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Influence of magnetic field on plasma sheath and electron temperature

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Experimental observation has been carried out to see the effect of magnetic field and grid biasing voltage in controlling the sheath thickness in a magnetized plasma system. The experiment is carried out in a stainless steel chamber which is divided into two regions by a mesh grid, via the source region and the diffused region. The characteristic behavior of the ion rich sheath formed across the grid under various conditions of the applied magnetic field and grid biasing voltage has been investigated experimentally. It has been observed that at both conditions of increasing magnetic field and grid biasing voltage, sheath width expands in the source region, whereas in the diffused region, no such noticeable variation has been found. This study has been accompanied by the measurement of the electron temperature in both regions of the chamber via the source region and the diffused region with the help of the Langmuir probe. Plasma is produced in the source region and it penetrates into the diffused region through the grid. It has been found that the electron temperature decreases with increasing magnetic field in the source region while kept at a constant grid biasing voltage. However, in the diffused region the opposite variation has been observed. The variation of electron temperature with grid biasing voltage in both regions is not very significant.
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I. INTRODUCTION

Nowadays, the phenomena of high heating efficiency at a low pressure ($\leqslant$10 mTorr) is drawing much attention[1–3] to the researchers because by this, a high density plasma source at a low pressure can be produced which in turn is an essential requirement for many industrial applications, viz., the etching process.[4] In contrast, the main disadvantage of high density ($=10^{10}/\mathrm{cm}^3$) source plasma is the low etch selectivity due to the high degree of dissociation with higher energy electrons and high electron density. So, the most important factor in such an application is to control the electron temperature which reduces the dissociation rate and increases the etch selectivity. Very little work on the electron temperature control phenomena has been done until now. Two methods have been suggested for the electron temperature control. One is the use of pulse modulated power[5] and the other is to use a coarse grid in the plasma environment and to bias it with dc power.[6] Kato *et al.*[7] modified the grid method by designing a slit in the grid and kept it at floating potential. The electron temperature is controlled by varying the slit area in the grid. However, no such work has so far been reported with proper application of external magnetic field using the grid biasing method for the electron temperature control. Our purpose of this observation is to determine the behavior of the electron temperature with various grid biasing voltage and to see the effect of the external magnetic field on it. Also, the magnetized sheath formed across the grid plays an important role in the characteristic features of the particle dynamics and hence the electron temperature in both the source and diffused regions. A substantial number of theoretical research activities on the boundary layer problem in both unmagnetized[8,9] and magnetized plasma[10,11] have been reported. Chodura[12] has shown that when a magnetic field is present at some oblique angle to the solid surface, magnetic presheath forms just before the Debye sheath, which produces a significant electric field in this region. He also showed that the development of this field makes the plasma flow toward the surface of the interacting wall. Chodura affirmed that the ion velocity at the entrance to the magnetic presheath is constrained to follow the Bohm–Chodura condition which depicts that the ion drift velocity parallel to the magnetic field at the magnetic presheath edge should be equal to or greater than the sonic velocity. The difference between this condition and the Bohm condition at the sheath edge, both of which should simultaneously be satisfied, is that at the (Debye) sheath edge, the ion drift velocity (equal to or greater than sonic) must be perpendicular to the interacting surface. The function of the electric field within the magnetic presheath is to turn the ion flow from being sonic along B to being sonic perpendicular to the interacting surface at the entrance of the sheath edge. Moreover, Stangeby[13] resolved the contradiction that arises due to the quasineutrality of the magnetic presheath region (i.e., $\Delta n_e=\Delta n_i$) where it might appear that ion flow velocity parallel to B should not be supersonic. He analyzed the magnetic presheath region more explicitly taking into account the role played by inertia in the $E\times B$ direction and confirmed that the supersonic flow of ion is allowed. The plasma wall interaction models proposed by Chodura[12] and Riemann[10] are recovered by Ahedo[14] for some particular cases via intermediate B, weak B, and strong B cases. He showed that the triple structure of the boundary layer, i.e., the presheath,

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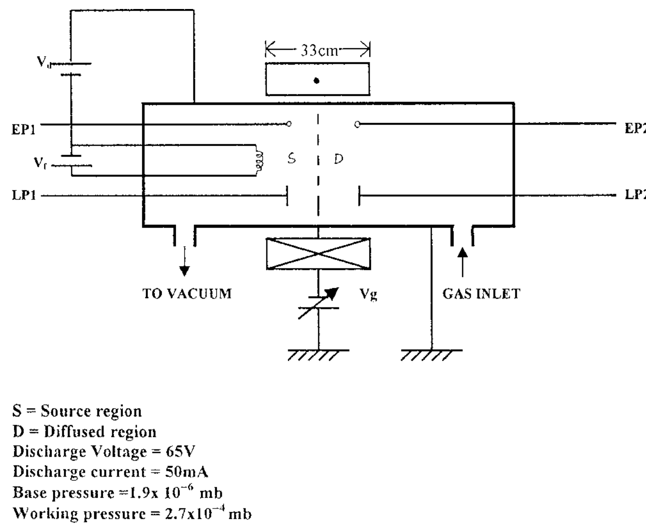


FIG. 1. Schematic diagram of the experimental setup.

the magnetic presheath, and the Debye sheath, exists only for the intermediate B case, whereas for weaker and stronger B cases magnetic presheath disappears forming the classical double structure. Ahedo stated that the space charge sheath region is partially magnetized only for the strong B case. Daybelge and Bein[15] investigated a magnetized sheath at small angles of B with respect to the solid surface using kinetic model and found that the sheath thickness is strongly dependent on the surface absorption characteristics. Most of the studies are centered mainly on using solid plates either theoretically or experimentally.[16] However, the experimental investigation on sheath across a mesh grid in the presence of external magnetic field has not yet been performed. Hence, the main emphasis of our study is to observe the behavior of the sheath across the mesh grid under the influence of the magnetic field and also at various grid biasing voltages. Moreover, it is understood that the changing behavior of the sheath is one important cause for controlling the electron temperature in both the source and the diffused region of the plasma system.

The mode of the present article is as follows. Section II describes the experimental setup and the diagnostic techniques. Experimental results and discussions are given in Sec. III.

II. EXPERIMENTAL SETUP

The experiment is carried out in a hollow stainless steel cylinder 1 m in length and 0.2 m in diameter. The schematic diagram of the experimental setup is shown in Fig. 1. A mesh grid of 95% transparency is placed vertically at a distance 46 cm apart from the right end of the chamber. It divides the system into two regions: source region(S) and diffused region (D) as shown in Fig. 1. The chamber is evacuated by a rotary pump followed by a Diffstak pump to attain a base pressure of 1.9×10^{-6} mbar. Argon gas is injected into the chamber at a working pressure of 2.7×10^{-4} mbar. Plasma is produced in the source region of the chamber by the hot filament discharge method. The plasma sustained in the diffused region is controlled by its production in the source region, which penetrates across the grid. In order to produce an external magnetic field perpendicular to the vertically placed grid, several turns of copper coil are wound in a region of 33 cm in the middle of the chamber. The strength of the applied magnetic field ranges from 66 to 388 G. An ion rich sheath is formed across the mesh grid by applying negative dc voltage into it. The plasma density at the source region ($10^9/\mathrm{cm}^3$) is found to be higher than that in the diffused region ($10^8/\mathrm{cm}^3$).

TABLE I. Sheath thickness in the source region for different B and V_g.

	B (G)			
V_g(V)	66 G (cm)	130 G (cm)	250 G (cm)	388 G (cm)
−60	1.050	1.090	1.267	1.750
−70	1.070	1.100	1.265	1.930
−80	⋯	1.820	2.020	2.180

Langmuir and emissive probes are the two diagnostic tools used for the entire set of experiments. The Langmuir probe is planer of 5 mm diameter. Considerable care has been taken to obtain accurate measurements from both diagnostic tools. As the Langmuir probe does not provide accurate measurement of the plasma parameters such as the plasma density n_e and the electron temperature T_e in the sheath and presheath region, it is employed at a considerable distance (8 cm) away from the grid. The calculated n_e and T_e give the bulk plasma measurements. The sheath thickness and the plasma potential are measured with the help of an emissive probe by adopting the inflection point method in the limit of zero emission.[17] The usual and convenient technique for measuring the plasma potential via the floating potential method is avoided as it leads to perturbation of the plasma environment due to the strong heating voltage applied to it because the method requires it to do so. The emissive probe filament is a thoriated tungsten wire of 0.05 mm diameter and 5 mm length.

III. RESULTS AND DISCUSSION

Characteristic behavior of the sheath in a two component plasma across a mesh grid in the presence of external magnetic field and also the influence of the grid bias voltage upon it have been investigated experimentally. Moreover, noticeable features of the electron temperature variation with the magnetic field as well as grid bias voltage in both source and diffused region have been observed. As stated earlier in Sec. II, plasma is produced in the source region and it penetrates through the grid in the diffused region. The experimental observations show that the sheath thickness is enhanced in the source region due to the external application of both magnetic field B and negative grid biasing voltage $-V_g$. The measurements of the sheath thickness and the electron temperature are carried out under various conditions of magnetic fields, viz: 66, 130, 197, 250, and 388 G and grid biasing voltages: −60, −65, −70, −75, −80, −85, and −90 V. The quantitative change of sheath thickness with V_g and B are shown in Table I. Those results are depicted in Figs. 2(a) and 2(b). Figure 2(a) shows the characteristic be-

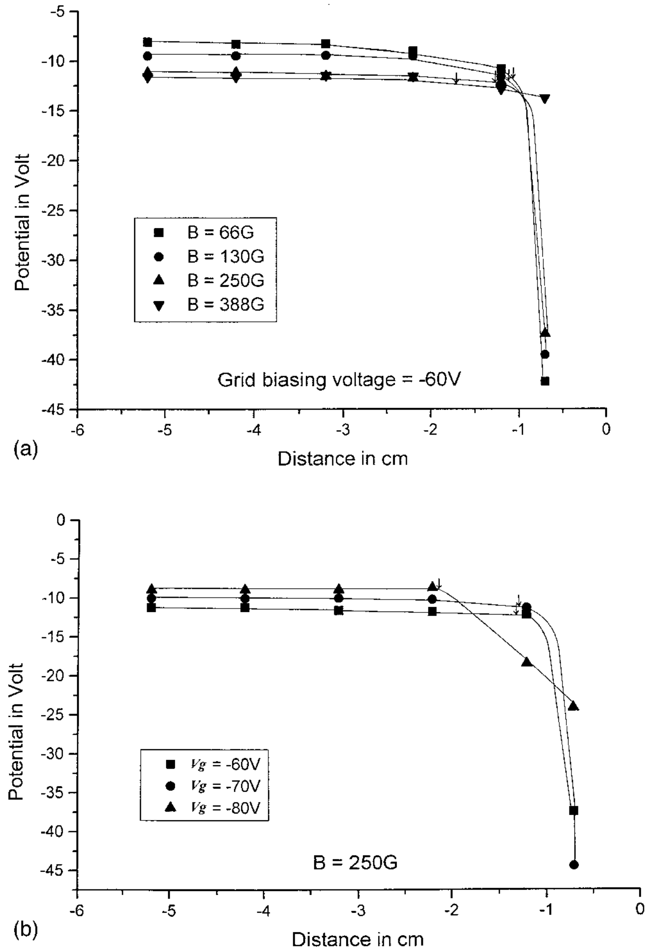


FIG. 2. (a) Sheath thickness variation in the source region with varying B and at constant $-V_g$. The downward arrows indicate the sheath edge. (b) Sheath thickness variation in the source region with varying $-V_g$ and at constant B. The downward arrows indicate the sheath edge.

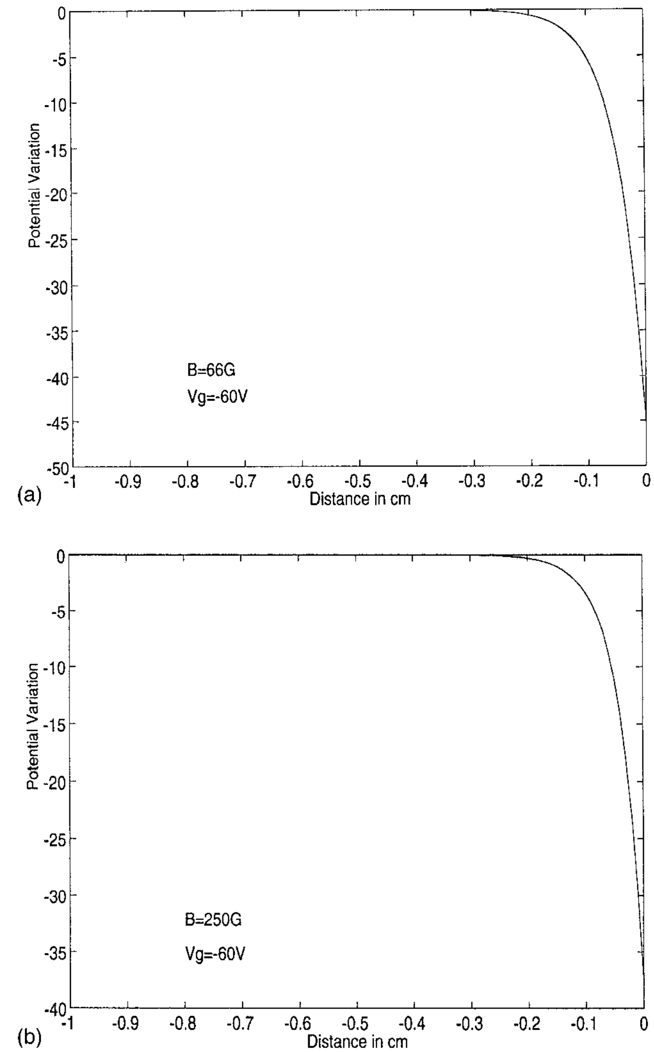


FIG. 3. (a) The spatial variation of potential near the grid in the source region at $B=66$ G and $V_g=-60$ V. (b) The spatial variation of potential near the grid in the source region at $B=250$ G and $V_g=-60$ V.

havior of the sheath across the grid in the source region at a particular grid biasing voltage -60 V and with various B viz: 66, 130, 250, and 388 G (in the figure, 0 on the X axis denotes the grid position). It has been observed that although sheath thickness increases with increasing B, it is prominent for the higher magnetic field only (the downward arrow in the profile gives the sheath edge). Figure 2(b) gives the various sheath thicknesses measured at a particular $B=250$ G with varying grid biasing voltages viz: -60, -70, and -80 V. It yields that at higher V_g, sheath thickness changes noticeably.

In the magnetized plasma system, if an interacting surface is placed at some angle to the direction of the magnetic field, then a magnetic presheath is formed upstream of the usual electrostatic presheath,[12] the length being given by

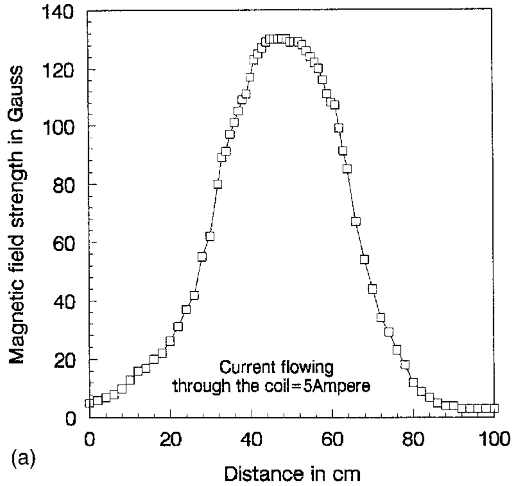
$$\lambda_m = r_{cs} \sin \Psi, \tag{1}$$

where, r_{cs} is the ion larmor radius and Ψ is the angle between the B direction and the normal to the surface. In our experimental model, $\Psi=0$, hence there is no room for magnetic preshaeth. Therefore, the boundary layer is comprised of the electrostatic presheath and the Debye sheath only. In order to satisfy the condition of formation of sheath near the grid, ions flow at acoustic velocity following the Bohm criterion. In both the prescribed sets of increasing magnetic field and $-ve$ grid biasing voltage, it has been experimentally observed that the sheath expands in the source region of the chamber, i.e., the ion flow is being enhanced.

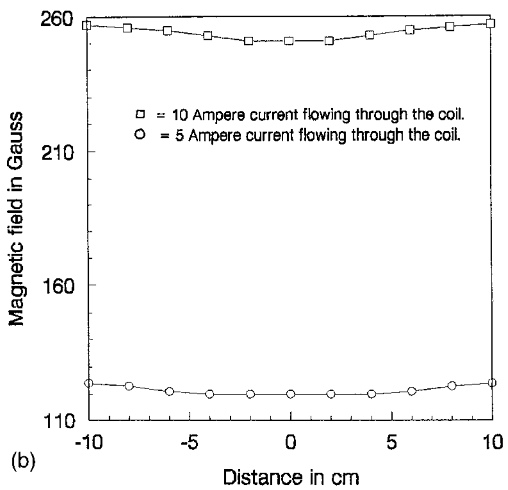
In this case of $\Psi=0$, the development of sheath near the grid can be approximated[18] by the e-folding relationship:

$$e\phi(x) = \exp(-X_D) e\phi(x=x_w), \tag{2}$$

where X_D is a dimensionless quantity proportional to x/λ_D, indicating the Debye length scaling of sheath and x_w denotes the position of the grid. Since the electric field generated within the sheath and the external magnetic field are aligned in the same direction, sheath formation can be followed from Eq. (2), as ion gyromotion is directed perpendicular to E within the sheath, otherwise the gyroradius to the Debye length ratio has to be considered.[18] Incorporating the experimental findings of the sheath potential profiles, Eq. (2) is numerically solved for different imposed conditions of B and $-V_g$. The numerical results are shown in Figs. 3(a) and 3(b), which also depict the exponential variation of sheath potential near the grid in the source region. Figure 3(a) de-

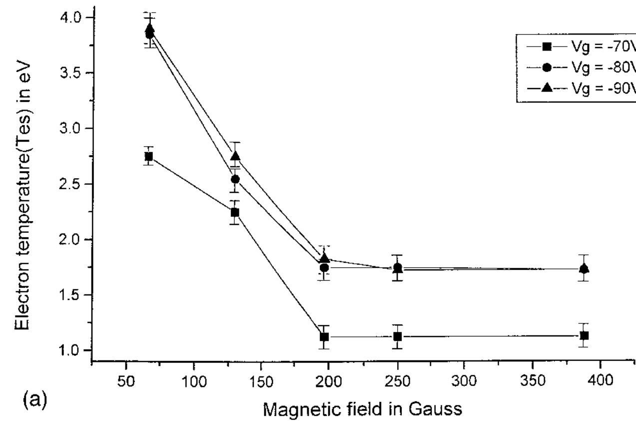


(a)

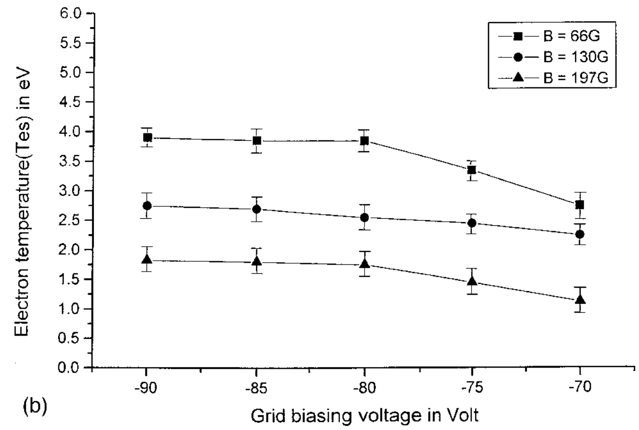


(b)

FIG. 4. (a) Axial profile of the external magnetic field throughout the chamber length when Current flowing through the coil is 5 A. (b) Radial profile of the external magnetic field at the position of 55 cm from the right end of the chamber when current flowing through the coil are 5 and 10 A, respectively (0 on the X axis denotes the center of the cylindrical cross section).



(a)



(b)

FIG. 5. (a) Electron temperature T_{es} in the source region with varying B at constant $-V_g$. Error bar shows the range of standard deviation in the electron temperature. (b) Electron temperature T_{es} in the source region with varying $-V_g$ at constant B. Error bar shows the range of standard deviation in the electron temperature.

scribes the potential variation at $B=66\,\mathrm{G}$ and $V_g=-60\,\mathrm{V}$, whereas Fig. 3(b) gives the potential variation at $B=250\,\mathrm{G}$ and $V_g=-60\,\mathrm{V}$.

Moreover, it can be concluded that the increase of ion accumulation while increasing B is a consequence mainly due to the ∇B drift of the particles, which plays a dominant role in our prescribed experimental setup and is explained explicitly hereafter.

The external magnetic field applied is not homogeneous in the plasma chamber in the axial direction as well as in the radial direction. The axial and radial profile of the magnetic field throughout the chamber is shown in Figs. 4(a) and 4(b), respectively. From these figures, it is seen that there are magnetic field gradients (∇B) in both the axial and radial direction. In addition, due to the presence of radial and axial inhomogeneity of the magnetic field, another magnetic field gradient at some particular direction making some finite angle with the direction of B also arises. The combined effect of all the magnetic field gradients causes a grad B drift of the plasma particles to occur in the source region,[19] which is given by the equation as

$$V_{\nabla B}=\pm\frac{1}{2}v_{\perp}r_L\frac{B\times\nabla B}{B^2}. \tag{3}$$

In the above equation, $v_{\perp}$ and r_L are the transverse velocity and Larmor radius of both the species, respectively. The direction of the drift velocity of both the species will be decided by the charge of the species. So, whenever a magnetic field is introduced at a constant V_g, sheath thickness expands due to both V_g and B. As we increase B more and more keeping V_g constant the $\nabla B/B$ ratio increases, which causes a large number of ions to drift toward the grid, resulting in more expansion of the sheath thickness. Furthermore, it is experimentally found that the sheath thickness increases with the increase of $-V_g$ at a fixed B [Fig. 2(b)]. As the negative grid biasing voltage increases, the ions experience more energy flowing toward the grid and as a result, quasineutarlity breaks down at an earlier position from the grid than the usual case of grid kept at the floating potential. Therefore, it causes enhancement of the sheath.

The study of the sheath behavior in the source region has also been accompanied by the study of the variation of the plasma parameters such as the electron temperature (T_{es}). The measurement of T_{es} is done within the homogeneous magnetic field region of the chamber. The result shows that the electron temperature decreases with the increase of B,

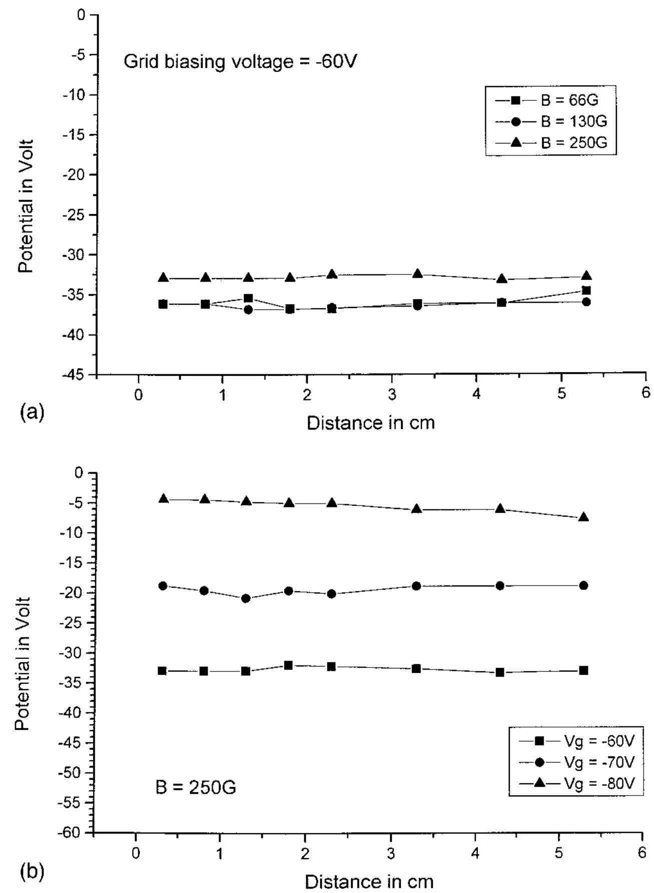


FIG. 6. (a) Sheath thickness variation in the diffused region with varying B at constant $-V_g$. (b) Sheath thickness variation in the diffused region with varying $-V_g$ at constant B.

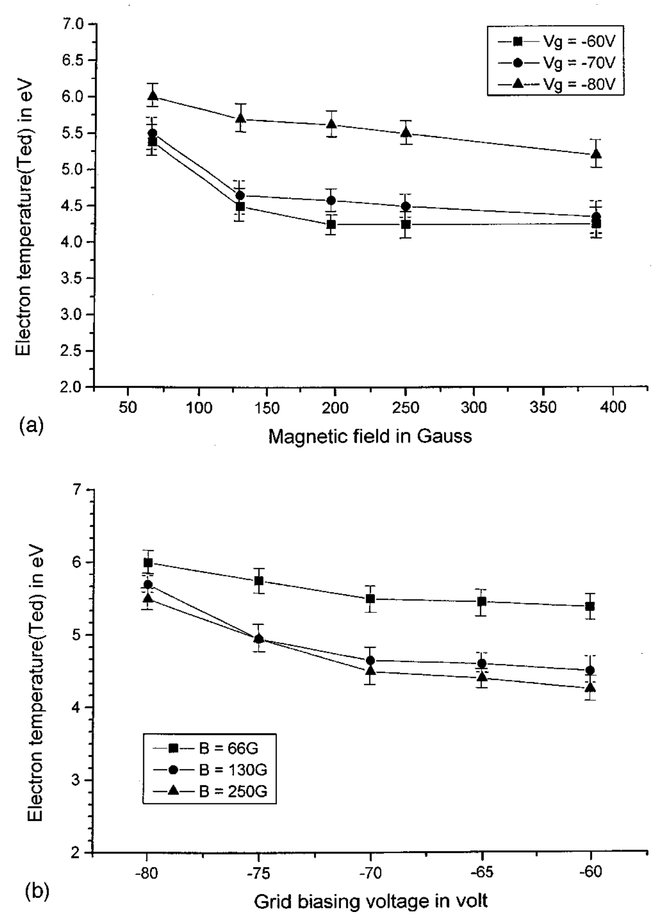


FIG. 7. (a) Electron temperature T_{ed} in the diffused region with varying B at constant $-V_g$. Error bar shows the standard deviation in the electron temperature. (b) Electron temperature T_{ed} in the diffused region with varying $-V_g$ at constant B Error bar shows the standard deviation in the electron temperature.

while the grid is maintained at constant negative biasing voltage [Fig. 5(a)]. The reduction of electron temperature is attributed mainly due to the magnetic confinement. In the presence of the external magnetic field, the plasma particle diffusion pattern changes. The particles diffuse along the magnetic field simply because of their mobility. On the other hand in the transverse direction particles diffuse at the step length of the Larmor gyro radius. As magnetic field increases, the Larmor radius decreases more and more and hence fewer particles diffuse out. Because of this, more particles are confined in the chamber, i.e., the plasma density increases which is also found experimentally. In this situation electron neutral collision dominates, which in turn causes more energy dissipation and hence lowers the electron temperature, although by varying $-V_g$ [Fig. 5(b)], T_{es} increases in the source region but the change is not as significant. This can also be concluded from the fact that V_g does not change the bulk plasma condition much.[20]

Similar kinds of observations in the diffused region have also been made. It is found that no such significant sheath [Figs. 6(a) and 6(b)] has been formed near the grid in this region in the presence of both magnetic field and grid biasing voltage. Figure 6(a) gives the observations done at $V_g = -60$ V with various $B = 66$, 130, and 250 G. On the other hand, in Fig. 6(b), observations are done under the condition of various $V_g = -60$, -70, and -80 V and at a particular $B = 250$ G. As in this region very little plasma is produced due to the primary electrons only and also the sheath formed near the grid in the source region acts as the potential barrier for the particles to cross over into the diffused region, plasma density is found to be lesser in comparison to the source region. Only the high energetic particles penetrate into the diffused region. Due to the low plasma density, the sheath is not prominent at all in this region.

Also, the electron temperature T_{ed} rises up with increasing B [Fig. 7(a)]. Though increasing B confines more particles in the diffused region, at the same time sheath thickness across the grid also increases. Hence, particles having more energy can only cross the high potential barrier. Moreover, confinement cannot lead to a high density plasma in this region which might cause collisions. So, electron temperature increases. Finally, electron temperature T_{ed} with varying V_g is found to increase [Fig. 7(b)], and though the variation is not so prominent as grid bias does not have much effect on the plasma parameters.

The experimental investigations of sheath in magnetized plasma are quite promising from the point of view of basic science and technological applications as well. Enhancement of sheath thickness with the plate biasing voltage is a well established phenomena. The study of the sheath phenomena at various imposed conditions provides knowledge regarding the different characteristic behaviors of sheath width, which is a prime requirement in many plasma processing works. However, the critical study of the modification of surface structure due to biasing voltage and magnetic field at some critical condition could lead one to modify any surface in a more purposeful way from an application point of view.

Furthermore, the control of electron temperature due to the grid bias and the external magnetic field is also being affected by the typical structure of the sheath formed across the grid. In turn, such electron temperature control in weakly ionized plasmas used for many kinds of material processing where various electron temperature dependant chemical processes are involved is of crucial importance.[6,7]

On the other hand, the ion drift with which the ions are approaching the plate in the presence of magnetic field is one of the most important and basic future studies of this work. This study also gives a qualitative idea of the enhancement of sheath structure at some orientation of magnetic field and normal to the plate surface, which has already been studied theoretically.[11] However, by addressing those theoretical approximations in this experimental condition, it could give a more comprehensible basis of sheath thickness enhancement and variation of electron temperature. Thus, in conclusion, we suggest that the future course of this work should address the basic problems combining both experimental and theoretical aspects.

ACKNOWLEDGMENT

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