Eur. Phys. J. D **46**, 303–306 (2008)
DOI: 10.1140/epjd/e2007-00316-1

THE EUROPEAN PHYSICAL JOURNAL D

Growth of electron energies with ion beam injection in a double plasma device

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Received 6 July 2007 / Received in final form 10 September 2007
Published online 23 November 2007 –

Abstract. This paper reports about the observed energy growth of both high and low energetic electron species in the target plasma region with the increase in plasma potential in the source region of a double plasma device. This situation can be correlated to the injection of an ion beam from source to target plasma region. Plasma is solely produced in the source region and a low-density diffuse plasma is generated in the target region by local ionization between the neutral gas and the high energetic electrons coming from the source region. The growth of electron energy is accompanied by a decrease in diffuse plasma density. It is observed that although energy of high energetic group increases with the injected beam energy, the diffuse plasma density falls due to their decreasing population.

PACS. 52.25.Jm Ionization of plasmas – 52.70.-m Plasma diagnostic techniques and instrumentation – 52.80.-s Electric discharges

1 Introduction

Generally, an ion or an electron beam injected in plasma plays a significant role in modifying the plasma parameters. Among the plasma parameters, the electron temperature is the most important parameter, which has to be controlled in a suitable manner for bringing about the desired changes in material processing. Usually grids are most commonly used to control electron temperature in the diffuse plasma region. Kato used a grid as well as slits of varying sizes to control the electron temperature in weakly ionized plasma [1,2]. Bai et al. also used a mesh grid to control electron temperature in the diffuse region of inductively coupled plasma (ICP) [3–5]. Recently, we have used a negatively biased grid to control energy of both high and low energetic electron species in the diffuse plasma region of a DP-device [6].

In a double plasma (DP) device lots of experiments related to low energy beams have been done till date [7–10]. In a DP device, a low energy ion beam can be injected by increasing the plasma potential in the source region with respect to the plasma potential in the target region. To achieve this, anode of the source plasma is biased positively with respect to the grounded anode of the target plasma. Source plasma always floats above the anode potential, a few times T_e/e more positive than the anode bias, establishing a weak sheath that limits the electron loss at the anode. The separation grid of the device is kept at negative potential in order to accelerate the ions and to cut out the low energy electrons from entering the diffuse region from the discharge region. The injected ion beam energy depends almost linearly on the applied anode bias voltage [11,12]. It is also reported that an injected ion beam changes the background plasma potential [13].

Whenever plasma is produced solely in the source region of a DP-device, low-density diffuse plasma is always observed in the target region. In the diffuse region, main plasma creation factor is the electron flux from the main discharge region. The amount of electron flux entering the diffuse region from the discharge region depends on the potential barrier between the plasma potential in the source region and the grid bias voltage [3].

The potential barrier $[e\Delta\Phi_{SP,G} = e(\Phi_{SP} - \Phi_G)]$ for electrons can be increased either by increasing the plasma potential in the source region (Φ_{SP}) or by increasing the negative grid bias voltage (Φ_G). Thus the amount of electron flux coming from source plasma to target plasma through the grid can be reduced either by increasing the source plasma potential or by increasing the negative bias applied to the grid.

When plasma potential in the source region is increased with respect to the plasma potential in the target region, the potential barrier for electrons increases. So only those electrons whose energy is higher than the potential barrier can enter the target region but such a high-energy electron population is very low. These electrons after crossing the grid may get further accelerated by the target plasma potential [4]. In this situation, an ion beam enters the target region (diffuse region) from the source region (discharge region).

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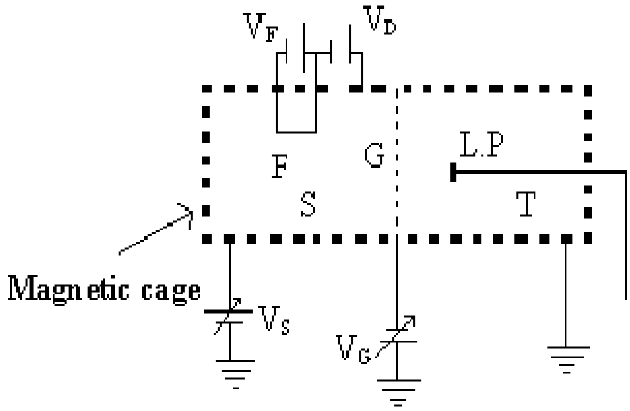
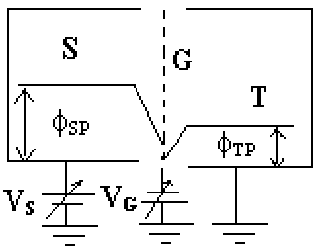


(a)



(b)

Fig. 1. (a) A sketch of the experimental set-up. S and T represent Source and Target region, G is the separation grid. LP is the Langmuir probe. The filament (F) is the cathode and the magnetic cage is the anode. V_D, V_F, V_S and V_G are the discharge voltage, filament voltage, source anode bias and separation grid bias voltage respectively. (b) Scheme of the potentials at source and target plasma for the ion beam generation. ϕ_{SP} is source plasma potential and ϕ_{TP} is target plasma potential.

Here, we have injected ion beams of different energies from the discharge region to the diffused plasma region and observed the energy growth of both high and low energetic electrons. It is also observed that the diffuse plasma density falls with the injected ion beam energy.

It has been mentioned by Oertl and Skoelv that in intermediate pressure range of around 10^{-4} mbar or above, the total electron distribution is consists of three Maxwellian namely high-energy group, intermediate-energy group and lowest energy group [14]. The high energetic group is the ionizing (primary) electrons, intermediate energy group may be those primaries, which have lost most of their energy due to collisions and lowest energetic electrons (plasma electrons) are produced by the ionization; they are born in pairs with ions, since the ions are singly charged. Here, we call both intermediate and lowest energy group as the low energy group as we have not differentiated in between these two groups due to their low energy span. Recently, Pilling and Carnegie have similarly considered dual electron distribution in their experiment [15]. In the present investigation, we have estimated the energy of high-energy group (T_{he}) and low-energy group (T_{le}) in the diffuse region using the slope method [6,14].

2 Experimental set-up

The experiment is carried out in a DP-device that consists of two identical cylindrical cage structures of length 35 cm and diameter 25 cm, 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 schematic diagram of the experimental set-up is shown in Figure 1a.

The base pressure of the chamber is 4×10^{-6} mbar. Plasma is solely produced in the source region by electron bombardment of neutral argon gas at 5×10^{-4} mbar applying a dc voltage between hot filament (cathode) and magnetic cage (anode). Electrons emitted from the hot filaments (cathode) ionize the background gas on their way to the anode (magnetic cage). The discharge voltage (V_D) and the discharge current (I_D) are fixed at 50 V and 30 mA respectively. A plane Langmuir probe of 4 mm in diameter is used to measure the diffuse plasma parameters. The measured diffuse electron plasma density is around $10^{15}\,\mathrm{m}^{-3}$. The plasma potential is determined as the probe voltage at which the first derivative of Langmuir probe characteristic has a maximum [16]. No plasma is produced inside the target plasma region and so no primary electrons are generated in this part. A negative voltage of –40 V is applied to the separation grid in order to accelerate the ions and to repel most of the low energetic electrons.

The plasma potential in the source region is increased with respect to the plasma potential in the target region by biasing the anode of the source plasma positively by a dc potential (V_S) with respect to the grounded anode of the target plasma. In this situation a stationary ion beam moves from source to target plasma region through the negatively biased grid. The energy of the injected beam can be externally controlled by changing the applied potential V_S. A schematic diagram of the potential structure in the plasma system is shown in Figure 1b.

3 Results and discussions

Langmuir probe characteristics are taken in the target region for $V_S = 10$ V, 20 V, 30 V and 40 V respectively. The electron distribution should be non-vanishing at least up to energies corresponding to the discharge voltage V_D. To collect the ion saturation current, the probe is biased at much lower voltage (V_P) than the discharge voltage in the main discharge region, so that the probe eventually does not collect any electron current beyond that voltage range. It is observed that ion saturation current at the probe decreases with the increase in source anode bias voltage V_S. Figure 2 shows the application of the ln I-V plot method to the probe data from which the electron temperatures

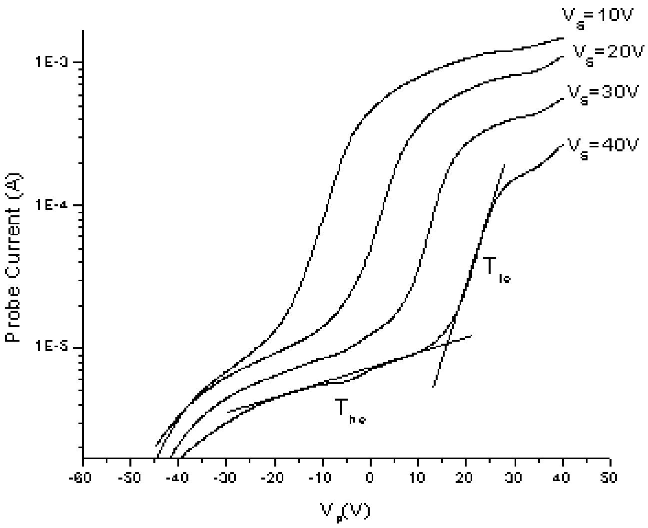


Fig. 2. A semi log plot of the probe characteristics taken in the target region for different applied source anode bias (V_S) and at a fixed grid bias of –40 V. The plot shows the high (T_{he}) and low (T_{le}) temperature nature of electrons.

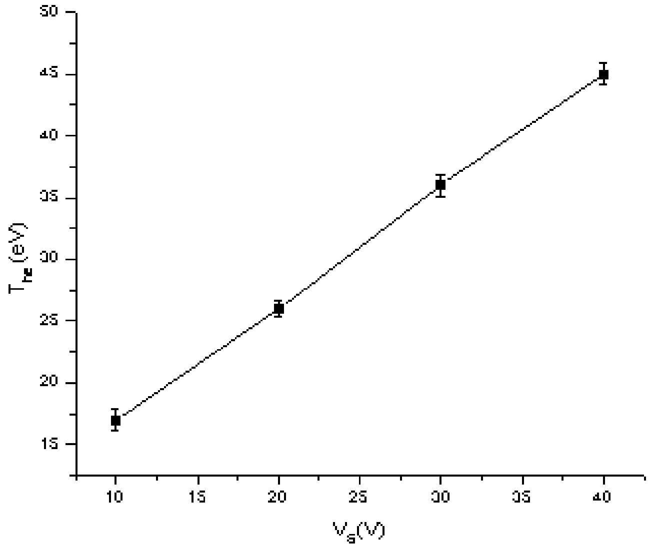


Fig. 3. Variation of effective temperature of high-energetic electron group (T_{he}) in eV with different source biasing voltage (V_S) in the target region at a fixed grid bias of –40 V.

can be obtained after the ion current component is removed by the method of extrapolation [14,15]. Two distributions of electrons can be seen in the plot, where the density of the high-energy distribution is much lower than that of low temperature electrons. The electrons therefore have a dual temperature distribution. The inverse of the slope of the straight portion above the floating potential gave the energy of low energetic electrons (T_{le}) and a similar method applied below the floating potential yielded the energy of high energetic species (T_{he}) [6,14]. The estimated temperature may have an associated error arising from the uncertainty in the slope of the straight lines as shown in Figure 2.

The estimated energy variation of high energetic electrons in the diffuse region with the increase in V_S is shown in Figure 3. From the slope method, it is found that the energy of high energetic electron group (T_{he}) increases in the diffused region with the increase in source anode bias voltage V_S. We think that this effect is due to those few electrons, which have enough energy to over come the potential barrier $e\Delta\Phi_{SP,G}$.

Figure 4 shows the diffuse plasma potential at different V_S obtained from the first derivative of the Langmuir probe characteristics. The shift in the peak position with a decrease in height towards the right signifies the rise in plasma potential with a fall in the bulk electron density. The plasma potential varies almost monotonically with the applied V_S. The diffuse plasma density estimated from the ion saturation current of the probe shows a decrease with the increase in source anode bias voltage V_S. The observed decrease in diffuse plasma density is due to the fact that only those electrons can enter the diffuse region which have enough energy to over come the potential barrier, but such a high energy electron population is not high (i.e. electron flux from source to target decreases), so as a

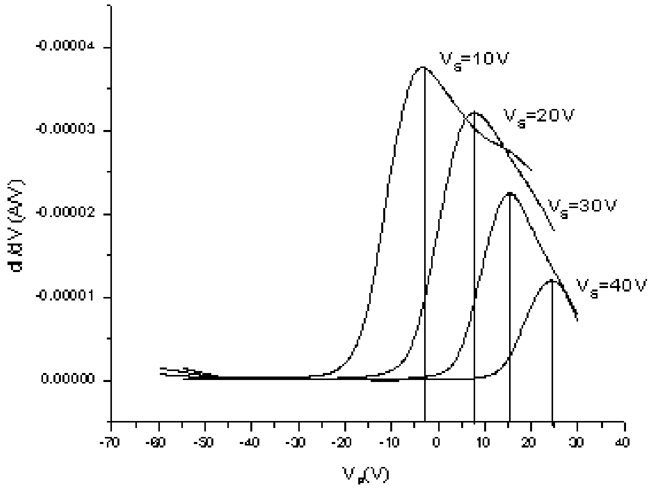


Fig. 4. First derivatives of probe characteristics at different source biasing voltages V_S. Abscissas of the maximums of the derivative curves correspond to the target plasma potential at the particular V_S.

result there occurs less number of ionizing collisions and hence the plasma density falls. That is shown in Figure 5.

The lowering of diffuse plasma density can also be interpreted from the balance between plasma production and diffusion loss rate. The rate of plasma diffusion depends on the square root of electron temperature, thus observed lowering of diffuse plasma density may be attributed to the observed rise in electron temperature [1,17].

The observed increase in temperature of low energetic electron group (T_{le}) with increase in V_S can be attributed to the decrease in electron-neutral collisions in the target region. As in our estimation, the temperature of low energetic group has contribution both from intermediate

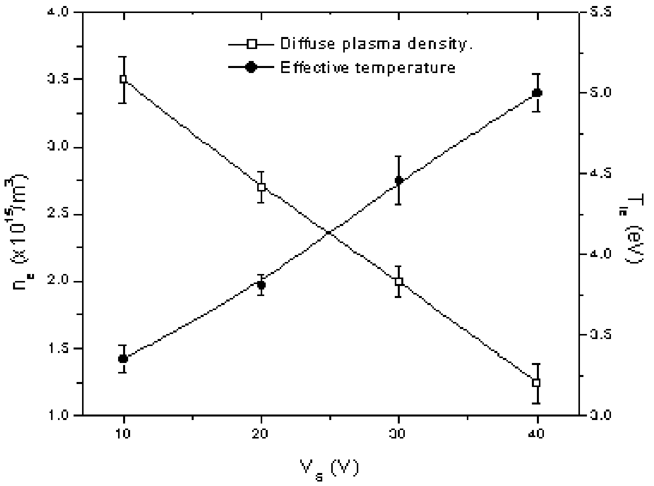


Fig. 5. Variation of plasma electron density n_e ($\times 10^{15}\,m^{-3}$) and effective temperature of low energetic electron group (T_{le}) in the target region with the source biasing voltage V_S.

and lowest energy group, the energy of intermediate group may increase due to the decrease in collisions between high energetic electrons and the neutrals in the diffuse region. It is also shown in Figure 5.

4 Conclusion

Concluding our report, we can say that two of the most important observations of this experiment are the electron energy and the plasma density control in the diffuse plasma region by injecting an ion beam from the main discharge region to the diffuse region of a DP-device. It is observed that the population is more important than the energy of high energetic electron species in order to have higher diffuse plasma density. The present observations show that for intermediate pressure of 10^{-4} mbar and above, energy of both high and low energetic electron species increases in the diffuse region with the increase in source plasma potential or injected ion beam energy. We think that the high energetic electron species in the diffuse region are those, which were the primaries in the main discharge region. They are the few electrons, which have enough energy to cross the potential barrier, but plasma potential in the target region may further accelerate them.

The diffuse plasma potential is enhanced by the injected ion beam. The diffuse plasma density may fall due to the reduced number of ionization with the increase in injected beam energy or due to the enhanced diffusion loss rate caused by the rise in electron temperature.

Authors are grateful to the unknown referee for the critical evaluation of the manuscript.

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