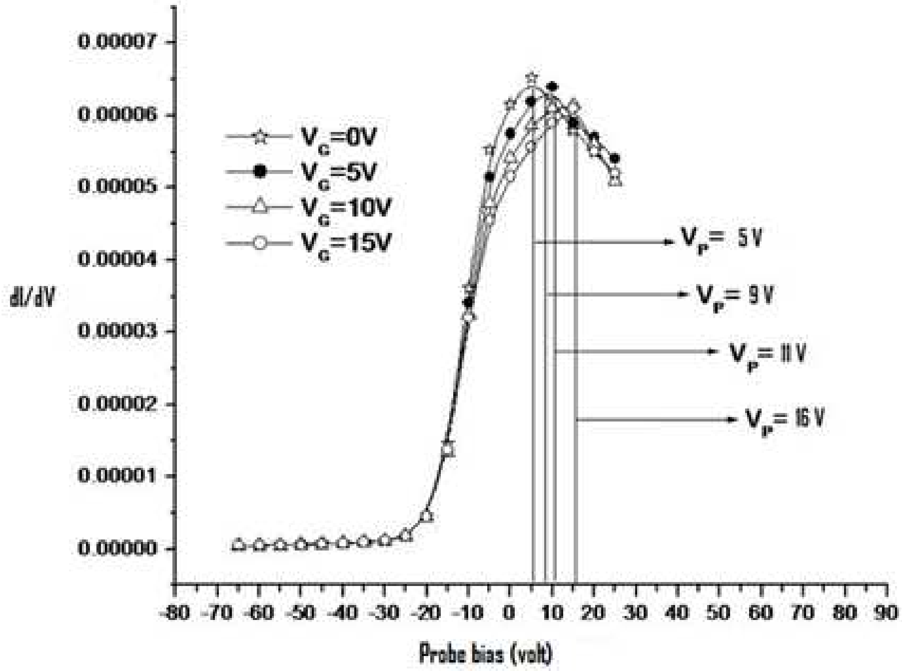

Figure 6. First derivative of the probe characteristics showing variation in the target plasma potential (V_P) for different grid bias (V_G). The maxima in these curves give the plasma potential.

gain energy from the grid electric field. Also in this case more number of electrons diffuse out from the target region as the positive bias on the grid increases and as a result there will be an increase in electron temperature [7,15]. Very low positive potential is applied to the separation grid as excess drainage of electron current may cause plasma perturbations.

The plasma potential as obtained from the first derivative of the probe characteristics, increases with the increase in positive grid bias as shown in figure 6. As the grid bias increases positively, more plasma electrons are pulled towards the grid and so the plasma raises its potential in order to retain these electrons and to increase the ion escape rate from the plasma so that quasineutrality is maintained in the plasma. Moreover, in order to trap the electrons effectively, the plasma potential must be approximately equal to the electron thermal energy ($\approx T_e$) [23,24]. It is also evident from the figure that the plasma potential is more positive than the grid bias voltage.

The double derivative of Langmuir probe characteristics (d^2I/dV^2) for different V_G plotted against $V_P - V$ is shown in figure 7. The curves demonstrate the Maxwellian distribution of the electrons. The distributions shifted towards the high energy side signify the rise in the plasma electron energy as the grid bias increases.

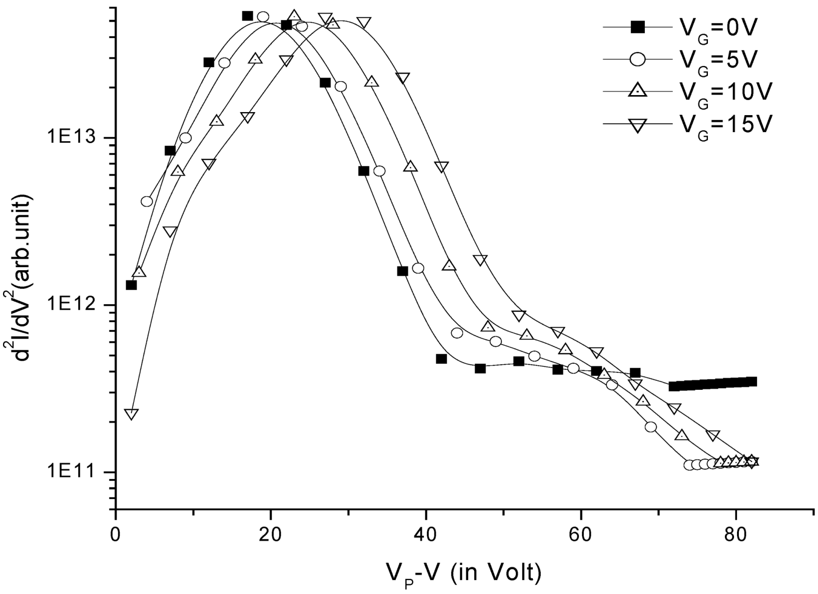

Figure 7. The double derivative of the probe characteristics (which is proportional to the EEPF) is plotted for different V_{G}. Along x-axis, $V_{\mathrm{P}} - V$ (which is proportional to the electron energy in the retarding portion of the probe characteristics) is plotted.

A typical I–V characteristics illustrating the changes in the plasma potential (V_{P}) from negative to positive values, when the floating grid changes to a positively biased one ($V_{\mathrm{G}} = 5$ V) is shown in figure 8. The source magnetic cage bias (V_{S}) is kept at -40 V for both cases. In the floating condition of the grid, more energetic electrons can come to the target section and hence there will be more ionizations and so more plasma electrons can contribute to the probe current. The plasma potentials are measured from $\mathrm{d}I/\mathrm{d}V$ (shown in figures 3 and 6), because of the absence of a sharp knee at the plasma potential in the probe traces.

4. Conclusion

In conclusion, a new modified mode of plasma production using a double plasma (DP) device is presented, which is free from any direct perturbations caused by the presence of electron emitting hot filaments. So more stable and noise-free quiescent plasmas may be produced by using such a configuration of the DP device. This configuration of plasma production has a relevance to the electron-beam-generated plasmas. In this configuration, the plasma parameters are controlled by varying the potentials applied to the source magnetic cage and the separation grid of the device.

In the present experiment, a DC discharge plasma is created in a region separated from the main electron emitting region by a mesh grid. The plasma is observed

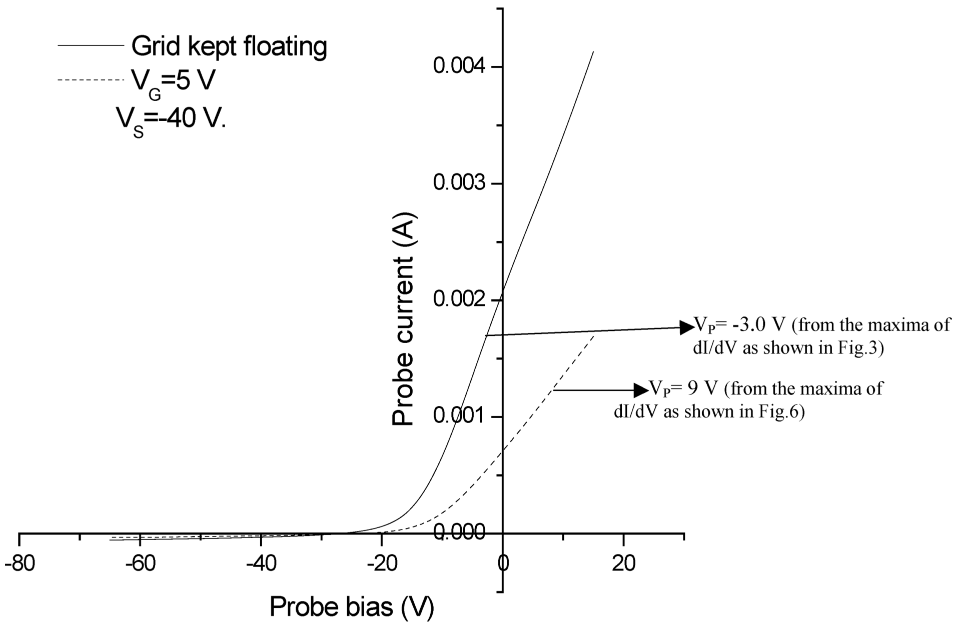

Figure 8. A typical probe I–V taken in the target of the device for a floating grid and a positively biased grid ($V_G = 5$ V) is shown. The source magnetic cage bias ($V_S = -40$ V) is kept fixed for the two cases.

mainly in the target region, which is devoid of any direct electron source. The plasma where the parameters are controlled is not the diffused one, rather here the plasma is produced in the target of the device by retarding the energetic electrons from the source by applying a negative potential to the source magnetic cage.

The electron temperature can be made to decrease with a rise in plasma density (when more primary electron fluxes are allowed to penetrate into the target) by increasing the negative bias of the source magnetic cage. The EEPFs exhibit Maxwellian distribution with 'bump'-like structures appearing in the high-energy tail. The origin of these bump-like structures in our plasma production configuration may be due to an electron beam formed in the system. On the other hand, to increase the plasma electron temperature, the separation grid is biased positively. Due to more diffusion loss of the plasma electrons to the positively biased grid, there occurs a fall in plasma density along with a rise in plasma potential. The observed EEPFs are Maxwellian and shifted towards the high energy side as the grid bias increases. Though we have presented the observations only for 5×10^{-4} mbar pressure, the same trend of parameter variations have also been observed for 1×10^{-4} mbar and 9×10^{-4} mbar pressures, in a range where the multidipole devices are often operated.

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