Effect of $E \times B$ electron drift and plasma discharge in dc magnetron sputtering plasma*

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Study of electron drift velocity caused by $E \times B$ motion is done with the help of a Mach probe in a dc cylindrical magnetron sputtering system at different plasma discharge parameters like discharge voltage, gas pressure and applied magnetic field strength. The interplay of the electron drift with the different discharge parameters has been investigated. Strong radial variation of the electron drift velocity is observed and is found to be maximum near the cathode and it decreases slowly with the increase of radial distance from the cathode. The sheath electric field, E measured experimentally from potential profile curve using an emissive probe is contributed to the observed radial variation of the electron drift velocity. The measured values of the drift velocities are also compared with the values from the conventional theory using the experimental values of electric and magnetic fields. This study of the drift velocity variation is helpful in providing a useful insight for determining the discharge conditions and parameters for sputter deposition of thin film.

Keywords: electron drift velocity, Mach probe, cylindrical magnetron, sputtering

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1. Introduction

Direct current (dc) cylindrical magnetron configuration is used for the sputter deposition of different compound films in a large number of technological fields.[1,2] Its principle is based on crossed electric (E) and magnetic (B) fields which confine electrons in closed $E \times B$ drift loops near a negatively biased cathode target, where E is provided by the plasma sheath and B is produced by permanent magnets or electromagnets.[3,4] Due to the negative bias of the cathode, a sheath is formed around it and the sheath thickness is normally a few times of the Debye length ($\lambda_{\rm d}$).[5,6] 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 a significant amount of energy and they impinge and sputter atoms from the target cathode, causing secondary electron emission. The velocity of ions and their fluxes are important parameters in a large number of plasma applications.[7−9] The role of electron drift is significant in the process for obtaining proper optimization of the film deposition. So, it is essential to determine and maintain a balance between the electron drift and the plasma discharge parameters for quality deposition of the film coating. The novelty of dc cylindrical magnetron sputtering system as compared with other deposition system configurations lies in the fact that high yield of uniform coating is possible over a large area of the substrates of different shapes. In an earlier study, we have shown the optimization of the plasma parameters for the deposition of titanium nitride (TiN) thin film as protective coating on bell-metal, an alloy of copper and tin having substantial commercial applications.[2]

Mach probes have been in use for many years to find out the ion drift velocity and plasma characteristics in the scrape-off layers of magnetized fusion plasmas.[7,10] It has also attracted interest in the field of fusion research to measure the plasma drift velocities in the plasma edge region of tokamaks or other magnetic confinement devices. This simple probe is also considered to be applied to in-situ measurements in space research. A planar Mach probe is generally a combination of two single-sided planar Langmuir probes mounted back to back with an insulator between them. For industrial processing and fusion plasmas, the various forms of Mach probes, to measure the plasma flow by measuring separately the upstream and downstream ion collection currents, are a very important application. The calibration of Mach

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probes in magnetized plasmas (when the ion Larmour radius is smaller than the probe dimension) has been established by theory and also been verified in experiments.[11−13]

The nature of the drift velocity of electrons in magnetron discharge has lot of implications in sustaining the discharge near the target and therefore, it has been a subject for study over the years.[4,14,15] A number of methods have been used for determining the $E \times B$ electron drift velocity. Sheridan *et al.*[16] used a planar Langmuir probe to determine the electron velocity distribution function and drift velocity in a cylindrically symmetric planar magnetron. Bradley *et al.*[17] used an emissive probe to determine the plasma potential profile in a dc planar magnetron discharge and calculated the electric field distribution. They then calculated the electron $E \times B$ drift velocity from the relation, E/B, where B is the radial magnetic field strength. In another study done by Rossnagel and Kaufman,[18,19] a Hall Effect sensor was used 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 a circular planar magnetron discharge. Fujita *et al.*[20] successfully measured the $E \times B$ drift of electrons in a dc planar magnetron system by comparing the electron saturation currents collected by planar probes facing upstream and downstream of the drift. In a recent study, Kakati *et al.*[21] has investigated the variation of the $E \times B$ drift velocity in an rf planar magnetron plasma device. Measurement of $E \times B$ drift in dc cylindrical magnetron device is required to understand the diffusion and transport mechanisms, 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 drift velocity of flowing plasmas can be obtained using a Mach probe having two directional probes on opposite sides separated from each other by an intervening insulating layer. A double-sided planar Langmuir probe (Mach probe) is used for determining the drift velocity of the electrons inside the discharge.[7] The $E \times B$ drift velocity inside the sheath is also determined by the E/B method and is compared with that of the results obtained using the Mach probe.

2. Experimental setup

The experimental magnetron device is a stainless steel cylindrical chamber of 30 cm in diameter and 100 cm in length. A titanium cylinder is placed co-axially inside the chamber as the cathode. The length of the cathode is 25 cm and its outer diameter is 3.25 cm. A schematic diagram of the experimental setup along with the probes and accessories is shown in Fig. 1(a). For the generation of a steady axial magnetic field, two coils are placed around the body of the chamber. Each coil is mounted over rails and fitted with castor wheels so that it can be easily moved along the axis of the chamber for the necessary adjustment of the distance between the coils. Each coil consists of enamel coated copper wire of rating 9 SWG and contains 1500 numbers of turns. 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 T in the central region of the plasma chamber.

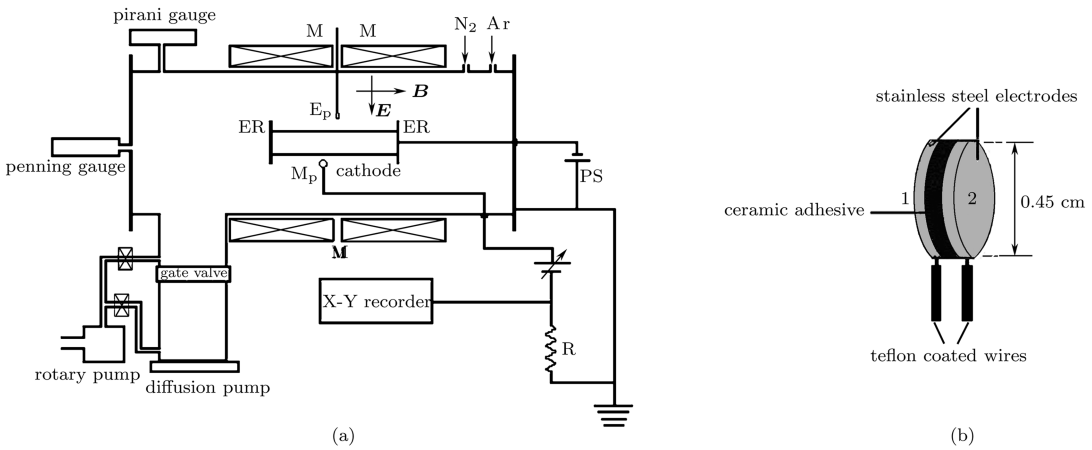


Fig. 1. Schematic diagram of (a) cylindrical magnetron device with different accessories: E – Electric field, B – Magnetic field, ER – End reflectors, E_p – Emissive probe, M_p – Mach probe, MM – Magnetic field coils, PS – dc power supply (1500 V, 5 A) and (b) Mach probe.

The vacuum unit consists of a rotary pump having a displacement capacity of 350 l/min and a diffusion pump with an effective pumping speed of 700 l/s. The base pressure of the chamber is on the order of 1.3×10^{-4} Pa (1 Torr = 1.3×10^{2} Pa). The discharge power is supplied from a stabilized dc power supply (1500 V, 5 A) working in the voltage-regulated mode. Argon gas is injected to the chamber to raise the neutral pressure up to 1.3×10^{-1} Pa by using a double valve system consisting of a stop valve and a needle valve. Plasma is produced by applying (400–700) V dc voltage between central cathode and the grounded chamber. A cylindrical Langmuir probe is used to measure the electron density and temperature.

The Mach probe constructed for determining the drift velocity of electrons consists of two plane Langmuir probes of diameter 0.45 cm each as shown in Fig. 1(b). Ceramic paste (∼0.05 cm thickness) is placed in between the probes to insulate them from each other. 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 therefore cannot collect the drifted electrons.

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 probe wire is suitably attached at two ends of two supporting stainless steel electrodes (each 0.025 cm in diameter). The supporting electrodes are covered by ceramic tubes for proper insulation with the plasma. The resistance used for floating potential measurement is 30 MΩ and accordingly the potential value is calibrated in the X-Y recorder. The continuous measurement of plasma potential profile is done by moving the probe slowly (1 cm/min) using a motor driving system attached to the emissive probe shaft.

3. Experimental results and discussions

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. The typical data of the measured axial magnetic field strength for 4 ampere of current flow which generates 0.01 T magnetic field are shown in Fig. 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 T) for a length of ∼30 cm in the central region (35 cm–65 cm). The field strength is found to gradually decrease on either side of this region.

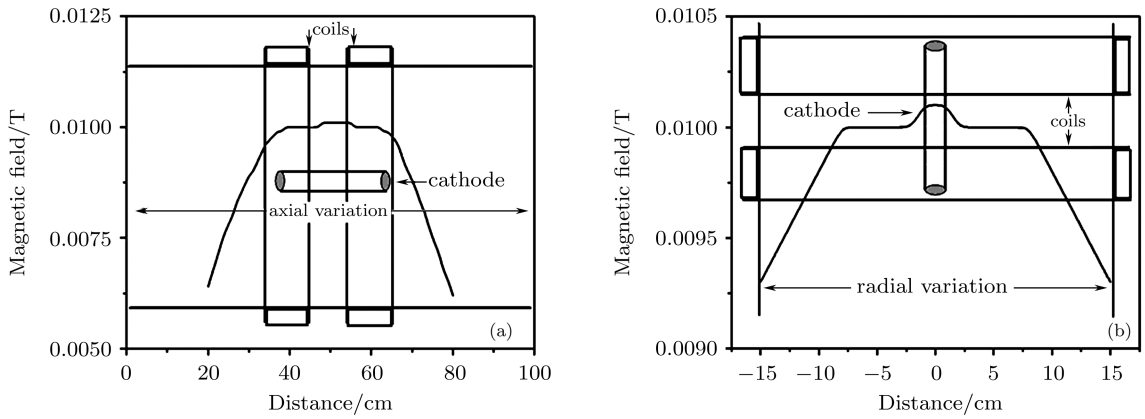


Fig. 2. Profile showing variations of magnetic field strength for 0.01 T in (a) axial direction and (b) radial direction.

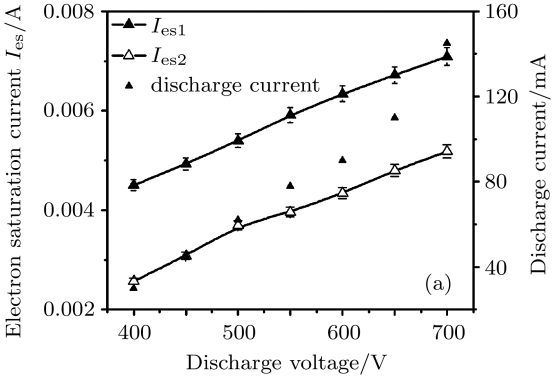
The measured radial variation of the magnetic field strength for the same current flow in the central region (at mid-point of the cathode and in the perpendicular direction of the cathode) is shown in Fig. 2(b). A steady magnetic field strength (∼0.01 T) is seen within a diameter of ∼15 cm. This profile is maintained along the length of the cathode.

3.2. Measurement of electron saturation current (I_{es})

The value of electron saturation current is measured from the semi-logarthimic plot of the electron current and is given by the intersection point between the two tangents; one is drawn at the Maxwellian part and the other at the electron saturation part of the I–V characteristics. I_{es1} and I_{es2} represent the electron saturation currents collected at the two opposite surfaces of the Mach probe respectively. Surface 1, which faces the $E \times B$ flow, collects the electron current of thermal electrons as well as drifted electrons. Surface 2 is along the direction of $E \times B$ flow, collects only the thermal electrons. The difference between 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.

3.2.1. I_{es} at different discharge voltages

The variation of electron saturation current with discharge voltage is shown in Fig. 3(a). The argon partial pressure is maintained at 2.66×10^{-1} Pa and the magnetic field strength at 0.01 T. The electron saturation currents 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 gain energy from the discharge which results in the increase in ionization rate and therefore, the increase in density and saturation current. Discharge current increases from ∼30 mA at 400 V to ∼175 mA at 700 V.



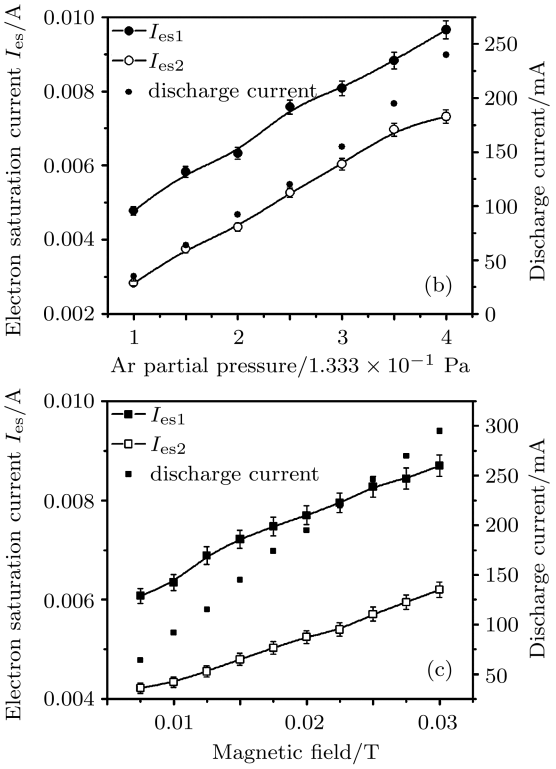


Fig. 3. Electron saturation current variation with (a) discharge voltage and discharge current at $B = 0.01$ T, $P_{Ar} = 2.66 \times 10^{-1}$ Pa and probe distance 3 cm from the cathode, (b) argon partial pressure at $B = 0.01$ T, discharge voltage = 600 V and probe distance 3 cm from the cathode. Corresponding discharge current variation is also shown and (c) applied magnetic field at $P_{Ar} = 2.66 \times 10^{-1}$ Pa, discharge voltage = 600 V and probe distance 3 cm from the cathode. Corresponding discharge current variation is also shown.

3.2.2. I_{es} at different argon partial pressures

In Fig. 3(b), the variation of electron saturation current with argon partial pressure is shown. The discharge voltage is at 600 V and the magnetic field strength is 0.01 T. It is found that the electron saturation current increases with the increase of argon partial pressure. The increase in argon partial pressure leads to an increase of the corresponding neutral density, and so the ionization rate also increases. This results in the increase in plasma density, leading to an increase in electron saturation current. Discharge current increases with increase in argon partial pressure.

3.2.3. I_{es} at different applied magnetic field strengths

The variation of electron saturation current with magnetic field strength is shown in Fig. 3(c). The corresponding discharge current variation is also shown

which increases from ∼64 mA at 0.0075 T to ∼295 mA at 0.03 T. Here, the discharge voltage is maintained at 600 V and the argon partial pressure is kept at 2.66×10^{-1} Pa. The electron saturation current is found to increase with the increase in applied magnetic field strength. There is an increase in effective confinement of electrons with the increase in applied magnetic field strength. This leads to an enhancement in ionization rate and plasma density.

3.3. Measurement of electron temperature (T_e)

The electron temperature is determined from the 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 following equation:

$$T_{\mathrm{e}} = \frac{\mathrm{d}V}{\mathrm{d}(\ln I)}, \tag{1}$$

where I and V are the probe current and the voltage respectively. The symbols T_{e1} and T_{e2} represent the electron temperatures at the two opposite surfaces (1 and 2) of the Mach probe. 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.

3.3.1. T_{e} at different discharge voltages

The variation of electron temperature with discharge voltage is shown in Fig. 4(a). The argon partial pressure is 2.66×10^{-1} Pa and the magnetic field strength is 0.01 T. The electron temperature is found to increase with the increase of discharge voltage. At a discharge voltage of 400 V, the electron temperature value for surface 1 is 1.7 eV, and it is found to increase to a value of 5.5 eV at a discharge voltage of 700 V. The electrons constituting the plasma gain momenta due to the increase in discharge voltage. This results in an increase in the thermal energy of the electrons, which will thereby result in the increase of electron temperature.

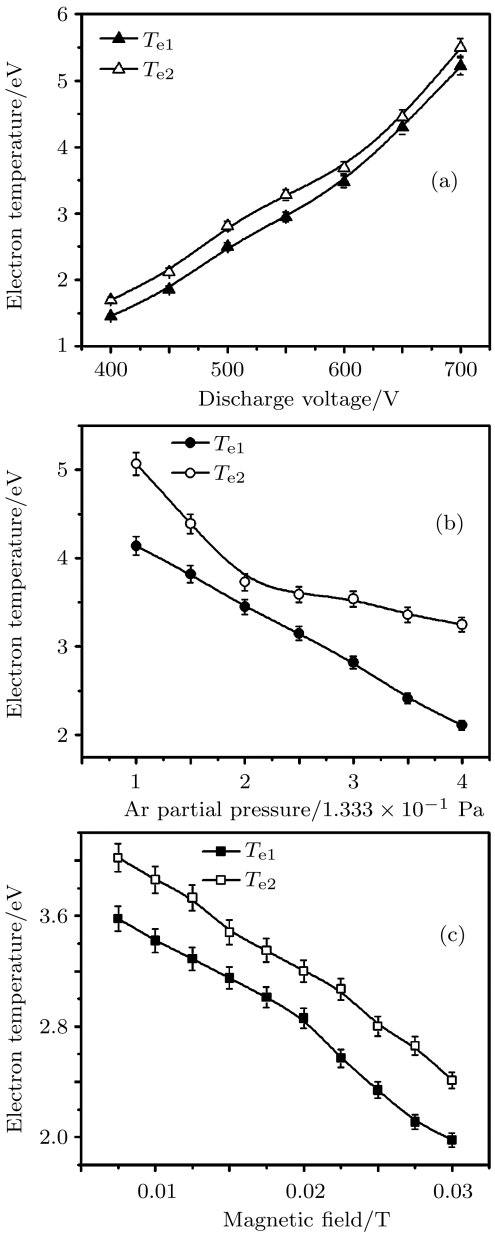


Fig. 4. Electron temperature variations with (a) discharge voltage at $B = 0.01$ T, $P_{\mathrm{Ar}} = 2.66 \times 10^{-1}$ Pa and probe distance 3 cm from the cathode. Discharge current varies from 30 mA at 400 V to 175 mA at 700 V, (b) argon partial pressure at $B = 0.01$ T, discharge voltage = 600 V and probe distance 3 cm from the cathode. Discharge current varies from 35 mA (1.33×10^{-1} Pa) to 240 mA (5.3×10^{-1} Pa) and (c) magnetic field at $P_{\mathrm{Ar}} = 2.66 \times 10^{-1}$ Pa, discharge voltage = 600 V and probe distance 3 cm from the cathode. Corresponding discharge current varies from 64 mA at 0.0075 T to 295 mA at 0.03 T.

3.3.2. T_{e} at different argon partial pressures

The variations of electron temperatures for the two surfaces of the Mach probe placed 3 cm away from the cathode at different argon partial pressures are shown in Fig. 4(b). The discharge voltage is

maintained at 600 V and the magnetic field is kept at 0.01 T. Electron temperature is found to decrease from 5.0 eV to 3.3 eV when the argon partial pressure is increased from 1.33×10^{-1} Pa to 5.3×10^{-1} Pa. Due to the increase in pressure, the neutral density increases. Increase in density will result in more number of collisions between the constituent electrons and the gas species which will lead to the loss of energy of these electrons. This energy loss will subsequently slow down their velocity and therefore, a decrease in 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 value is more here as compared with the drop at higher argon pressure.

3.3.3. T_e at different applied magnetic field strength

The variation of electron temperature with magnetic field strength is shown in Fig. 4(c). Here, the discharge voltage is maintained at 600 V and the argon partial pressure is kept at 2.66×10^{-1} Pa. The electron temperature is found to decrease from 4.0 eV to 2.4 eV with magnetic field strength increasing from 0.0075 T to 0.03 T. This is because more electrons are confined within the plasma and these electrons lose their energy to a greater extent due to both elastic and inelastic collisions. Further, as the plasma is confined at the cathode due to the higher magnetic field, less high energy electrons will reach the probe. As such the electron temperature will decrease. This results in decrease in electron temperature value with the increase in applied magnetic field strength.

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.[22] The electron saturation currents, I_{es1} and I_{es2}, collected at the two opposite surfaces (1 and 2) of the Mach probe, are measured. The ratio between the electron drift velocity (v_d) and the electron thermal velocity (v_t) is obtained. For surface 1 facing the drift,

$$I_{es1} = en_e(v_t + v_d)S, \tag{2}$$

similarly, the electron saturation current for the probe surface not facing the drift direction is given by

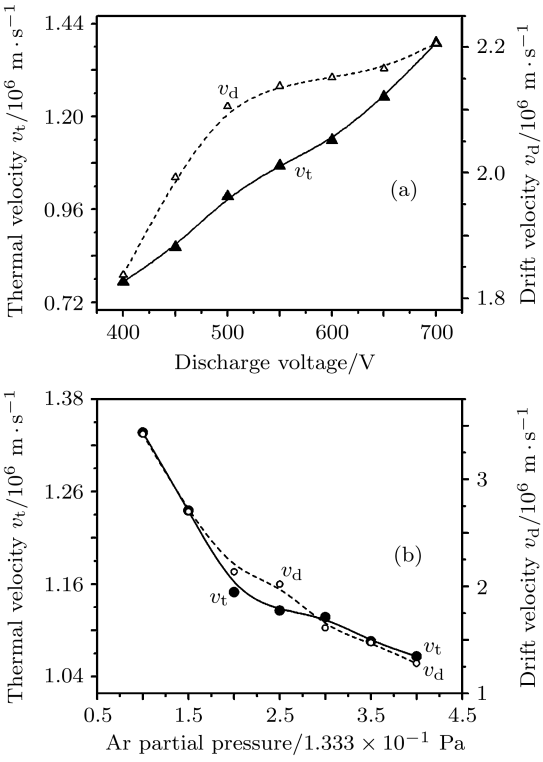
$$I_{es2} = en_e(v_t - v_d)S, \tag{3}$$

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 obtained from the relation as

$$v_d = \frac{I_{es1} - I_{es2}}{I_{es1} + I_{es2}} v_t, \tag{4}$$

where the thermal velocity is given by the following expression: $v_t = \sqrt{(T_e/2\pi m_e)}$.

The measured thermal velocities for different discharge voltages, argon partial pressures and applied magnetic field strengths are shown in Figs. 5(a), 5(b) and 5(c) respectively. The thermal velocity is found to increase with discharge voltage increasing as the electric field increases, which results in electrons gaining momenta. Such electrons are necessary to help sustain the glow discharge. With the increase of argon partial pressure and applied magnetic field strength, the thermal velocity decreases due to more number of collisions and higher confinement.



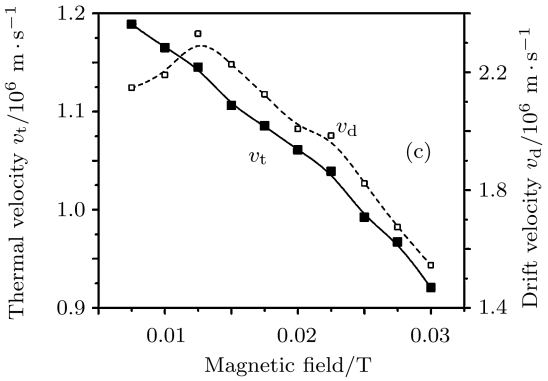


Fig. 5. Dual plots of thermal velocity and electron drift velocity varying with (a) discharge voltage at $B = 0.01$ T, $P_{\rm Ar} = 2.66 \times 10^{-1}$ Pa and probe distance 3 cm from the cathode, (b) argon partial pressure at $B = 0.01$ T, discharge voltage = 600 V and probe distance 3 cm from the cathode and (c) magnetic field at $P_{\rm Ar} = 2.66 \times 10^{-1}$ Pa, discharge voltage = 600 V and probe distance 3 cm from the cathode.

The measured $E \times B$ drift velocity with varying of discharge voltages, argon partial pressures and applied magnetic field strengths are also shown in Figs. 5(a), 5(b) and 5(c). The increase of discharge voltage increases the sheath electric field, thereby increasing the drift velocity (Fig. 5(a)). With the increase in the drift velocity of the electrons, they are able to travel enough distance away from the cathode with a sufficient amount of energy still left within them to contribute to the deposition process. Another parameter which has significant importance in the deposition process of thin films is the partial pressure of the discharge gas. The electron drift velocity is found to decrease with the increase in 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 pressure increasing (Fig. 5(b)). This decrease in electron drift velocity with the increase in partial pressure is not desirable for most deposition cases. The increase in 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 magnetic field also affects the ionization process, initial small increase in drift velocity is due to nominal increase in sheath electric field due to the increase of plasma density (Fig. 5(c)). Although the increase in magnetic field increases the ionization due to the increase in electron confinement, this aspect of confining the electrons very near to the cathode at high magnetic field is detrimental to the deposition process as there will not be sufficient energy transfer at the substrate surface placed away from the cathode.

The radial variation of the $E \times B$ drift velocity of the electrons is determined using the E/B method from the radial potential profile data measured with the help of an emissive probe. The floating potential method is used to measure the plasma potential. Figure 6 shows the profiles of the radial plasma potential at discharge voltages 400 V, 450 V, 500 V, 550 V and 600 V, with magnetic field fixed at 0.01 T and argon partial pressure at 2.66×10^{-1} Pa. 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 accurately measuring plasma potential in dc discharge.[9] The floating potential method is used to measure the plasma potential.[23] To determine the plasma potential by the floating potential method, the filament wire is heated by passing current so as to produce 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 is saturated. Then the axial sheath electric field (E) is determined from the measured potential structure. The electron drift velocity is then determined at radial position corresponding to that of the radial position of the Mach probe using the relation

$$v_{\rm d} = \frac{E \times B}{B^2} = \frac{E}{B}. \tag{5}$$

This is shown in Fig. 7(a). It is found that the electron drift velocity is very high near the cathode and it decreases away from the cathode. An important observation here is that this drift velocity matches very well to that determined from the Mach probe characteristic.

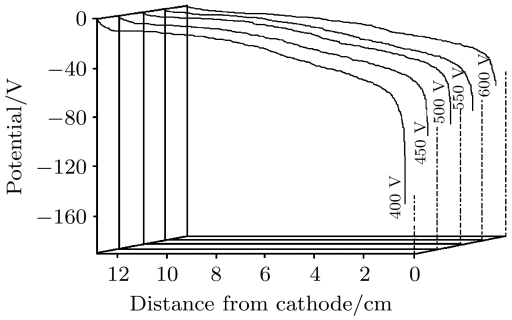


Fig. 6. Variations of radial plasma potential profiles at different discharge voltages using an emissive probe at $B = 0.01$ T and $P_{\rm Ar} = 2.66 \times 10^{-1}$ Pa.

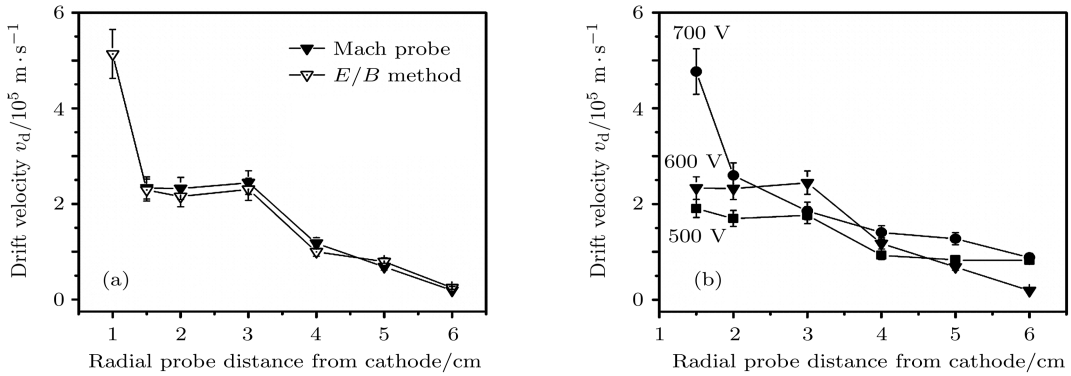


Fig. 7. Radial variations of electron drift velocity measured by (a) both Mach probe and emissive probe at $B = 0.01$ T, $P_{Ar} = 2.66 \times 10^{-1}$ Pa and discharge voltage = 600 V and (b) Mach probe at different discharge voltages at $B = 0.01$ T, $P_{Ar} = 2.66 \times 10^{-1}$ Pa.

The electron drift velocities measured using the Mach probe at different radial positions away from the target cathode at three different discharge voltages are shown in Fig. 7(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 maintains 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 the increase of 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 the sheath electric field decreases away from the cathode, the drift velocity decreases. It is found that the drift velocity decreases from 10^5 m·s^{-1} to 10^4 m·s^{-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.

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 the radial direction, the drift velocity gradually decreases from the cathode centre toward the anode region where it becomes mimimum. The measured potential profile using emissive probe indicates that the sheath dimension is nearly a few tens of Debye length. The observed drift also mainly occurs within the cathode sheath region. The $E \times B$ effect on electrons is effective mainly near the cathode region due to the higher strength of radial electric field. The drift velocities of electrons calculated both from Mach probe characteristics and E/B method accord well with each other all throughout. The estimated drift velocity helps to understand the electron diffusion in the magnetron sputtering device and determines the appropriate discharge conditions and plasma parameters for deposition process of thin films.

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References

[1] Borah S M, Bailung H, Pal A R and Chutia J 2008 *J. Phys.* D: *Appl. Phys.* **41** 195205

[2] Borah S M, Pal A R, Bailung H and Chutia J 2008 *Appl. Surf. Sci.* **254** 5760

[3] Wendt A E, Lieberman M A and Meuth H 1988 *J. Vac.*

Sci. Technol. A **6** 1827
[4] Sheridan T E, Goeckner M J and Goree J 1990 *J. Vac. Sci. Technol.* A **8** 30
[5] Riemann K U 1992 *Phys. Fluids* B **4** 2693
[6] Kakati H, Pal A R, Bailung H and Chutia J 2006 *J. Appl. Phys.* **100** 083303
[7] Oksuz L and Hershkowitz N 2004 *Plasma Sources Sci. Technol.* **13** 263
[8] Kato I, Nakano Y and Yamaguchi N 2000 *Jpn. J. Appl. Phys. Part 1-Regular Papers Short Notes Rev. Papers* **39** 6404
[9] Fisher E R 2002 *Plasma Sources Sci. Technol. (Special Issue)* **11** A105
[10] Koltai L, Hildebrandt D, Bakos J S and Bachmann P 1990 *J. Nucl. Mater.* **176** 1044
[11] Hutchinson I H 1988 *Phys. Rev.* A **37** 4358
[12] Chung K S and Hutchinson I H 1988 *Phys. Rev.* A **38** 4721
[13] Gunn J P, Boucher C, Devynck P, Duran I, Dyabilin K, Horacek J, Hron M, Stokel J, Van Oost G, Van Goubergen H and Zacek F 2001 *Phys. Plasmas* **8** 1995
[14] Pal A R, Chutia J and Bailung H 2004 *Phys. Plasmas* **11** 4719
[15] Adhikary N C, Pal A R, Bailung H and Chutia J 2006 *Phys. Lett.* A **350** 380
[16] Sheridan T E, Goeckner M J and Goree J 1998 *J. Vac. Sci. Technol.* A **16** 2173
[17] Bradley J W, Thompson S and Aranda Gonzalvo Y 2001 *Plasma Sources Sci. Technol.* **10** 490
[18] Rossnagel S M and Kaufman H R 1987 *J. Vac. Sci. Technol.* A **5** 88
[19] Rossnagel S M and Kaufman H R 1987 *J. Vac. Sci. Technol.* A **5** 2276
[20] Fujita H, Yagura S, Ueno H and Nagano M 1986 *J. Phys.* D: *Appl. Phys.* **19** 1699
[21] Kakati H, Pal A R, Bailung H and Chutia J 2007 *J. Phys.* D: *Appl. Phys.* **40** 6865
[22] Yamada M and Hendel H W 1978 *Phys. Fluids* **21** 1555
[23] Coakley P, Hershkowitz N, Hubbard R and Joyce G 1978 *Phys. Rev. Lett.* **40** 230