Chapter 3

Studies on post magnetron discharge plasma

3.1 Introduction

Magnetron sputtering sources are low-pressure plasma devices in which externally applied magnetic field confines electrons near the cathode surface to form electron traps [Thornton-1978]. Penning (1935) first studied the low pressure sputtering in which a transverse magnetic field was superimposed on a dc glow discharge tube. He found that superimposition of the magnetic field of 300 Gauss lowered the sputtering gas pressure by a factor of ten and increased the deposition rate of sputtered films. In a magnetron, the transverse magnetic field $B$ is superposed on the electric field $E$. Due to the combined affect of electric and magnetic fields, the electron shows cycloidal motion with a gyro frequency

$$\omega = \frac{eB}{m_e} \quad (3.1)$$

and the center of the orbit drifts in the direction of $EXB$ with the drift velocity $(v_d)$ represented by

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\[ v_E = \frac{ExB}{|B|^2} = \frac{|E|}{|B|} \]  

(when \( E \) and \( B \) are perpendicular to each other) \( (3.2) \)

When the applied magnetic field strength is such that it affects the electrons but not the ions, a current density \( (J_\perp) \) will flow in the direction of \( E \). It is represented by the expression

\[ J_\perp = eN_e\mu_{e\perp}E + eN_i\mu_{i\perp}E \]  

(3.3)

Where \( N_e \) and \( N_i \) are plasma electron density and ion density, \( \mu_{e\perp} \) and \( \mu_{i\perp} \) are the mobility of electrons and ions in the direction perpendicular to the magnetic field and \( e \) is the electronic charge. Due to \( ExB \) drift, an electron Hall current density \( (J_H) \) will flow in the \( ExB \) direction, which is represented by

\[ J_H = \frac{\omega_c}{v_e} J_\perp = \frac{\omega_c}{v_e} eN_e\mu_{e\perp}E \]  

(3.4)

Where \( \omega_c \) is the cyclotron frequency and \( v \) is the collision frequency for the species under consideration. The mobility perpendicular to the magnetic field is given by

\[ \mu_\perp = \frac{\mu}{1 + \left( \frac{\omega_c}{v} \right)^2} \]  

(3.5)

Where \( \mu = e/(m\nu) \) is the mobility in the absence of a magnetic field or along the field line \( (\mu_0) \) and \( m \) and \( e \) are the mass and charge of the species under consideration. The diffusion coefficients can be written as \( D = \mu k T / e \) (\( k \) is Boltzman constant) and therefore can be represented as

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With increasing the magnetic field, as $\omega_e$ increases significantly, the diffusion coefficient reduces across the magnetic field and hence particle loss rate is decreased. Also due to EXB drift the electrons lifetime and also the path length of the electrons around the cathode increases. This type of electron motion increases the collision probability between the electrons and the atoms, therefore the ionization rate increases. The resultant effect is that, the plasma density becomes very high in the vicinity of the cathode due to enhanced ionization rate and lower diffusion rate. As the plasma density increases, the current density at the cathode becomes higher and therefore the sputtering rate also increases.

There are several types of magnetrons for practical sputtering applications [Roth 1995, Edwin et al 1991]. One among them is the post magnetron having cylindrical geometry and axial magnetic field, which consists of two coaxial cylinders with inner cylinder as target-cathode. When the inside of the outer chamber becomes the target, the arrangement is known as an inverted magnetron [Chapman 1980]. Although the electrons are constrained in their radial motion, there is little to restrict their axial motion and they can therefore diffuse towards the end of the target. These end losses can be prevented by various types of end containment, to increase the effectiveness of the discharge [Thornton 1978, Yeom et al 1989a]. High currents and sputtering rates can be obtained, at moderate and near constant voltages, even at low pressures. This characterizes what has been known as magnetron mode of operation. Thornton (1978) has experimentally investigated the basic properties of cylindrical magnetron discharges. It was found that with proper choice
of magnetic field, magnetron mode operation with near common I-V characteristics has been achieved for a wide range of apparatus sizes in both cylindrical post and cylindrical hollow configurations. The discharge current-voltage characteristics and plasma parameters like plasma potential, plasma density, electron temperature etc. have also been studied in cylindrical post and hollow magnetron configurations both for dc and rf operations [Yeom et al 1989a, b]. It is revealed in that study that in case of rf operation, the discharge does not generally operate in the magnetron mode though it is possible to design magnetrons specifically for ac operation. In such a design the electron traps are located at each electrode and joined at their periphery by common field lines so the anode current flow is not totally frustrated. The dependence of plasma parameters on the values of magnetic field has been studied numerically in case of a glow discharge in a transverse magnetic field [Pekker 1995] where the condition under which the cathode fall would disappear is obtained.

The plasma instabilities under EXB flow have been investigated extensively since last few decades [Simon 1963, Thomassen 1966, Coppi et al 1967, Sheridan et al 1989, Sakawa et al 1992, Martines et al 2001]. Such instabilities may occur in case of fusion plasmas in toroidal devices [Thomas Jr. et al 2003], ionospheric plasmas, cylindrical and planar magnetron discharges etc. The basic theory of the EXB driven instability in a partially ionized magnetized plasma and the corresponding nonlinear transport in crossed electric and magnetic fields, is given by Simon and Hoh [Simon 1963, Hoh 1963, Kim and Simon 1968, Simon 1968a, b]. Simon and Hoh's theory mainly deals with the EXB flow and density gradient in the plasma. In the presence of magnetic shear, localized non-convective normal modes of instability are shown to exist due to ion temperature gradients.
A few numbers of experiments have also been performed to study the EXB instability and related anomalous cross-field transport mechanism [Thomassen 1966, Sheridan et al 1989, Sakawa et al 1992, van der Straaten et al 1998b, Martines et al 2001, Thomas Jr. et al 2003]. Anomalous diffusion arising from low frequency flute instability is investigated in a penning discharge by Thomassen (1966) where a small magnetic well is also created to suppress the instability and lower the loss rate. Sakawa et al (1992) have observed a modified Simon-Hoh instability in a collisionless plasma column that is produced by a weak electron beam. The nonlinear evolution of that instability is found to occur through a sequence of side band instabilities, which was thought to be induced by trapped ions. In the experiment by Thomas Jr. et al (2003), a low frequency instability has been observed in the frequency range below the ion cyclotron frequency. The experiment is performed in a linear magnetized plasma device and found that the instabilities have long azimuthal wavelengths and are localized in the plasma region where the sheared flow is maximized and are anticorrelated to both density gradients and field-aligned currents. Most of the experiments detected the instability near the ion plasma frequency range as predicted from the original works of Simon and Hoh. Theoretical work is still going on to explore the various aspects of the EXB driven instabilities and EXB sheared flows [Tao et al 1994, Krasheninnikov et al 1995, Burrell 1997, Ganguli 1997, Chen 1998, van der Straaten and Cramer 2000]. Pekker [1995] has shown analytically that for long magnetron discharges where electrons as well as ions are magnetized, the discharge can exist without cathode fall at certain discharge conditions. This is due to the fact that, for high magnetic field strength, the electron mobility decreases and the classical electron mobility transverse to the magnetic field approaches the value of ion mobility. This leads to a decrease in the
cathode fall voltage and an increase in the anode fall voltage. Cramer (1997) has used a semi-analytical method to study the steady state magnetized discharge with fluid equations. He concluded that, at a pressure of 5 mTorr and a magnetic field of 300 Gauss, transition from positive space charge (PSC) mode to negative space charge (NSC) mode takes place. Another investigation by Van der Straaten et al. [1998a], where a low pressure cylindrical post cathode dc short magnetron (where only the electrons and not the ions, are magnetized) discharge is studied using one dimensional PIC code, found that there is a transition from the usual PSC mode to NSC mode at higher values of magnetic field to pressure ratio, B/P (~100 Gauss/mTorr).

Though the transition from PSC to NSC mode is predicted by fluid models [Pekker 1995, Cramer 1997, Pekker and Krasheninnikov 2000] as well as by one-dimensional particle-in-cell (PIC) simulation [Van der Straaten et al 1998a] experimentalists are not able to confirm the transition of the discharge to so called NSC mode in the magnetron discharges operated in the similar ranges of pressure and magnetic fields as used in the theory and simulation [Van der Straaten et al 1998a]. The persistence of cathode fall at low pressure and high magnetic fields suggests that the electron transport co-efficients across the magnetic field lines are much greater than the classical values. Unstable electrostatic waves in the EXB direction may be a cause of enhanced electron transport above the classically predicted level [Van der Straaten and Cramer 2000].

In the earlier theoretical works on the instabilities due to EXB flow [Simon 1963, Hoh 1963, Kim and Simon 1968, Simon 1968a, b], the authors considered the quasineutrality of the plasma and also neglected the inertia of both the electrons and the ions, so that the dispersion relation they obtained was applicable to the frequencies below
the ion cyclotron frequency and ion collision frequency. In a recent work by Van der Straaten and Cramer (2000), the ion inertia is also taken into account to study the dispersion relation for electrostatic modes in a cylindrical magnetron discharge. They found the existence of the solutions with large growth rates of the order of electron transit time, at frequencies of the order of several MHz. Such instabilities could cause a significant increase in the second-order \( (E \times B) \times B \) radial electron transport, which in turn supports that the instabilities may contribute to the anomalous transport of electrons that prevents the transition of PSC mode to NSC mode.

The results of an experimental investigation of the discharge properties, sheath and related instabilities in a post magnetron plasma system, is presented in this chapter. The generation, growth and suppression of instabilities in the frequency range of 45 MHz to 100 MHz have been studied. The variation of the frequency and amplitude of the instability with magnetic field, discharge voltage and gas pressure has also been investigated in detail. Possible reasons for generation of this type of instabilities and its affect on particle transport is discussed.

### 3.2 Experimental set up and measurement techniques:

Fig. 3.1(a) represents the post magnetron device used in this experiment. The device consists of a stainless steel cylindrical chamber with 20 cm in diameter and 100 cm in length. A small stainless steel cylinder with 1.5 cm in diameter and 15 cm in length is placed co-axially inside the chamber. This small cylinder acts as a cathode and the grounded plasma chamber itself is used as anode of the discharge system. To prevent the
end loss of energetic electrons, two stainless-steel discs of 5 cm in diameter are fixed at both ends of the cathode, which acts as end reflectors (ER) for the electrons. An axial magnetic field up to 200 Gauss is produced by passing direct current through two solenoid coils wrapped around the body of the chamber. The magnetic field is axially uniform within a length of 18 cm at the central region of the chamber. Low pressure is created using a combination of Rotary and Diffusion pumps. The base pressure of the chamber is 6x10⁻⁶ mbar and working argon pressure is varied within the range of (1x10⁻¹ - 5x10⁻¹) mbar. A pirani gauge and a penning gauge are used for measurement of pressure. The discharge power is supplied from a stabilized dc power supply (1000 V, 1 A) working in the voltage-regulated mode. The positive terminal of the output of the power supply is grounded and the negative terminal is connected to the cathode through co-axial cable.

A cylindrical Langmuir probe (Lp) made of tungsten having 0.5 mm in diameter and 5 mm in length, is used to record the fluctuation in the electron saturation current by biasing it at the plasma potential. The same probe is also used to measure plasma density ($n_e$) and Temperature ($T_e$) from its I-V characteristics. The probe is placed in such a way that its collecting surface remains perpendicular to the magnetic field lines so that no significant depletion in the electron collection current can occur.

The use of Langmuir probe for fluctuation measurement at high frequencies requires care in order to avoid resonances induced by parasitic capacitances and inductances due to both circuit elements and the plasma sheath. In this experiment the measurements are taken in the plasma region and not within the cathode sheath, hence the effect of cathode sheath is avoided. Also while taking the data we have biased the probe at a potential equal to the plasma potential, so there is no chance of sheath formation in front
of the probe, hence the effect of probe sheath is also avoided. The probe size is also kept as small as possible. The size of the probe cannot be reduced further since in that case the probe draws too small amount of current to give any significant information about the plasma. When the current drawn by the probe becomes very low, noise dominates and it becomes difficult to measure the plasma parameters correctly. In this experiment, the main control variables are magnetic field, gas pressure and discharge voltage. The data are taken at an applied voltage range of (525 - 700) V, magnetic field range of (45-200) Gauss and gas pressure range of (1x10^{-3} - 5x10^{-3}) mbar. The discharge current is within the range of 25 mA to 900 mA in the present experiment. An emissive probe (E_p) of 0.05 mm in diameter and 2.5 mm in length is used to measure the plasma potential by inflection point method [Smith et al 1979, Boruah et al 2003]. The plasma potential is found to vary within 0 to -30 V for the present experimental conditions. The electron temperature and the density measured with the help of the Langmuir probe is found within (2-8) eV and (10^8 - 10^{10}) cm^{-3} respectively. To record the instability, the fluctuation in the electron saturation current of the Langmuir probe is recorded by biasing the probe at plasma potential. The signal picked up by the Langmuir probe, is fed into a Digitizing Storage Oscilloscope (DSO) through co-axial cable and dc blocking capacitor (0.1 μF). The Fast Fourier Transform (FFT) of the signal is done using the inbuilt FFT software package of the oscilloscope. The digital Fourier transformed data (frequency spectra) are transferred to a computer. The frequency and amplitude of the instability generated in the plasma is measured from these frequency spectra. The investigation is carried out in a short magnetron device where only electrons are magnetized. Ions are unmagnetized in the sense that their gyro radius is large compared with the system dimensions.
3.3 Experimental Results and Discussion:

3.3.1 Discharge current voltage characteristics:

The current-voltage characteristics of the discharges operating in the magnetron mode obey an I-V relationship of the form $I \propto V^n$, where $n$ is an index of the performance of the system. Discharge current-voltage characteristics at three different magnetic fields ($B = 75$ Gauss, 150 Gauss and 200 Gauss) at an argon pressure $P_{Ar} = 3 \times 10^{-3}$ mbar are presented in Fig. 3.2(a). Discharge current is found to increase with the magnetic field as well as with the discharge voltage. With increasing the magnetic field from 75 Gauss to 200 Gauss the discharge current increases from 13 mA to 80 mA at a discharge voltage of 550 V and it changes from 25 mA to 400 mA at a discharge voltage of 800 V. Discharge current up to 900 mA is recorded at $P_{Ar} = 4.5 \times 10^{-3}$ mbar when the magnetic field is 200 Gauss and the discharge voltage is 525 V (Fig. 3.2(b)).

The parameter $n$, which gives the discharge current-voltage relationship $I \propto V^n$, is plotted against magnetic field at different pressures in Fig. 3.3. At low magnetic field the value of $n$ is 1.75 at a pressure of $1.5 \times 10^{-3}$ mbar and it is found to increase with the magnetic field, but the rate of rise is faster at higher magnetic fields above 150 Gauss. With increasing the gas pressure $n$ takes higher values. The $n$ value up to 7.5 is obtained at a magnetic field of 200 Gauss and gas pressure of $4.5 \times 10^{-3}$ mbar.

3.3.2 Density and temperature measurements:

The radial profiles of electron temperature measured from Langmuir probe $I-V$ characteristics are presented in Fig. 3.4(a) for three different magnetic fields at a fixed
discharge voltage of 650 V and argon pressure of $3 \times 10^{-3}$ mbar. The electron temperature is higher near the cathode i.e. within the magnetic trap and it goes on decreasing radially away from the cathode as the electrons lose their energy in collision and ionization while traveling radially outward. Near the cathode surface at a distance of 2.5 cm, the electron temperature ($T_e$) is very high. $T_e = 6.5$ eV when the magnetic field is 200 Gauss and it takes a lower value (4.5 eV) at a magnetic field of 75 Gauss. The high value of the electron temperature within the magnetic trap is due to the confinement of the energetic electrons by the magnetic field. Electron temperature decreases towards the bulk plasma region when one moves away from the cathode surface. $T_e = 3.5$ eV at a magnetic field of 75 Gauss, but it is found to take the value of 2.5 eV when the magnetic field is 200 Gauss. This is due to the fact that electrons lose their energy to a greater extent due to elastic and inelastic collisions when it moves away from the cathode surface. The electron temperature slightly increases near the anode. The increase of electron temperature near the anode is due to an energy gain in the anode sheath region where the electrons convert such energy into thermal energy through collision [Passoth et al 1999].

Fig. 3.4(b) represents the radial plasma density profiles at three different magnetic fields ($B = 75$ Gauss, 150 Gauss and 200 Gauss) at an argon pressure $P_{Ar} = 3 \times 10^{-3}$ mbar and a fixed discharge voltage $V_d = 650$ V. Plasma density is measured from the ion saturation current of the Langmuir probe. With increasing the magnetic field from 75 Gauss to 200 Gauss, the electron density increases from $4.75 \times 10^9$ cm$^{-3}$ to $9.50 \times 10^9$ cm$^{-3}$ at a
FIG. 3.2: Discharge current-voltage characteristics at different magnetic fields for argon pressures (a) $3 \times 10^{-3}$ mbar and (b) $4.5 \times 10^{-3}$ mbar.
FIG. 3.3: The parameter $n$, which gives the discharge current-voltage relationship $I \propto V^n$, is plotted against magnetic field at different pressures.
FIG. 3.4:  (a) Electron temperature profiles at different magnetic fields  
(b) Plasma density profiles at different magnetic fields
distance of 2.75 cm from the cathode surface. For all the three magnetic fields a sharp radial gradient in the electron density is noted. With increasing the magnetic field, the electrons become confined nearer to the cathode. Their lifetime increases, they follow a cycloidal path around the cathode due to combined effect of the magnetic field and $ExB$ flow. The electron gyro-radius is $10^{-4} - 10^{-3}$ meters and their gyro-frequency ($\omega_{ce}$) is 200 ~ 500 MHz. The electron collision frequency ($v_e$) in the present experiment is 5 ~ 45 MHz. The plasma density increases with the magnetic field due to higher rate of ionization and enhanced confinement as the diffusion co-efficient is reduced according to the equation (3.6). The increase of discharge current with magnetic field and discharge voltage as observed in Fig. 3.2, is mainly due to increase of plasma density.

3.3.3 Plasma potential measurement:

Fig. 3.5 represents the radial plasma potential profiles measured by the emissive probe using the inflection point technique. The potential profiles at three different magnetic fields ($B = 75$ Gauss, 150 Gauss and 200 Gauss) at fixed argon pressure $P_{Ar} = 3 \times 10^{-3}$ mbar and discharge voltage $V_d = 650$ V are presented in Fig. 3.5(a). With increasing the 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 three magnetic fields a sharp radial gradient in the plasma potential and hence strong electric field is noted near the cathode region. Though the density increases, the cathode
FIG. 3.5(a): Radial potential profiles for three different magnetic fields ($B = 75$ Gauss, $150$ Gauss and $200$ Gauss) at fixed argon pressure $P_{Ar} = 3 \times 10^3$ mbar and discharge voltage $V_d = 650$ V
FIG. 3.5(b): Radial potential profiles for three different discharge voltages ($V_d = 600 \, V$, $650 \, V$ and $700 \, V$) at fixed argon pressure $P_{Ar} = 3 \times 10^{-3} \, \text{mbar}$ and magnetic field $B = 150 \, \text{Gauss}$.
FIG. 3.5(c): Radial potential profiles for three different argon pressures \( P_A = 1.5 \times 10^{-3} \) mbar, \( 3 \times 10^{-3} \) mbar and \( 4.5 \times 10^{-3} \) mbar \) at a fixed magnetic field \( B = 200 \) Gauss and a discharge voltage \( V_d = 650 \) V.
sheath is found to expand with the magnetic field. This is due to the enhanced confinement of electrons near the cathode surface, which reduces the effective positive ion concentration within the sheath. With increasing the discharge voltage the cathode sheath is found to expand (Fig. 3.5(b)). The potential profiles are also recorded for different argon pressures keeping the discharge voltage and the magnetic field unchanged (Fig. 3.5(c)). Sheath expansion occurs with lowering the gas pressure, but transition to the negative space charge (NSC) mode, which is characterized by a very weak cathode fall and broad anode fall, does not take place even when the magnetic field is \( B = 200 \) Gauss and pressure is \( P_{Ar} = 1.5 \times 10^{-3} \) mbar (i.e. \( B/P_{Ar} = 175 \) Gauss/mTorr).

Since according to the theoretical work and particle simulation, the transition to the NSC mode should take place when the ratio \( B/P_{Ar} = \sim 100 \) Gauss/mTorr, but it is not taking place in a practical situation, so it is predicted that there may be some kind of instability responsible for the enhanced transport of electrons above the classically predicted value. The rest part of this chapter represents the results of investigations on the instabilities under \( EXB \) flow in the post magnetron discharge plasma.

### 3.3.4 Study of plasma instabilities:

Typical frequency spectra of instability, observed with the help of a Langmuir probe and recorded in a digitizing oscilloscope, when the discharge voltages are 575 V, 625 V and 675 V respectively, are presented in Fig. 3.6(a, b & c), for different magnetic fields at argon pressure of \( 3 \times 10^{-3} \) mbar. The Langmuir probe is placed at a distance of 3.25 cm from the cathode surface. An unstable signal is observed within the frequency range of
FIG. 3.6(a): Typical frequency spectra of instability at a discharge voltage of 575 V for six different magnetic fields, recorded with the help of a Langmuir probe and Digitizing Oscilloscope. The arrow mark indicates the instability.
FIG. 3.6(b): Typical frequency spectra of instability at a discharge voltage of 625 V for six different magnetic fields, recorded with the help of a Langmuir probe and Digitizing Oscilloscope. The arrow mark indicates the instability.
FIG. 3.6(c): Typical frequency spectra of instability at a discharge voltage of 675 V for six different magnetic fields, recorded with the help of a Langmuir probe and Digitizing Oscilloscope. The arrow mark indicates the instability.
FIG. 3.7: Time series signal of instability showing the growth of a constant small amplitude sinusoidal external signal when the frequency of the external signal matches with the frequency of instability.
FIG. 3.8: Frequency spectra of instability showing the growth of a constant small amplitude sinusoidal external signal when the frequency of the external signal matches with the frequency of instability.
FIG. 3.9: Plot of the electron saturation current of the Langmuir probe ($I_s$) vs Discharge voltage ($V_d$) for three different magnetic fields ($B = 75$ Gauss, $100$ Gauss and $125$ Gauss) at a pressure $P_{Ar} = 3 \times 10^{-3}$ mbar. The Current-Voltage characteristics form Hysteresis loop.
45 – 100 MHz, the frequency and amplitude of that signal is found to vary with the magnetic field and the discharge voltage.

3.3.4.1 Growth of an externally applied test signal:

To verify the existence of instability, a nearly equal amplitude test signal is subjected to interact with the observed unstable mode. The test signal is a continuous sinusoidal signal with varying frequency, applied to the plasma through the cathode when the excited instability frequency is set at 70 MHz. A 0.1 μF capacitor is connected in between the cathode and the signal generator to block the high voltage dc. Modified perturbations of the time series signal during interaction are recorded with the Langmuir probe using the DSO and presented in Fig. 3.7 for $B = 85$ Gauss, $V_d = 625$ V and $P_{Ar} = 3 \times 10^{-1}$ mbar. The frequency of the test signal is varied from 55 MHz to 85 MHz. When the frequency of the test signal (55 MHz) is much lower than the instability frequency (Fig. 3.7(b)) the amplitude of the test signal is unaffected which signifies that the interaction does not occur at this stage. The FFT signal of this time series data clearly shows two equal amplitude peaks at frequencies 55 MHz and 70 MHz (not shown Figure). The interaction begins when test signal frequency is increased to 65 MHz (Fig. 3.7(c)) and the amplitude of the received signal becomes nearly equal to the sum of the interacting signals. When test signal frequency is increased to 70 MHz i.e. equal to the instability frequency (Fig. 3.7(d)), a resonant interaction occurs and received signal amplitude becomes nearly four times that of the individual interacting wave amplitude. This confirms the non-linear energy exchange of the instability with the test wave. With further increase in frequency of the test signal, the interaction becomes weaker (Fig. 3.7(e)) and disappears completely.
when test signal is 85 MHz (Fig. 3.7(f)). The frequency spectra of the instability along with the applied signal are presented in Fig. 3.8 for a different magnetic field of 100 Gauss where the observed instability frequency is 80 MHz. The frequency of the applied signal is varied from 55 MHz to 95 MHz at the step of 5 MHz. The arrow mark indicates the external applied signal. It is clearly seen that the external signal grows when the frequency of the external signal matches with the frequency of observed instability.

3.3.4.2 Formation of hysteresis loop in the current-voltage characteristics:

In Fig. 3.9 the electron saturation current of the Langmuir probe ($I_{sat}$) vs. discharge voltage ($V_d$) is plotted for three different magnetic fields ($B=75$ Gauss, 100 Gauss and 125 Gauss) at a pressure $P_{Ar}=3\times10^{-3}$ mbar. The electron saturation current forms hysteresis loop when the discharge voltage is increased from 540 V to 700 V and then decreased back to 540 V. The observed instability threshold and growth are found to be well within the hysteresis loop [Timm and Piel 1992] shown in Fig. 3.9. A hysteresis loop is commonly used to infer the available free energy of a system.

3.3.4.3 Measurement of frequency and amplitude of instability:

The frequency and the amplitude of instability are measured from the frequency spectra. In Fig. 3.10(a) the variation of the frequency ($f$) of the instability with the magnetic field ($B$) at a fixed pressure ($P_{Ar}=3\times10^{-3}$ mbar) is plotted for three different discharge voltages ($V_d=600$ V, 650 V and 700 V). It is found that when the magnetic field is increased at a fixed discharge voltage of 600 V, instability starts at a magnetic field of 75 Gauss and initially the frequency of instability increases rapidly from 60 MHz onwards.
and at higher magnetic fields the rate of increase in frequency with magnetic field becomes low. With increasing the discharge voltage the frequency of instability also increases from 60 MHz to 70 MHz when $V_d$ is increased from 600 V to 700 V at a magnetic field of 75 Gauss. At high discharge voltages, the frequency tends to saturate.

The Variation of the frequency ($f$) of the instability with the argon pressure ($P_{Ar}$) is presented in Fig. 3.10(b) at a fixed discharge voltage ($V_d = 625$ V) for three different magnetic fields ($B = 75$ Gauss, 150 Gauss and 200 Gauss). At $B = 75$ Gauss the frequency of instability increases from 65 MHz onwards with increasing the pressure from $1.75 \times 10^{-1}$ mbar to $2.5 \times 10^{-3}$ mbar and the frequency becomes saturated at 70 MHz with further increase of pressure. At high magnetic field ($B = 200$ Gauss) the frequency increases from 100 MHz to 105 MHz within a very small range of pressure $P_{Ar} = 1.75 \times 10^{-1}$ mbar to $2.0 \times 10^{-1}$ mbar and it becomes saturated thereafter. The frequency spectra are also recorded at various radial positions to measure the radial variation of frequency and amplitude of the instability. No significant radial variation of the frequency of instability is noted; only the amplitude of instability is found to decrease radially outward.

Fig. 3.11(a) represents the variation of the amplitude ($A$) of the instability with the magnetic field ($B$) at a fixed pressure ($P_{Ar} = 3 \times 10^{-3}$ mbar) for three different discharge voltages ($V_d = 600$ V, 650 V and 700 V). The amplitude of instability is evaluated from the height of the peak in the frequency spectra. The amplitude is found to increase initially with increasing magnetic field and it peaks at an intermediate magnetic field and after that the amplitude decrease. At higher discharge voltages the amplitude become maximum at
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FIG. 3.10: Variation of the frequency (f) of the instability: (a) with the magnetic field (B) at a fixed pressure (P_{Ar} = 3 \times 10^{-3} mbar) for three different discharge voltages (V_d = 600 V, 650 V and 700 V). (b) with the argon pressure (P_{Ar}) at a fixed discharge voltage (V_d = 625 V) for three different magnetic fields (B = 75 Gauss, 150 Gauss and 200 Gauss).
FIG. 3.11: Variation of the amplitude (A) of instability (a) with the magnetic field (B) at a fixed pressure ($P_{Ar} = 3 \times 10^{-3}$ mbar) for three different discharge voltages ($V_d = 600$V, $650$V and $700$V) (b) with argon pressure.

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FIG. 3.12: Plot of discharge voltage \( V_d \) vs. magnetic field \( B \) for instability threshold and instability peak at a fixed argon pressure \( P_{Ar} = 3 \times 10^{-3} \) mbar.
lower magnetic fields. At a very high discharge voltage or magnetic field the instability ceases to occur. The variation of the amplitude \( A \) of the instability with the argon pressure \( P_{Ar} \) at a fixed discharge voltage is also recorded Fig. 3.11(b). The amplitude of the instability is found to decrease steadily with increasing the gas pressure. With the increase in gas pressure, the electron-neutral collision rate also increases and hence decrease in the amplitude may be due to collisional damping.

3.3.4.4 The instability threshold:

Fig. 3.12 represents the plot of threshold values for discharge voltage \( V_d \) and magnetic field \( B \) for excitation of the instability. The corresponding value of magnetic field and discharge voltage at which the instability amplitude becomes maximum, is also presented. It is noted that with the increase of magnetic field the instability is excited at lower discharge voltages. When the values of magnetic fields are 75, 100 and 125 Gauss, the discharge voltages required for instability threshold are 620, 565 and 545 V. These observations are supported by the observed hysteresis loop (Fig. 3.9). From the observations, it can be inferred that a strong electric field inside the sheath is necessary to excite this instability. When the sheath expands after a threshold value, the instability dies down.

3.3.4.5 Measurement of \( EXB \) drift current:

The electrons are drifted in the azimuthal direction due to the action of \( EXB \) flow. The \( EXB \) drift current of electrons \( I_{de} \) is measured using two Langmuir probes (5mm diameter plane molybdenum) placed back to back with proper insulation. The first probe,
which faces the $EXB$ flow, collects the electron current of thermal electrons as well as drifted electrons. The second probe, whose collecting surface is opposite to the direction of $EXB$ flow, collects only the thermal electrons. So the difference in electron saturation currents collected by these two probes gives a measure of $EXB$ drift current of electrons ($I_{de}$). The plane collecting-surfaces of the two probes used to measure the $EXB$ flow, are aligned properly above the cathode surface, perpendicular to the $EXB$ direction. Also while taking the readings, the drift current is at first measured keeping the magnetic field in one direction and after that it is measured again by reversing the magnetic field direction. The mean value of the two readings is taken for measurement of drift current. Fig. 3.13 represents the Langmuir probe $I-V$ characteristics for a typical set of discharge parameters for direct and reversed magnetic fields. It is clearly seen that the values of current collected by the two probes is interchanged when the magnetic field is reversed, which confirms the existence of $EXB$ drift currents in the system. In Fig. 3.14(a), $I_{de}$ is presented as a function of magnetic field. It is found that with increasing magnetic field, the drift current initially increases rapidly and after that it changes at a slower rate at higher magnetic fields. It is also found that with increasing discharge voltage the drift current ($I_{de}$) initially increases and the increase is slow at higher discharge voltages (Fig. 3.14(b)). Drift current increases mainly due to the increase of plasma density with magnetic field and discharge voltage.

3.3.4.6 Growth rate of instability:

An estimation of the growth rate of the observed high frequency has been done in the post magnetron plasma system. For measurement of the growth rate of instability, the time series signal collected by the Langmuir probe is recorded for different
FIG. 3.13: I-V characteristics of two planar Langmuir probes placed back to back above the cathode surface at a distance of 3.25 cm from the cathode surface. The collecting surfaces of the probes are perpendicular to the azimuthal direction.
FIG. 3.14: (a) EXB drift current vs. magnetic field at a fixed discharge voltage.
(b) EXB drift current vs. discharge voltage at a fixed magnetic field.
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Frequency = 82 MHz
Growth rate = \(4.15 \times 10^7\) s\(^{-1}\)

<Diagram>

Frequency = 62 MHz
Growth rate = \(1.6 \times 10^7\) s\(^{-1}\)

<Diagram>

FIG. 3.15: Typical time series data used for measurement of growth rate of instability.
FIG. 3.16: Variation of growth rate ($\gamma$) with the frequency ($f$) of instability.
frequencies of the instability. From these data the growth rate of instability ($\gamma$) corresponding to different frequencies are estimated. Typical frequency spectra for two different instability frequencies (62 MHz and 82 MHz) are presented in Fig. 3.15 (a & b). The corresponding growth rates are $1.6\times10^7$ s$^{-1}$ and $4.15\times10^7$ s$^{-1}$ respectively. The growth rate is found to increase from $1\times10^7$ s$^{-1}$ to $5\times10^7$ s$^{-1}$ for a frequency change of 50 - 95 MHz. After that, it slowly decreases to $3.5\times10^7$ s$^{-1}$ at a frequency of 103 MHz as shown in Fig. 3.16. The growth rate of the observed instability estimated from the time series signal shows the order of $10^7$ per second i.e. 10 per microsecond. So it is concluded that this instability grows significantly and enhances the radial electron transport within few microseconds, which is the typical time scale required to establish a steady state discharge. Hence it can destabilize a discharge operating in a particular mode.

3.3.4.7 Mode number, wave number and phase velocity of instability:

To determine the azimuthal mode number ($m$) of the instability, two cylindrical Tungsten Langmuir probes $P_1$ and $P_2$ (0.5 mm diameter and 5mm long) are placed (Fig. 3.1(b)) at two different azimuthal positions of same radial distance (3.25 cm from the cathode surface) [Thomassen 1966, Beall et al 1982, Levinson et al 1984, Martines et al 2001]. The angular separation between the two probes is kept at $20^\circ$. The time series signals picked up by the Langmuir probes are fed into a digitizing storage oscilloscope (LECROY LT-264) and are recorded simultaneously and then transferred to the computer.
FIG. 3.17: Typical sets of fluctuation in electron saturation current received by two Langmuir probes placed at two different azimuthal positions of same radius: (a) for $V_d = 600 \, V$, $P_{Ar} = 3 \times 10^{-2} \, \text{mbar}$ and $B = 75 \, \text{Gauss}$; (b) for $V_d = 600 \, V$, $P_{Ar} = 3 \times 10^{-3} \, \text{mbar}$ and $B = 200 \, \text{Gauss}$
The signals are divided into 10 equal intervals, then Fast Fourier Transforms ($H$) of each signal interval is done and the frequency and corresponding phase is determined. From these, the mode number ($m$) corresponding to a particular frequency ($f$) is calculated using the relation:

$$m(f) = \frac{\arg H_i(f) - \arg H_j(f)}{\Delta \theta}$$  \hspace{1cm} (3.7)

Where $\arg H_i(f)$ is the phase of the signals with frequency $f$ picked up by the $i^{th}$ or $j^{th}$ probe and $\Delta \theta$ is the angle between the $i^{th}$ and $j^{th}$ probe. The measured phase difference of the signals are used to obtain the mode numbers. The average of these 10 results is taken. By changing the magnetic field, the mode number corresponding to different frequencies is determined. The whole experiment is repeated for ten times and the average result is taken.

Two typical sets of the signals picked up by the probes are presented in Fig. 3.17. For $B = 75$ Gauss, $V_d = 600$ V and $P_{Ar} = 3 \times 10^{-3}$ mbar (Fig. 3.17(a)), the frequency of the instability is 52 MHz and the corresponding mode number is 3. For $B = 200$ Gauss, $V_d = 600$ V and $P_{Ar} = 3 \times 10^{-3}$ mbar (Fig. 3.17(b)), the frequency of the instability is 96 MHz and the corresponding mode number is 6.

A plot of mode number vs. frequency of instability is presented in Fig. 3.18. It is found that mode number almost steadily increases from ~3 to ~7 when the instability frequency increases from 50 MHz to 100 MHz, but the rate of increase is higher for frequency above 80 MHz where the rate of change of frequency with magnetic field is very low. Since the amplitude of instability is maximum for the frequencies nearly 75 MHz in
FIG. 3.18: Plot of azimuthal mode number (m), wave number (k) and phase velocity ($V_{ph}$) vs. frequency of instability.
this condition, it can be concluded that ‘m’ = 5 mode is dominant. The wave number (k) is calculated using the relation \( k = m \times r \) where \( r \) is the radial position of the probe. The phase velocity \( (V_p) \) is also calculated using the relation \( V_p = \frac{2\pi f}{k} \). These two parameters are also plotted vs. frequency (f) in Fig. 3.16. The wave number initially increases from 0.6 (cm\(^{-1}\)) to 1.6 (cm\(^{-1}\)) for the frequency change of 50 MHz to 100 MHz. The initial phase velocity is \( 4.6 \times 10^8 \) cm/sec at a frequency of 50 MHz, it decreases with increasing frequency and ultimately becomes almost constant at \( 3.8 \times 10^8 \) cm/sec at higher frequencies though some random variations are there. Since the measured phase velocity of the instability is of the order of \( 10^8 \) cm/sec, which is significantly low as compared to that of the electromagnetic waves. So it may be concluded that the observed instability is electrostatic.

In this experiment the electron cyclotron frequency is \( (200 \sim 500) \) MHz and ion plasma frequency is 900 kHz \( \sim 10 \) MHz. The observed instability frequency lies between the electron collision frequency (\( \sim 45 \) MHz at an argon pressure of \( 3 \times 10^{-3} \) mbar) and the electron cyclotron frequency. The electron plasma frequency is much higher (300 \( \sim 900 \) MHz) in this case.

In the present experiment the magnetic field and the Cathode-Anode gap is such that, only the electrons become significantly magnetized and but not the massive ions. Therefore only the electrons are drifted significantly in the azimuthal direction under the action of \( E \times B \) flow. So a charge separation is created in azimuthal direction due to the difference in drift velocities of electrons and ions. A charge separation is created by the
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difference in drift velocities only when a non-axisymmetric initial perturbation takes place. In this set up this type of perturbation may take place as follows:

Since in this set up, initially when there is no magnetic field, the electrons move in all possible directions. After application of the magnetic field, the field affects the electrons moving in the azimuthal and radial directions, which are perpendicular to the magnetic field. But the electrons moving parallel to the field are not affected; hence there exist a parallel velocity component of the electrons after application of the magnetic field. This parallel velocity component may be responsible for the non-axisymmetric initial perturbation. The Argon ions have a mass comparable to that of neutral atoms so the collision between the argon ions and the neutrals take place effectively and hence difference in the drift velocity between electrons and ions increases further due to the viscous drag on ions by neutrals. The reduction in the drift of electrons is very small due to very large mass difference of electrons with the neutrals. Due to the difference in the drift velocity of electrons and positive ions, charge difference and hence a fluctuating electric field \( E_{\phi} \) is produced in the azimuthal direction. Once this electric field is produced, the electrostatic waves are generated in the azimuthal direction. As there is a radial density gradient in cylindrical post magnetron discharge plasma, these waves may grow up gaining the required free energy from the density gradient and become unstable. The frequency of the instability depends on the electric field \( E_{\phi} \) which is influenced by the charge separation growing in the azimuthal direction due to \( EXB \) drift. The flux of the drifted electrons controls the charge separation.

It has been observed from Fig. 3.14 and Fig. 3.10 that the trend of variation of \( EXB \) drift current and frequency of instability with magnetic field and discharge voltage is
similar. At high magnetic field and also at high discharge voltage, the cathode sheath expands and hence the main ionizing region shifts away from the cathode. Due to this effect the density profile may become flat. Also when the amplitude of the instability becomes very high, it affects the density profile to become flat due to enhanced nonlinear transport [Van der Straaten and Cramer 2000]. When the density profile becomes flat the instability amplitude falls down as observed at high magnetic field and also at high discharge.

3.4 Conclusion:

Theoretical works of Simon and Hoh (Simon 1963, 1968, Hoh 1963) predicted unstable modes due to EXB flow and density gradient. Recently Van der Straaten and Cramer (2000) have shown that inclusion of ion inertia leads to unstable modes occurring below the electron collision frequency. The observed instability in the present experiment is higher than the electron collision frequency (~ 45 MHz at an argon pressure of 3×10⁻³ mbar). Possible origin of this instability may be EXB/density gradient or some other nonlinear mechanism. Its characteristics cannot be compared with existing theories at present. As the frequency (45 - 105 MHz) and the growth rate (~10 per μs) of the observed instability is very high, it is predicted that this type of instability enhances the anomalous electron transport across the magnetic field and possibly prevents the transition of positive space charge mode to stable negative space charge mode at high magnetic field and low pressure. Due to the electron loss, the efficiency of a magnetron sputtering system may be decreased and also the properties of a deposited film may be affected significantly due to
substrate bombardment by the $E \times B$ drifted energetic electrons in the radial direction. A detailed study on the anomalous electron transport under such instability is much needed but beyond the scope of the present work.