Chapter 4

STUDY OF EXB DRIFT OF ELECTRONS AND SHEATH BEHAVIOUR IN DC MAGNETRON PLASMA
Chapter 4: Study of ExB drift plasma

STUDY OF ExB DRIFT OF ELECTRONS 
AND SHEATH BEHAVIOUR IN DC 
MAGNETRON PLASMA

4.1. Introduction

The principle of cylindrical direct current magnetron sputter deposition technique is based on crossed electric (E) and magnetic (B) fields which confine electrons in closed ExB drift loops near the cathode [Wendt et al. 1988, Sheridan et al. 1990], where E is provided by the plasma sheath due to the discharge voltage applied and B is produced by permanent magnets or electromagnets. Due to the negative bias applied to the cathode, a sheath is formed and the sheath thickness is normally few times of the Debye length (\(\lambda_D\)) [Riemann 1992a, Kakati et al. 2006]. These electrons in turn are responsible for the ionization of the neutral gas atoms. Consequently, ions are formed which are accelerated towards the cathode with significant amount of energy and they impinge and sputter atoms from the target cathode causing secondary electron emission. The velocity of ions at the sheath boundary and their fluxes to the sheath are important parameters in a large number of plasma applications. Damages caused to the surfaces in various plasma applications are mainly due to high ion momentum [Oksuz and Hershkowitz 2004]. In some other cases, they provide surface heating [Kato et al. 2000] or enhance surface reactions [Fisher 2002]. Probe diagnostics of various types are applied to determine plasma characteristics near plasma sheath boundaries. A few such diagnostics are Langmuir probes, Emissive probes [Hershkowitz 1989], Mach probes [Oksuz and Hershkowitz 2004] and energy analysers. Langmuir probes provide information about the plasma electron.
Chapter 4: Study of $E\times B$ drift, plasma temperature ($T_e$), both ion and electron densities ($n_{i,e}$) and also the plasma potential ($\phi_p$). Emissive probes provide accurate data of the plasma potential \cite{Kemp and Sellen Jr 1966}. Information about the energy distribution function and temperature of ions and electrons can be obtained with the help of gridded energy analysers \cite{Lipschultz et al 1986}. Mach probes are in use for many years to find out the ion drift velocity and plasma characteristics in the scrape-off layers of magnetized fusion plasmas \cite{Oksuz and Hershkowitz 2004, Koltai et al 1990}. A planar Mach probe is generally a combination of two single-sided planar Langmuir probes mounted back to back with an insulator between them. A number of theories using fluid \cite{Stangeby 1984, Hutchinson 1987}, particle \cite{Smith and Langmuir 1926} and kinetic models \cite{Chung 1991}, have been derived to describe such probes in both unmagnetised \cite{Hudis and Lidsky 1970} and magnetized plasmas. Work done by Hutchinson \cite{Hutchinson 2002a, 2002b} provides numerical results on unmagnetised plasmas using Mach probes.

The nature of the drift velocity of electrons in magnetron discharge has lot of implications in sustaining the discharge near the target and hence has been a subject for study over the years \cite{Sheridan et al 1990, Pal et al 2004, Adhikary et al 2006}. A number of methods have been used for determination of the $E\times B$ electron drift velocity. Sheridan et al used a planar Langmuir probe to determine the electron velocity distribution function and drift velocity in a cylindrically symmetric planar magnetron \cite{Sheridan et al 1998}. Bradley et al used an emissive probe to determine the plasma potential profile in a DC planar magnetron discharge and calculated the electric field distribution \cite{Bradley et al 2001}. They then calculated the electron $E\times B$ drift velocity from the relation, $E/B$, where $B$ is the radial magnetic field strength \cite{Smith and Langmuir 1926}. In another study, Rossanagel and Kaufman \cite{Rossanagel and Kaufman 1987a, 1987b} used a Hall Effect sensor to measure the reduction in the
magnetic field due to electron $E \times B$ drift which indicated the existence of anomalously high cross field transport rates in the circular planar magnetron discharge. Fujita et al successfully measured the $E \times B$ drift of electrons in a DC planar magnetron system by comparing the electron saturation current collected by planar probes facing upstream and downstream of the drift [Fujita et al 1986]. In a recent study, Kakati et al have investigated the variation of the $E \times B$ drift velocity in RF planar magnetron plasma device [Kakati et al 2007b]. Measurement of $E \times B$ drift in DC cylindrical magnetron device has been taken up in this study to understand the diffusion and transport mechanism, and also the density and potential characteristics. These parameters are considered to be important for achieving efficient sputtering, which is the characteristics of these devices.

The $E \times B$ drift velocity of flowing plasmas can be obtained using a Mach probe having two directional probes at opposite sides separated from each other by an intervening insulating layer. As for the flow in unmagnetised plasmas, attempts have been made to analyse atmospheric torch plasma [Chung et al 1995], mirror plasma for rotation [Chung et al 2004], basic plasma [Oksuz et al 2001], linear divertor stimulators [Kado et al 2004, Chung et al 2006] and ion sources [Tanga et al 2004]. The relationship between the ratio ($R$) of upstream electron saturation current density ($J_{up}$) to downstream current density ($J_{dn}$) and the normalized drift velocity ($M_\infty$) of plasma can generally be fitted to an exponential form as [Chung 2006]

$$R = \frac{J_{up}}{J_{dn}} = \exp[KM_\infty]$$  \hspace{2cm} (4.1)

where, $K$ is a calibration factor depending on the magnetic flux density, collisionality, viscosity and electron temperature of plasmas. If there is no flow (i.e. $M_\infty=0$), the
collection of electrons on one side of the probe ($J_{up}$) is the same as that on the opposite side of the probe ($J_{dn}$), thereby giving the relation

$$R = \frac{J_{up}}{J_{dn}} = 1$$  \hspace{1cm} (4.2)

whereas, if there is directional flow (i.e. $M > 0$), the ratio of the current density on the upstream side to that on the downstream side is greater than one i.e.

$$R = \frac{J_{up}}{J_{dn}} > 1$$  \hspace{1cm} (4.3)

This principle is assumed in the present investigation for determining the $E \times B$ drift velocity of the plasma generated inside the cylindrical magnetron system. The mass of $Ar^+$ ions constituting the plasma is very high in comparison to that of the electrons and therefore, its Larmour radius is typically greater than the dimension of the plasma under study. In the present study, therefore, the $Ar^+$ ions are assumed not to experience the $E \times B$ drift.

Study on the investigation of plasma sheath behaviour in a plasma containing electrons, positive ions etc. have gained considerable attention in recent years. The sheath behaviour influences the plasma processing techniques such as surface coating with reactive sputtering, plasma etching, chemical vapour deposition and therefore, it is essential to have a better understanding of the plasma sheath formed near the physical boundary to optimize the processing performance in such plasma processes [Bailung et al 2004b]. Bohm formulated the criteria for sheath formation and introduced the idea of presheath [Bohm 1949]. The sheath electric field around the cathode controls the ions accelerated towards the cathode to cause sputtering. On the other hand, the electrons are accelerated through the sheath away from the cathode to initiate ionization. A substantial number of theoretical researches on the boundary
layer problem in both unmagnetised and magnetized plasma have been reported [Singha et al 2001]. The sheath potential structure variation is very important to understand the processing characteristics. Plasma sheath is making significant influence on the charged particles and their energy flux to the wall, which in turn greatly modifies the absorption, emission of impurities and the sputtering and deposition. In this study, the sheath potential structure in a direct current magnetron plasma sputtering discharge has been investigated.

4.2. Experimental set up

The experimental magnetron device is a stainless steel cylindrical chamber with a small titanium cylinder being placed co-axially inside the chamber which acts as the cathode. A detailed description of the experimental set up has been given in chapter two. A schematic diagram of the experimental set up along with the probes and accessories is shown in figure 4.1(i). Two coils which are placed around the body of the chamber are used to generate a steady axial magnetic field. Direct current is passed through both the coils in the same direction which produces an axial magnetic field parallel to the cathode surface. One ampere current through the coils generates a magnetic field of 0.0025 Tesla at the central region of the plasma chamber. Low pressure is created inside the chamber using a combination of rotary and diffusion pumps. A Pirani gauge and an ionization gauge are used for measurement of pressure inside the chamber. Argon gas is taken as the working gas. Plasma is produced by applying (400 – 700) V DC bias between central electrode as cathode and the grounded chamber as anode. The plasma potential profile is recorded with the help of an emissive probe ($E_p$), made of 1% thoriated tungsten wire of 0.005
cm in diameter and 0.3 cm in length. The supporting electrodes are covered by ceramic tubes for proper insulation from the plasma.

The Mach probe constructed for the determination of the drift velocity of electrons consists of two plane Langmuir probes of diameter 0.45 cm each as shown in Figure 4.1: Schematic diagram of (i) cylindrical magnetron device with different accessories and (ii) Mach probe.

![Diagram](image)

**Figure 4.1:** Schematic diagram of (i) cylindrical magnetron device with different accessories and (ii) Mach probe.

The Mach probe constructed for the determination of the drift velocity of electrons consists of two plane Langmuir probes of diameter 0.45 cm each as shown...
in figure 4.1(ii). Insulated ceramic paste (~0.05 cm thickness) is placed in between the two planes to avoid contact in between them. The Mach probe is inserted into the discharge in such a way that surface 1 is facing the drift and hence collects the thermal electrons as well as the drifted electrons, while surface 2 is along the direction of the drift and hence cannot collect the drifted electrons.

4.3. Experimental results and discussions

4.3.1. Magnetic field distribution

Axial magnetic field is produced inside the cylindrical device by flowing DC current to two coils placed around the chamber body. Magnetic field inside the device is measured with the help of an InAs Hall probe. A typical data of the measured axial magnetic field strength for 4 ampere of current flow which generates 0.01 Tesla magnetic field is shown in figure 4.2(a). The location of the magnetic field generating coils and the axial position of the cathode are also schematically shown in the figure. The axial variation of the applied magnetic field is found to maintain a uniform value (~ 0.01 Tesla) for a length of ~30 cm at the central region (35 cm - 65 cm). The field strength is found to gradually decrease on either side of this region.

The measured radial variation of the magnetic field strength for the same current flow in the central region (at mid-point of the cathode and in perpendicular direction of the cathode) is shown in figure 4.2(b). A steady magnetic field strength (~ 0.01 Tesla) is seen within a diameter of ~ 15 cm. This profile is maintained along the length of the cathode.
Figure 4.2: Profile showing variation of magnetic field strength for 0.01 Tesla in (a) axial direction and (b) radial direction.
4.3.2. Current – voltage characteristics of the Mach probe

Figure 4.3: Current-voltage characteristics for the two surfaces of the Mach probe.

In order to measure the $E\times B$ drift velocity, the upstream and downstream electron current flow is measured using the Mach probe. A typical plot of the current – voltage ($I$ - $V$) characteristics for the two opposite surfaces (1 and 2) of the Mach probe is shown in figure 4.3. The Mach probe is placed along a radial line at a distance of 3 cm from the target cathode, such that the probe surface is perpendicular to the electron $E\times B$ drift direction. The plasma discharge parameters are as follows – discharge voltage is 600 V, discharge current is 120 mA, argon partial pressure is $2\times10^{-3}$ Torr and the applied magnetic field strength is 0.01 Tesla. It is found that the electron saturation current has a higher value for surface 1 of the Mach probe than that of surface 2. This indicates that surface 1 is facing the $E\times B$ drift and surface 2 is along the direction of the drift. This difference in the value of the electron saturation
currents between the two opposite surfaces of the probe is used to determine the $E\times B$ drift velocity of the electrons.

The value of electron saturation current is measured from the semi-logarithmic plot of the electron current and is given by the intersection point between the two tangents drawn one at the Maxwellian part and another at the electron saturation part of the $(I - V)$ characteristics (shown inset in figure 4.3). $I_{es1}$ and $I_{es2}$ represent the electron saturation currents collected at the two opposite surfaces of the Mach probe. Surface 1, which faces the $E\times B$ flow, collects the electron current of thermal electrons as well as drifted electrons. Surface 2, whose collecting surface is along the direction of $E\times B$ flow, collects only the thermal electrons. The difference in electron saturation currents collected by these two surfaces gives a measure of $E\times B$ drift current of electrons. The measured variation of electron saturation current obtained from the two surfaces of the Mach probe placed 3 cm away from the cathode is presented in the following sections.

**4.3.2.1. $I_{es}$ at different discharge voltages and currents**

The variation of electron saturation current with discharge voltages and discharge currents are shown in figure 4.4(a). The argon partial pressure is maintained at $2\times10^{-3}$ Torr and the magnetic field strength is 0.01 Tesla. The electron saturation current for both the surfaces are found to increase almost linearly with the increase of discharge voltage as shown in the figure. When discharge voltage increases, the electrons constituting the plasma discharge gains energy from the discharge which results in the increase in the ionization rate and therefore, the increase in the density and the saturation current. Discharge current increases from ~ 30 mA at 400 V to ~ 175 mA at 700 V.
4.3.2.2. $I_{es}$ at different argon partial pressures

In figure 4.4(b), the variation of electron saturation current with argon partial pressures is shown. The discharge voltage is at 600 V and the magnetic field strength is 0.01 Tesla respectively. It is found that the electron saturation current increases with the increase of argon partial pressure in the plasma discharge. Increase in the argon partial pressure leads to an increase of the corresponding neutral density and therefore, the collision and ionization rates also increases. This will result in the
increase in the plasma density thereby increasing the electron saturation current value. Discharge current increases with increase in the argon partial pressure.

![Graph](image_url)

Figure 4.4(b): Electron saturation current variation with argon partial pressures at \( B = 0.01 \) Tesla, discharge voltage = 600 V and probe distance 3 cm from the cathode. Corresponding discharge current variation is also shown.

4.3.2.3. \( I_{es} \) at different applied magnetic field strengths

The variation of electron saturation current with magnetic field strength is shown in figure 4.4(c). The corresponding discharge current variation is also shown which increases from \( \sim 64 \) mA at 0.0075 Tesla to \( \sim 295 \) mA at 0.03 Tesla. The discharge voltage is maintained at 600 V and the argon partial pressure is at \( 2 \times 10^{-3} \) Torr. Similar trend of an increase in the electron saturation current with the increase in the applied magnetic field strength is observed. There is an increase in the effective confinement of electrons with the increase in the applied magnetic field strength. This
leads to an enhancement in the ionization rate and the plasma density. Consequently, increase in the electron confinement results in the increase in the electron saturation current.

![Graph showing electron saturation current variation with applied magnetic field.](image)

Figure 4.4(c): Electron saturation current variation with applied magnetic field at $P_{Ar} = 2 \times 10^{-3}$ Torr, discharge voltage $= 600$ V and probe distance $3$ cm from the cathode. Corresponding discharge current variation is also shown.

### 4.3.3. Measurement of electron temperature ($T_e$)

The electron temperature is determined from the Mach probe $I - V$ characteristics. It is obtained from the slope of the $\ln(I)$ vs. $V$ curve of the Mach probe in the Maxwellian region using the equation:

$$T_e = \frac{dV}{d\ln(I)}$$  \hspace{1cm} (4.4)
The symbols $T_{el}$ and $T_{e2}$ represent the electron temperatures at the two opposite surfaces (1 and 2) of the Mach probe. We have experimentally determined the electron temperatures of both the surfaces of the Mach probe but only the electron temperature value obtained from surface 2 of the Mach probe has been taken into consideration for determining the drift velocity. This is done to nullify the effect of the electron drift and to eliminate overestimation of the electron temperature value.

The measured variation of electron temperature for the two surfaces of the Mach probe placed 3 cm away from the cathode is presented in the following sections.

4.3.3.1. $T_e$ at different discharge voltages

![Graph showing electron temperature variation with discharge voltage](image)

Figure 4.5(a): Electron temperature variation with discharge voltages at $B = 0.01$ Tesla, $P_{Ar} = 2 \times 10^{-3}$ Torr and probe distance 3 cm from the cathode. Discharge current varies from 30 mA at 400 V to 175 mA at 700 V.

The variation of electron temperature with discharge voltage is shown in figure 4.5(a). The argon partial pressure is $2 \times 10^{-3}$ Torr and the magnetic field strength is 0.01 Tesla. The electron temperature is found to increase with the increase of the
discharge voltage. At a discharge voltage of 400 V, the electron temperature value for surface 1 is 1.7 eV which is found to increase to a value of 5.5 eV at a discharge voltage of 700 V. The electrons constituting the plasma gain momentum due to the increase in the discharge voltage. This results in an increase in the energy of the electrons which will thereby result in the increase of the electron temperature.

4.3.3.2. $T_e$ at different argon partial pressures

![Figure 4.5(b): Electron temperature variation with argon partial pressures at $B = 0.01$ Tesla, discharge voltage = 600 V and probe distance 3 cm from the cathode. Discharge current varies from 35 mA ($1\times10^{-3}$ Torr) to 240 mA ($4\times10^{-3}$ Torr).](image)

The variation of electron temperature for the two surfaces of the Mach probe placed 3 cm away from the cathode at different argon partial pressures is shown in figure 4.5(b). The discharge voltage is maintained at 600 V and the magnetic field strength at 0.01 Tesla respectively. Electron temperature is found to decrease from 5.0
eV to 3.3 eV when the argon partial pressure is increased from $1 \times 10^{-3}$ Torr to $4 \times 10^{-3}$ Torr. Due to the increase in the pressure, the neutral density increases. Increase in the density will result in more number of collisions between the constituent electrons and the gas species which will lead to an increase in the loss of energy of these electrons. This energy loss will subsequently slow down their velocity and thus, a decrease in the electron temperature of these electrons is observed. There are two distinct regions of electron temperature variation. At lower pressure, since the electron density in the discharge is less, the efficiency in energy transfer mechanism is more. Therefore, the drop in $T_e$ values is more here as compared to the drop at higher argon pressures.

4.3.3.3. $T_e$ at different applied magnetic field strength

![Graph showing electron temperature variation with magnetic field strength](image)

Figure 4.5(c): Electron temperature variation with magnetic field at $P_{Ar} = 2 \times 10^{-3}$ Torr, discharge voltage = 600 V and probe distance 3 cm from the cathode. Corresponding discharge current varies from 64 mA at 0.0075 Tesla to 295 mA at 0.03 Tesla.
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Again, the variation of electron temperature with magnetic field is shown in figure 4.5(c). The discharge voltage is maintained at 600 V and the argon partial pressure is at $2 \times 10^{-3}$ Torr. The electron temperature is found to decrease from 4.0 eV to 2.4 eV with the increase of the magnetic field from 0.0075 Tesla to 0.03 Tesla. This is because of the fact that more number of electrons gets confined within the plasma and these electrons lose their energy to a greater extent due to both elastic and inelastic collisions. This results in the decrease in the electron temperature value with the increase in the applied magnetic field strength.

4.3.4. Measurement of electron $E \times B$ drift velocity

The electron $E \times B$ drift velocity has been determined on the basis of the Yamada and Hendel model [Yamada and Hendel 1978]. The difference of the electron saturation currents, $I_{es1}$ and $I_{es2}$, collected at the two opposite surfaces (1 and 2) of the Mach probe are measured. Again, from the electron saturation currents of the two surfaces of the Mach probe, the ratio between the electron drift velocity ($v_d$) and electron thermal velocity ($v_t$) is found out. In this model, the electron saturation current facing the drift is given by

$$I_{es1} = e n_e (v_t + v_d) S$$

(4.5)

Similarly, the electron saturation current for the probe surface away from the drift direction is given by

$$I_{es2} = e n_e (v_t - v_d) S$$

(4.6)

where $e$, $n_e$ and $S$ are electronic charge, electron density and probe surface area respectively. Using the above two equations, the electron drift velocity can be expressed as

$$v_d = \frac{I_{es1} - I_{es2}}{I_{es1} + I_{es2}} v_t$$

(4.7)
where the thermal velocity is given by, 
\[ v_t = \sqrt{\frac{T_e}{2\pi m_e}}. \]

The measured thermal velocity for different discharge voltages, argon partial pressures and applied magnetic field strengths are shown in figures 4.6(a), 4.6(b) and 4.6(c) respectively. The thermal velocity is found to increase with increasing discharge voltage as the electric field increases which results in the electrons gaining momentum. With increasing argon partial pressure and applied magnetic field strength, the thermal velocity decreases due to more number of collisions and higher confinement.

Figure 4.6(a): Dual plots of thermal velocity and electron drift velocity variations with discharge voltage at \( B = 0.01 \) Tesla, \( P_{Ar} = 2 \times 10^{-3} \) Torr and probe distance 3 cm from the cathode.
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Figure 4.6(b): Dual plots of thermal velocity and electron drift velocity variations with argon partial pressure at $B = 0.01$ Tesla, discharge voltage = 600 V and probe distance 3 cm from the cathode.

Figure 4.6(c): Dual plots of thermal velocity and electron drift velocity variations with magnetic field at $P_{Ar} = 2 \times 10^{-3}$ Torr, discharge voltage = 600 V and probe distance 3 cm from the cathode.
The measured $E \times B$ drift velocity with variation of discharge voltages, argon partial pressures and applied magnetic field strengths are also shown in figures 4.6(a), 4.6(b) and 4.6(c). The increase of the discharge voltage increases the sheath electric field which increases the drift velocity (Figure 4.6(a)). The electron drift velocity is found to decrease with the increase in the argon partial pressure in the discharge. Increase in energy transfer from the electrons due to their increased collisional impact with the argon atoms leads to the decrease in their thermal velocity. Decrease of drift velocity is due to the enhanced electron-neutral collisions with increasing pressure (Figure 4.6(b)). The increase in the applied magnetic field strength increases the electron confinement within the plasma which consequently hinders the diffusion of the electrons and also decreases their drift around the cathode. Increase in the magnetic field also affects the ionization process, initial small increase in the drift velocity is due to nominal increase in the sheath electric field due to the increase of the plasma density.

The radial variation of the $E \times B$ drift velocity of the electrons has also been determined using the $E/B$ method from the radial potential profile data measured with the help of an emissive probe. Figure 4.7 shows the profiles of the radial plasma potential at discharge voltages 400 V, 450 V, 500 V, 550 V and 600 V keeping magnetic field fixed at 0.01 Tesla and argon partial pressure at $2 \times 10^{-3}$ Torr. A sharp potential gradient occurs within 2 cm from the cathode surface for each of these discharge voltages. Use of an emissive probe in magnetron discharge to determine the plasma potential is necessary to eliminate the coating effect of the sputtered materials on the probe surface itself. Emissive probe has been used for accurate measurement of plasma potential in DC discharges [Fisher 2002]. The floating potential method [Coakley et al 1978] is used to measure the plasma potential. To determine the plasma
potential by the floating potential method, the filament wire is heated by passing current through it for strong electron emission. Due to the emission of electrons, the floating potential of the probe increases towards positive value until it becomes equal to the plasma potential where it saturates. To compare this result with the result obtained using the Mach probe, the potential difference ($\partial V$) is measured corresponding to a distance $\partial r = 0.45$ cm (Mach probe dimension). Then the axial electric field is determined from the relation, $E = - (\partial V/\partial r)$. The electron drift velocity is determined at radial positions corresponding to that of the radial positions of the Mach probe using the relation given below as shown in figure 4.8(a).

$$v_d = \frac{E \times B}{B^2} = \frac{E}{B}$$  \hspace{1cm} (4.8)
Figure 4.8(a): Radial variation of electron drift velocity by both Mach probe and emissive probe at $B = 0.01$ Tesla, $P_{Ar} = 2 \times 10^3$ Torr and discharge voltage = 600 V.

Figure 4.8(b): Plot of radial variation of electron drift velocity by Mach probe at different discharge voltages at $B = 0.01$ Tesla, $P_{Ar} = 2 \times 10^3$ Torr.
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The radial variation of the electron drift velocity measured using the Mach probe at different distances away from the target cathode at three different discharge voltages is shown in figure 4.8(b). This figure shows that the electron $E \times B$ drift velocity is maximum near the cathode target which corresponds to the sheath region of the plasma. In the vicinity of the region where the transition from the plasma sheath to its presheath occurs, the electron drift velocity decreases and maintain a steady profile up to 3 cm. This region corresponds to the glow region of the plasma. Further away from the cathode, the $E \times B$ drift velocity of the electrons decreases. The electron drift velocity increases with increasing discharge voltage. The strong increase of drift velocity in the sheath region is due to the gain of energy of electrons from the strong sheath electric field. Since sheath electric field decreases away from the cathode, so the drift velocity also decreases. It is found that the drift velocity value decreases from $10^5 \text{ms}^{-1}$ to $10^4 \text{ms}^{-1}$ at larger radial distances from the cathode surface. Measurement of drift velocity very near the cathode surface (at distances less than 1.5 cm from the cathode) is not possible using the Mach probe because the probe dimension causes significant perturbation in the plasma discharge thereby giving erroneous result.

The experimental results of the electron drift velocity have been obtained using non-reactive argon gas. In order to relate these results to the actual deposition process, titanium nitride thin films have been deposited on bell-metal (an alloy of copper and tin) substrates suitably placed at different distances (2 cm, 4 cm and 6 cm) from the cathode by introducing reactive nitrogen gas in the plasma chamber. Depositions were done at (a) discharge voltage = 400 V, $B = 0.02$ Tesla, $P_{Ar-N_2} = 4 \times 10^{-3}$ Torr, (b) discharge voltage = 500 V, $B = 0.015$ Tesla, $P_{Ar-N_2} = 3 \times 10^{-3}$ Torr and (c) discharge voltage = 600 V, $B = 0.01$ Tesla, $P_{Ar-N_2} = 2 \times 10^{-3}$ Torr. Adhesion test done on the films deposited on the substrates placed very near to the cathode (2 cm) at
each of the three above conditions have been found to very poor. The adhesion test is
done by scotch tape according to the standard tape test method [Nema et al 2004] using scotch tape (3M, USA). For this test, the scotch tape is fixed on the coated surface and pulled off to realize the adhesion quality of the coating. Almost the entire film was pulled off indicating very poor adhesion. At a distance of 4 cm, film deposition at condition (c) shows better adhesion than at (a) and (b). Still the films deposited at 4 cm gets peeled off. Titanium nitride thin film deposited at 6 cm distance from the cathode at condition (c) shows the best quality adhesion. The film remained intact on pulling off the tape showing good adhesion.

4.3.5. Plasma sheath variation study

Figure 4.9: Sheath thickness and discharge current variation with discharge voltages at B = 0.01 Tesla, P_{Ar:N_2} = 2\times10^3 Torr at Ar:N_2 = 1:1.

The plasma sheath potential variation is measured continuously in radial direction between the cathode and the anode magnetron chamber body by varying different plasma parameters like the discharge voltage, the gas pressure and the
applied magnetic field strength. The sheath thickness is measured from the plasma potential profiles from semi-logarithmic plot of the plasma potential versus distance. The intersection point of the tangents drawn one in sharp fall region of potential closer to cathode and the other in constant plasma region in the bulk plasma is taken as the measure of sheath. Figure 4.9 represents the variation of sheath thickness and discharge current with discharge voltage as a parameter at fixed argon nitrogen total pressure of $2 \times 10^{-3}$ Torr and magnetic field of 0.01 Tesla. Both sheath thickness and discharge current increases with increase in the discharge voltage which influence the space charge density near the cathode.

![Figure 4.10: Sheath thickness and discharge current variation with argon pressures at B = 0.01 Tesla, discharge voltage = 600 V.](image)

The variation of sheath thickness and discharge current with argon pressure as a parameter at fixed discharge voltage of 600 V and magnetic field of 0.01 Tesla is shown in figure 4.10. The sheath thickness is 1.12 cm at $1 \times 10^{-3}$ Torr argon pressure.
and it decreases to 0.84 cm at $3 \times 10^{-3}$ Torr argon pressure. As plasma density increases with increasing argon pressure, the space charge density in the cathode sheath increases and the current density to the cathode also increases resulting in the contraction of the plasma sheath.

Figure 4.11: Sheath thickness and discharge current variation with magnetic field at discharge voltage = 450 V and $P_{\text{Ar:N}_2} = 1 \times 10^{-3}$ Torr.

Figure 4.11 represents the variation of sheath thickness and discharge current with magnetic field as a parameter at fixed argon nitrogen total pressure of $1 \times 10^{-3}$ Torr and discharge voltage of 450 V. With increasing magnetic field, the plasma potential is found to decrease. At higher magnetic fields the electrons become more and more confined, therefore the plasma potential becomes more negative to control the ion loss rate and maintain the quasi-neutrality of the plasma. For all the magnetic fields, a sharp radial gradient in the plasma potential and thus, strong electric field is present near the cathode region resulting in the formation of the sheath. The enhanced
Chapter 4: Study of $E \times B$ drift, plasma confinement of electrons near the cathode surface will reduce the effective positive ion concentration within the sheath. This should effectively result in the expansion of the cathode sheath. On the contrary, there occurs an interesting observation in the sheath thickness when magnetic field is increased. The cathode sheath is found to contract with the increase in the magnetic field. The increase in the overall plasma density is responsible for the decrease in the cathode sheath thickness. Here, the plasma density influence on the nature of the cathode sheath thickness is more dominating than the electron confinement factor.

For quality deposition of thin films, it is necessary to optimize the magnetron sputtering by maintaining the argon and reactive gas (nitrogen) partial pressures. This variation in the argon and nitrogen partial pressures influences the plasma sheath, thoroughly discussed in chapter three, which is significant in the ionization process as well as the plasma transport mechanism of the discharge. It has been observed that the space charge density in the cathode sheath and the current density to the cathode decreases when nitrogen concentration is increased. With the increase in sheath thickness, the strength of the sheath electric field decreases which in turn will lead to the lowering of the energy of the ions bombarding the cathode resulting in low rate of sputtering.

4.4. Conclusion

Variation of the electron $E \times B$ drift velocity in radial direction is estimated in the cathode sheath region of a direct current cylindrical magnetron sputtering device using a planar Mach probe. In radial direction, the drift velocity gradually decreases from the cathode centre toward the anode region where it becomes minimum. Measured potential profile using emissive probe indicate that the sheath dimension is
nearly few tens of Debye length. The observed drift also mainly occurs within the
cathode sheath region. The $E \times B$ effect on electrons is mainly effective near the
cathode region due to higher strength of radial electric field. The drift velocity of
electrons calculated both from Mach probe characteristics and $E/B$ method agrees
well all throughout. The estimated drift velocity can be used to understand the
diffusion processes in the magnetron sputtering device.

This experimental observation gives an understanding on the variation of the
plasma sheath potential in a direct current cylindrical magnetron sputtering system.
Also, the dynamics of the gas species near the target of a magnetron sputtering system
depend on the potential structure, which in turn controls the ionization and sputtering
rates in the plasma discharge. It has been observed that both the sheath thickness and
the discharge current variations are influenced by discharge voltage, gas pressure and
the magnetic field strength.