The Magnetized Plasma Effect on Cathode Fall Thickness for Helium Gas Discharge

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Author's contribution

This whole work was carried out by the author ARG.

Original Research Article

ABSTRACT

Our previous study showed that the thickness of the cathode fall region in magnetized DC argon plasma was about 3.3mm has been investigated using two different methods, namely: the axial potential distribution and the current density distribution along the glow discharge regions. The present study demonstrates the same measurements but carried out for Helium gas discharge at the edge and center of the cathode surface for the same characteristic of the DC (cold cathode) magnetron sputtering unit. The I_a–V_a characteristic curves of the glow discharge and the axial potential distribution and the current density distribution have been investigated. Under the influence of magnetic field, the thickness of the cathode fall region for he discharge is about 2.5mm for the two methods in pressure (P) range of 1-4mbar. Apparently for helium gas discharge, a reduction of the cathode fall thickness (about 20%) has been found in the presence of a magnetic field at the center of the cathode and (about 37%) at the edge, furthermore stronger electric field at the edge of the cathode fall, and hence high rates of sputtering are expected.

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1. INTRODUCTION

Low-temperature plasma generators are extensively used in different branches of industry, and the technological processes developed on their basis have been long applied at many project. One of the possible ways of raising energy and efficiency of plasma technologies is the use of magnetic field.

Recently, the performance of plasma in magnetic field has been improved in many non-equilibrium glow discharge plasma, used in dispensation of semiconductor materials for many processes such as etching and coating, because the application of a magnetic field results in enhancement of some attractive features of specific plasma sources [1].

Experimental and theoretical studies of the electric field distribution in the cathode-fall (CF) region of an obstructed abnormal glow discharge in hydrogen were discussed [2]. It is shown that the cathode temperature influences significantly the main parameters (electric field distribution, thickness of the cathode fall layer, current density, gas temperature) of the cathode fall of the self-sustained normal DC atmospheric pressure glow discharge [3].In the early days, people focus on the plasma free of the magnetic field; in the later days, many studies have been done on plasma in a magnetic field, but most of them were about common laboratory plasma, i.e., in which the magnetic field is not strong enough to make an ion do a cyclotron motion in the sheath before it strikes the wall [4].

The magnetic field parallel to the axis of the positive column of a discharge is used by Von Engel [5] known to impart a rotary component on the radial motion of electrons. This reduces the flow of both positive ions and electrons to the wall, causing a corresponding decrease in the radial and longitudinal components of the electric field and in the electron temperature.

In the present work, we report on study the cathode fall thickness under the influence of the magnetic field by two different method for He gas discharge, the axial potential distribution method and the current density distribution method.

2. EXPERIMENTAL SETUP

Fig. 1a. shows a schematic diagram of the experimental setup. A stationary DC-glow discharge was generated between two circular metallic electrodes of about 5cm in diameter, inside cylindrical discharge cell, which consists of a stainless steel chamber that has few glass ports, connected to vacuum system and evacuated to 10^{-4}Torr. The used gases were then admitted to the system via needle valves. Moreover there are two parallel, circular and movable electrodes are enclosed in the discharge cell, anode was made of copper and the cathode of aluminum according to the sputtering purposes. The two electrodes are 3cm apart, furthermore there are two hollow permanent circular magnets are placed around the cathode surface to produce the magnetic field, to cause the region between the two electrodes as a magnetized plasma plume), the discharge cell is evacuated using rotary pump to a base pressure of 7mtorr then the gas is allowed to fill the tube at the desired flow rate. Helium gas is used as working gas and fills the discharge cell under continuous flow through needle valve. A vacuum gauge is connected to the discharge tube to measure the inside gas pressure. The discharge current (I_a) was varied between 4 and 30mA and the gas pressure (P) was in the range 0.5 to 6mbar. The device was operated using discharge voltage (V_a) varied between 200 to 1000V DC, whereas the current density was between 2 and 15mA/m^2.
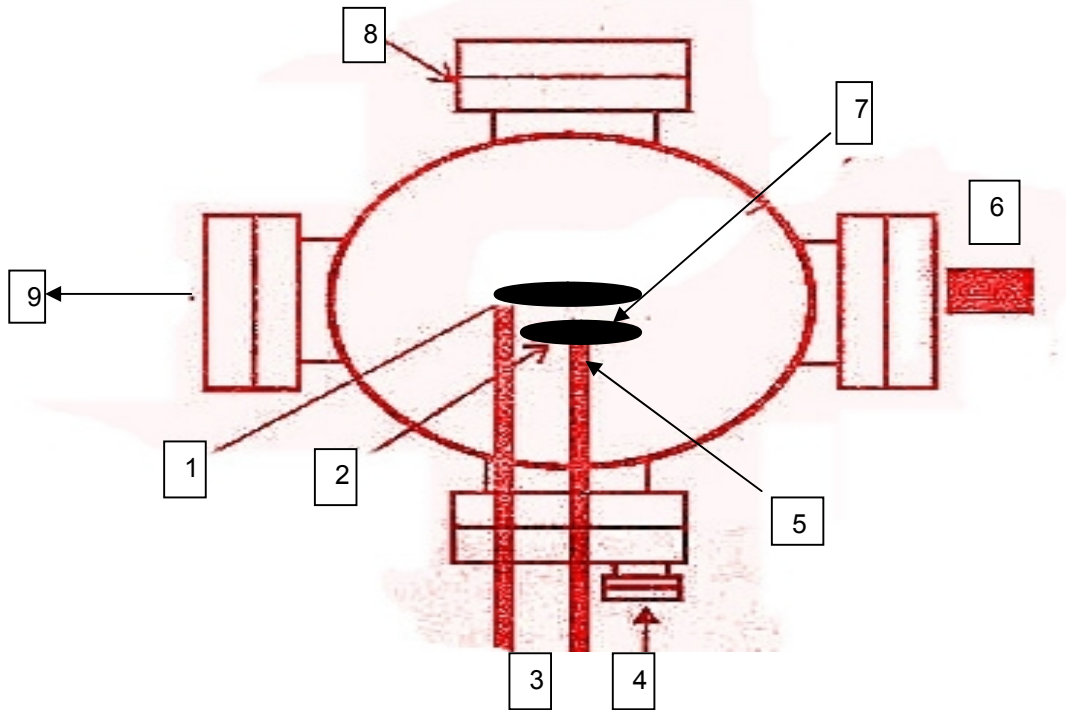
Fig. 1a. A schematic diagram of the plasma cell contains

1- *Anode copper surrounded by Insulator material*
2- *Aluminum cathode surrounded by Insulator material*
3- *Two electrodes contacted with the electrical circuit*
4- *Helium Gas supply*
5- *Two Hollow permanent magnet under the cathode*
6- *Quartz windows for probes and microscope*
7- *Plasma plume*
8- *Quartz windows*
9- *To the rotary pump*

Single cylindrical Langmuir probe made of molybdenum wire of 0.3mm diameter and length of 2 mm is used. The wire is isolated by a thin glass tube and the tip of a probe is immersed inside the glow discharge plasma.

The axis of the cylindrical Langmuir probe should always be positioned perpendicular to the electric field otherwise changes of the space potential along of the probe may distort the probe characteristic, especially in the vicinity of the space potential (it may round off the knee of the probe characteristic). The probe was periodically cleaned by ion bombardment to remove all possible hysteresis effects of the probe characteristic.

Fig. 1b. shows the geometry and the dimension of the magnet. The MG-4D Hall probe, which is a fully portable hand-held Hall effect gauss meter, is used to measure the magnetic field strengths (B). A cylindrical single probe 1.0-mm diameter and length 0.5mm, molybdenum wire is used to measure the axial potential distribution of the discharge. More details about the magnetized DC plasma electrical circuit has been discussed briefly in our previous work [6].
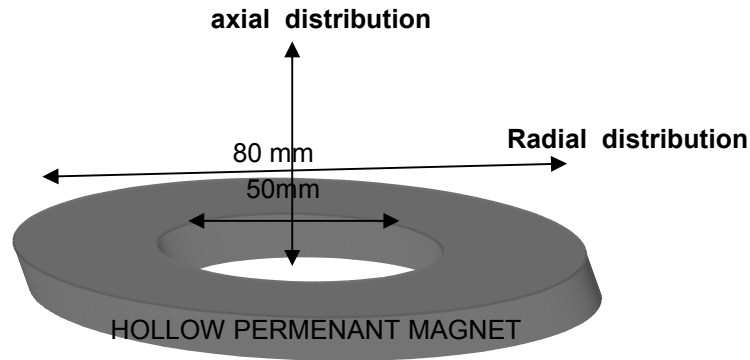
axial distribution

Radial distribution

80 mm

50mm

HOLLOW PERMENANT MAGNET

Fig. 1b. The radial and axial distribution for the magnetic field strengths

3. RESULTS AND DISCUSSION

3.1 Distribution of the Magnetic Field Strengths

In our previous study, we discussed briefly axial and radial distribution of the magnetic field strength B, where it observed that B was maximum at the two cathode edges and minimum at the center of cathode and hollow magnets. Moreover B was maximum at the cathode surface (cathode fall region) then it began to decreased faraway the cathode, i.e. toward the anode (passing through the negative glow and positive column regions).
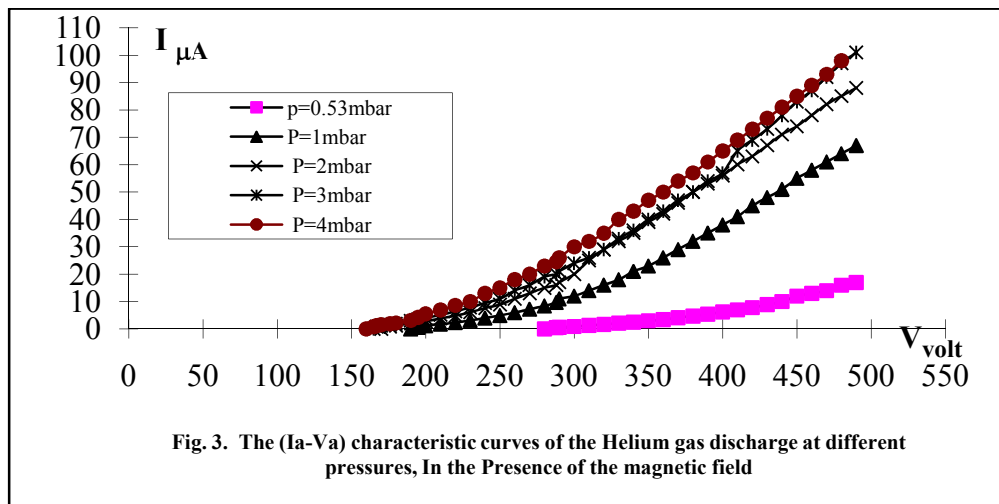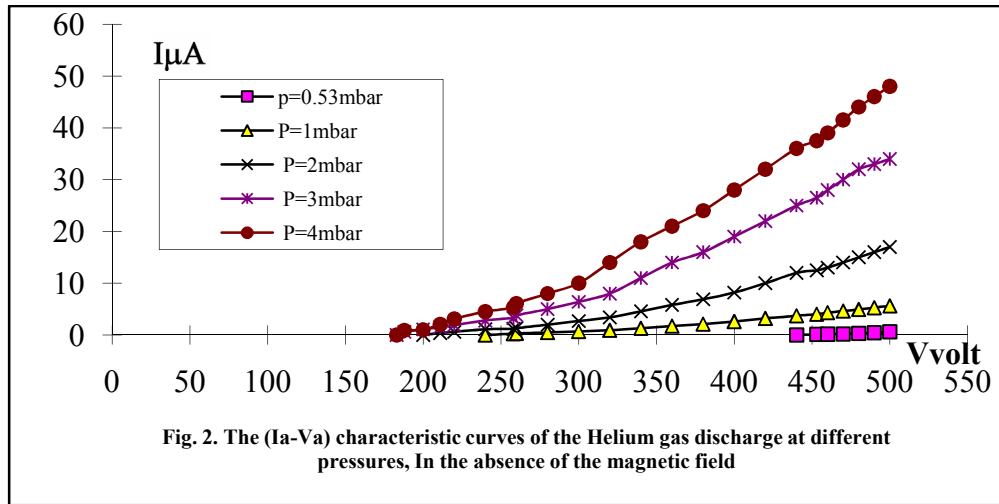
3.2 The Different Characteristics of the Magnetized DC-Glow Discharge

3.2.1 Breakdown potentials

Fig. 2 shows the (I_a-V_a) characteristic curves of the helium gas discharge in the pressure range of (0.53 - 4.0) mbar, whereas the distance between the two electrodes was fixed at (3 cm). This distance is long enough for the existence of the different regions of the glow discharge [7]. The upper limits of I_a and V_a are limited by the power of the DC power supply. Since at low pressure, the probability of electron ionizing collisions with atoms will decrease (i.e. the mean free path will increase) large values of the discharge voltage will be required to maintain the discharge and a small discharge current I_a is expected. At high pressures number of electron-atom ionizing collisions increases.Thus, more electrons and positive ions are produced and consequently, the discharge current is increased at the same voltage [8].

On the other hand, the (I_a-V_a) characteristic curves of Helium gas at pressures of (0.53, 1 2, 3, and 4mbar) when the external magnetic field is applied are shown in Fig. 3. The curves are similar to those without magnetic field.

Figs. 2,3 show that the breakdown potentials (V_B) of the discharge are lower when the magnetic field is applied, this can be explained as follows: the current density can be increased by the magnetic field ,due to the effective increase in the gas pressure. This is related to the fact that the presence of the magnetic field increases the apparent gas pressure and thus decreasing the mean free path, hence more excitation and ionization processes occurred and consequently the breakdown potential decreased.

Fig. 2. The (Ia-Va) characteristic curves of the Helium gas discharge at different pressures, In the absence of the magnetic field

Fig. 3. The (Ia-Va) characteristic curves of the Helium gas discharge at different pressures, In the Presence of the magnetic field

The decrease of the discharge voltage in the magnetic field results from the increase in the number of collisions between the primary electrons and neutral gas atoms. The effects of the magnetic field are qualitatively considered to be effective pressure P_e, given by [9].

$$\frac{P}{P_e} = [1 + (\omega t)]^{1/2} \tag{1}$$

Where ω is the cyclotron frequency of the electron and τ is the mean free time of the electron since [10]

$$\omega = \frac{eB}{r} \tag{2}$$

and

$$\tau = \frac{\lambda_0}{P[2(\frac{e}{m})V_0^{1/2}]} \tag{3}$$

then

$$\omega\tau = \frac{B\lambda_0(\frac{e}{m})^{1/2}}{\sqrt{2}\,PV_0^{1/2}}$$

(4)

Where λ_o is the mean free path of the electron at 1Torr, B is the strength of the magnetic field, (e/m) is the specific charge of the electron and Vo is the acceleration voltage for the electron. Taking B=100Gauss, P=1Torr (He), V_o=100Volt and λ_o=0.05cm, we obtain $\omega\tau$= 5x10^3, and P_e=0.05Torr. Values of the discharge current in the presence of the magnetic field for helium are smaller to those in the absence of the magnetic field. Thus, slopes of the $(I_a$-$V_a)$ curves in the presence of the magnetic field are smaller than those in the absence of magnetic field, (i.e. the resistance of the discharge is larger when no magnetic field is applied).
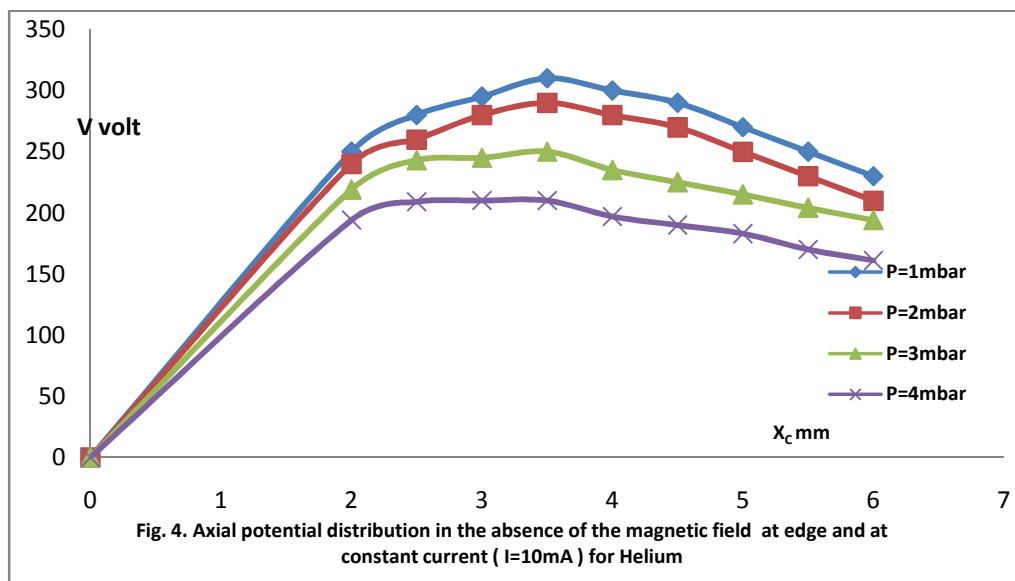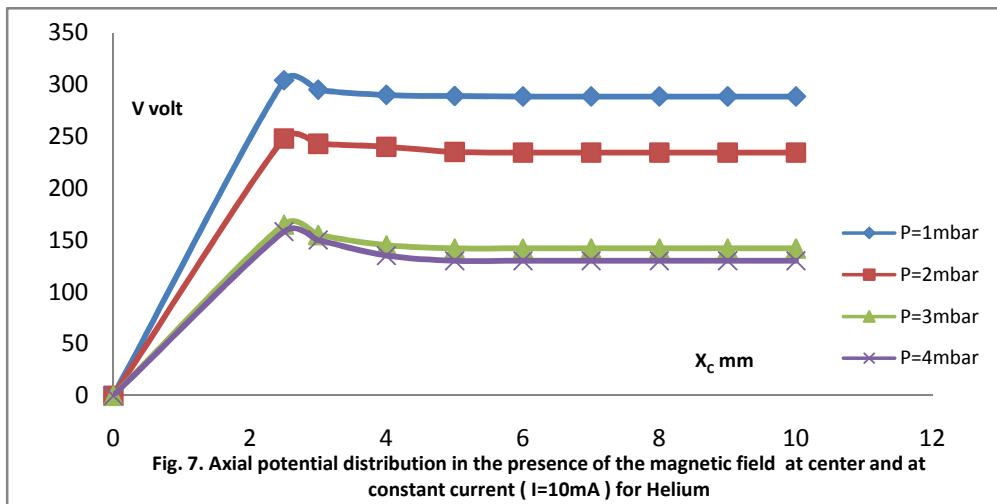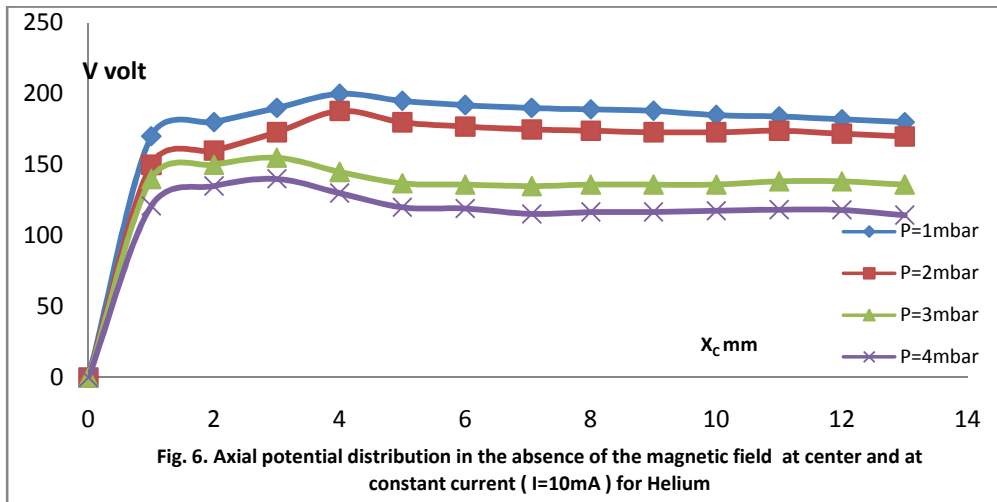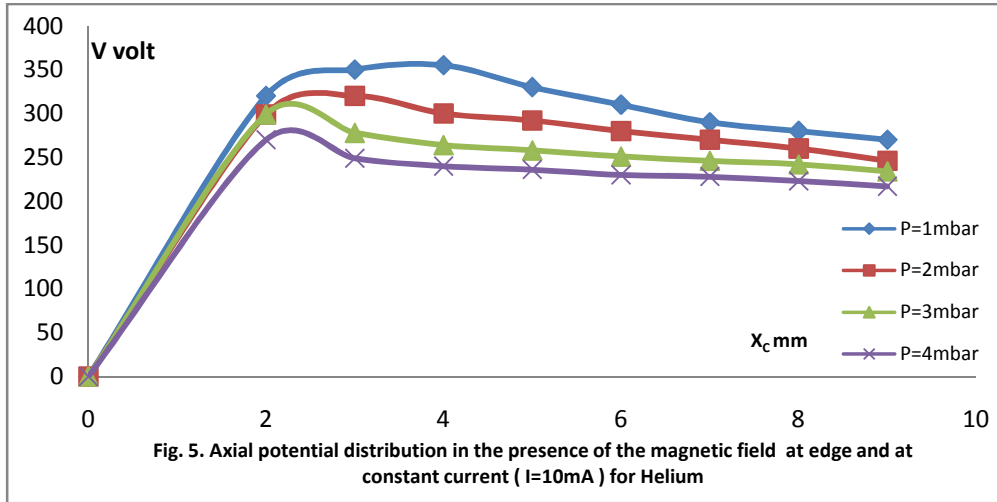
3.2.2 Cathode fall thickness

The cathode fall thickness can be determined by two methods:

3.2.2.1 The axial potential distribution over the cathode fall thickness

The axial potential distribution has been measured along the axis of the discharge tube using single probe; at different gases pressure for He gas shown in Figs. 4,5,6,7 measurements in the absence and in the presence of the magnetic field, at the edge and at the center of the cathode.

Figs. 4,5,6,7 show that, the potential increases rapidly axially near the cathode until it reaches a maximum value at the end of cathode fall region, this rapid increase in potential can be referred to the existence of positive space charge within the cathode fall region. After the peak, the potential decreases less rabidly due to the existence of the reversal field in the negative glow and at the beginning of Faraday dark space (FDS) [11].

Fig. 4. Axial potential distribution in the absence of the magnetic field at edge and at constant current (I=10mA) for Helium

Fig. 5. Axial potential distribution in the presence of the magnetic field at edge and at constant current (I=10mA) for Helium

Fig. 6. Axial potential distribution in the absence of the magnetic field at center and at constant current (I=10mA) for Helium

Fig. 7. Axial potential distribution in the presence of the magnetic field at center and at constant current (I=10mA) for Helium

On the other hand, Fig. 8 shows the cathode fall thickness (d_c) at the edge measurements, in the presence and in the absence of the magnetic field, at different He gas pressure. It can be seen that (d_c) decreases with increasing in the gas pressure. The decreases in d_c as the gas pressure increases can be attributed to the increase in the ionizing collision frequency and hence the discharge needs less distance to create the negative glow region. Also Fig. 9 show that the thickness of the cathode fall, in the presence and in the absence of the magnetic field, at the edge more than at the center of the cathode.

Fig. 8. Shows the cathode fall thickness (d_c) measurements at the edge in the presence and in the absence of the magnetic field at different He gas pressure

Fig. 9. The thickness of the cathode fall (mm)in the presence and in the absence of the magnetic field, at the edge and at the center, of the cathode at Pressure 2mbar
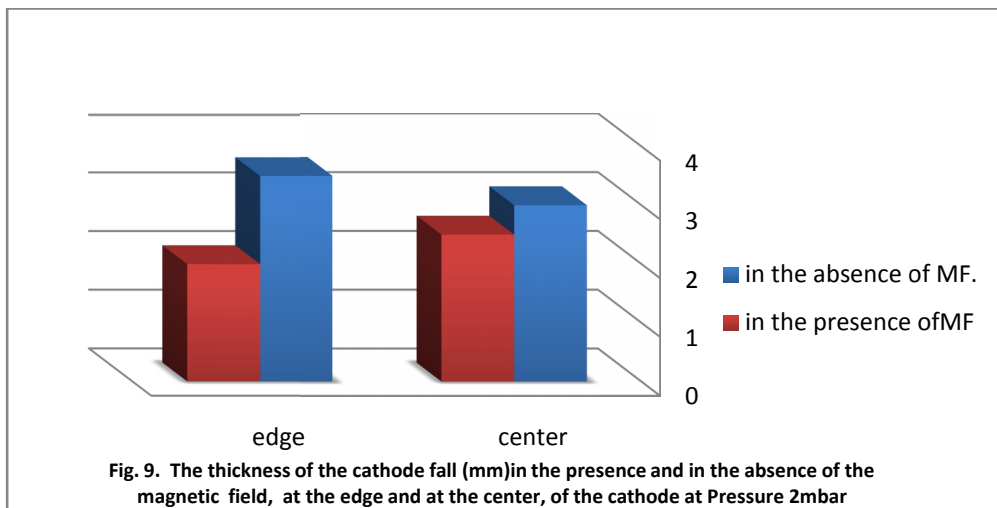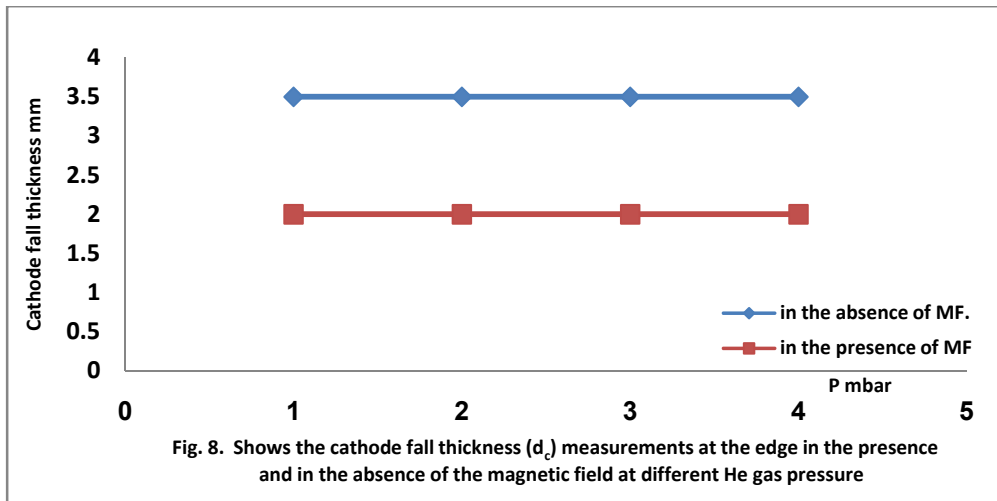
3.2.2.2 The current density distribution over the cathode fall thickness

Determination of the cathode fall dimensions (thickness) of the abnormal cathode fall region is considered theoretically elsewhere in one of our previous studies [12], by a comparison between the theoretical formula and the experimental results in the presence and in the absence of the magnetic field. We can get an expression for the current density [13], as follow:

$$\frac{J_c}{P^2} = \{ \frac{4[1+(\omega/\alpha)]\varepsilon_o (\frac{e\lambda_i}{M})^{1/2} V_c^{3/2}}{(P.d_c)^{5/2}} \}$$

(5)

Where J_c is current density for the cathode fall region, ω/α is the average number of secondary electron produced per ionizing collision in the gas e is charge of the electron, ε_0 is permittivity of free space, α is first Towsend ionization coefficient , M is mass of the ion, λ_ι is mean free path of ion , where d_c cathode fall thickness can be calculated from the following relation :

$$d_c = \frac{1}{\alpha} \ln[\frac{1+(\omega/\alpha)}{(\omega/\alpha)}]$$

(6)

In many discussions [14] the ratio α/E is very useful since it represents physically the number of ions produced by electron collision per unit electric field. This ratio is designated ionization efficiency, η , and is given by:

$$\eta = \alpha/E = \frac{\alpha/p}{E/p} = \frac{A \ P \ e^{-B_p/E}}{E}$$

(7)

Then α can be calculated using equation (7), furthermore substitute with α values into equation (6) to get values of the cathode fall thickness (d_c) [15].

Figs. 10 and 11 show the relation between values of the cathode fall thickness (d_c), as a function of J/p^2, for He gas, in the presence and in the absence of the magnetic field, respectively. Where d_c (thickness of the cathode fall region) decreases as the current density increase. Furthermore the experimental data agrees, reasonably, with the theoretical curves. The main effects of the magnetic field on the present measurements are summarized in the following :

1- The rate of plasma loss by diffusion can be decreased by a magnetic field [16], then the current and current density increase in the presence of the magnetic field as shown in Fig. 10.

2- If D is the diffusion coefficient in the absence of the magnetic field and $D_\perp$ is the diffusion in the presence of the magnetic field, thus

$$D_i = KT/m\nu = \frac{\sqrt{KT}}{N_n <Q>_{i-n}} \frac{1}{\sqrt{2m_i}}$$

(8)

KT is Temperature in eV, N_n is equal to 3.55×10^{16} P where P in mbar, $<Q>_{i-n}$ is the Cross section, m_i is Mass of ions, $\nu = N_n <Q>_{i-n}$ v, where

$$D_{i\perp} = \frac{D_i}{1 + \omega^2 \tau^2} \tag{9}$$

A comparison between the equation (7) and (8), show that in the presence of the magnetic field, the plasma loss due to diffusion for He is decreased more than those in the absence of the magnetic field. Then the current density increased but with different ranges, because of if the magnetic field increase (B=100 Gauss), then the diffusion decrease sharply ($D_\perp$ decrease by $\cong 10^4$ times)

When magnetic field is applied, the cathode fall and negative glow regions are compressed, so higher values of potential are expected. It decreased the length of the cathode fall region (d_c). This effect is very powerful because electrons have beam-like properties in this region This is very clear in Figs. 10,11, where the cathode fall region reduced. This will of course increase the electric field in this region and thus ions would accelerate more and efficient sputtering would increase.
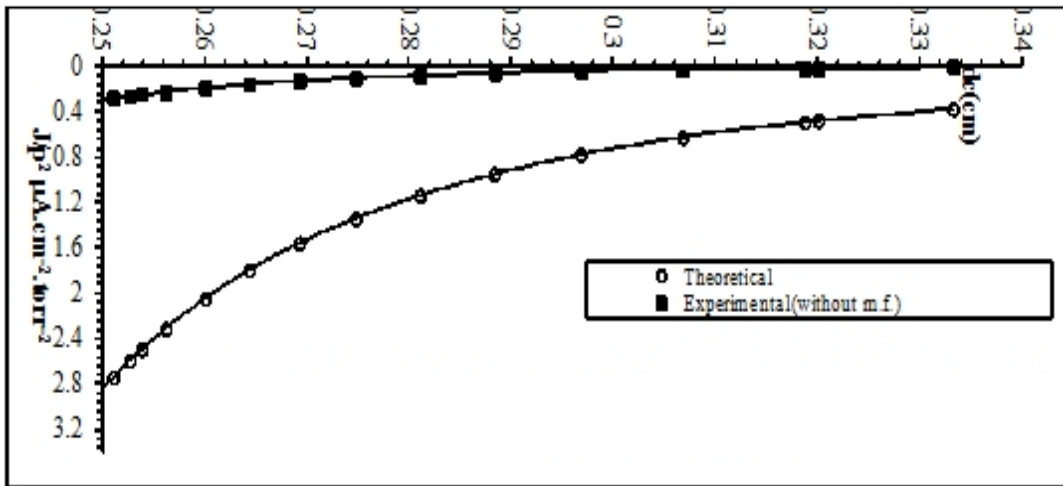

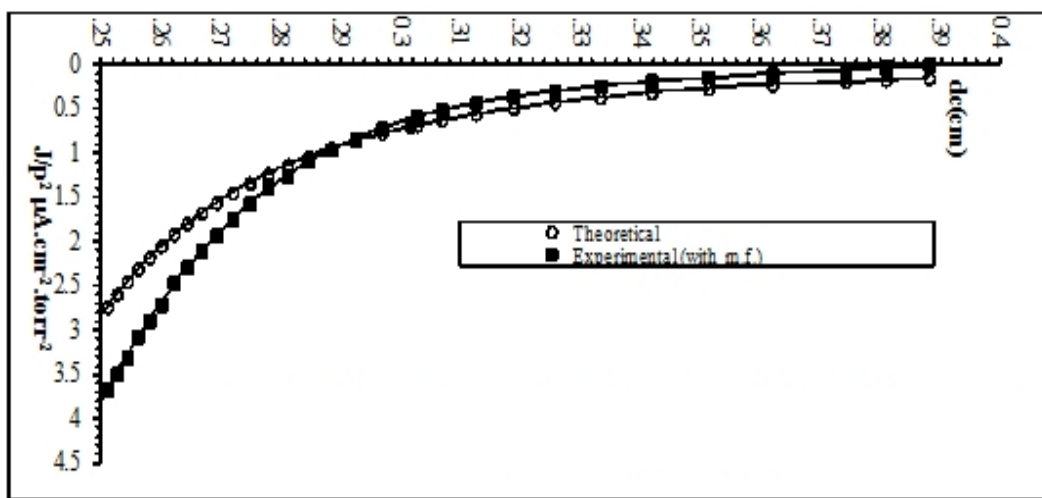**Fig. 10. Cathode fall thickness de Vs. Current density J/p2 for Helium gas in the absence of the magnetic field**

Fig. 11. Cathode fall thickness dc Vs. Current density J/p2 for Helium gas in the presence of the magnetic field

4. CONCLUSION

The thickness of the CF region (d_c) was determined in magnetized low-pressure Helium glow discharge. Where experimental results cover experimental pressure range from 1-4mbar only, because of at less than 1mbar, the axial potential distribution has been measured by single probe, suffer difficulties to initiate at the edge due to the reduction of the cathode fall, in addition the sheath, dust plasma and contamination around the probe leads to difficulties in measuring the potential between the probe and the cathode.

Two independent methods namely the axial potential distribution method defined accurately the thickness of the cathode fall region (d_c) was about 2.5-3.5mm. depends upon the gas pressure (P). The data agree fairly with the second method namely theoretical and experimental for the current density of ions (J) distribution method of ions, was about 2.5-3.9mm. Depending upon the gas, pressure (*P*) has been obtained in the presence and the absence of the magnetic field either at the edge or the center of the cathode. It is concluded that a notice reduction of the CF thickness (about 20%) has been found in the presence of the magnetic field at the center of the cathode and (about 37%) at the edge. Thus, a stronger electric field is produced and consequently more acceleration of the ions is expected that enhances the sputtering processes rate of the cathode surface.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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