Distributions of electron density and electron temperature in magnetized DC discharge

Abstract

The distribution of electron temperature T_e and density N_e in a dc glow discharge that is created by a pair of circular parallel electrodes were studied using double probes. The measurement was carried out for the following two modes: in the present and in the absence of the magnetic field. In the absence of the magnetic field, for the radial distribution, temperatures have almost the same values, in the same discharge region (cathode fall or negative glow or positive column region) , except at the edge. For the axial distribution of T_e , the distribution profiles of T_e were showed that T_e is decreased, and N_e continues to increase toward the anode . In the presence of the magnetic field, the radial distribution of the electron density has its highest value at the edge whereas the magnetic field is maximum. The electron temperature changes very little. The density begins to increases also from the cathode fall region, at the edge, to the negative glow region and then it began to decrease sharply at the positive column region. The plasma is very intense in the cathode fall region (very thin bright ring), and very brighter and sharp in the negative glow region (extends several mm from the cathode fall region). But in the positive column, the density begins to decrease.

Keywords : magnetic field ;Argon; electron density; electron temperature ;glow discharge

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1- INTRODUCTION

The direct current dc glow discharge appears to be an ideal means to coat a metallic substrate by plasma polymerization because the polymer deposition [1-2] occurs nearly exclusively on the surface of cathode. The fundamental phenomenon of glow discharge has been often explained by the dc glow discharge, particularly in the classical literature of the 1920s and 30s, whereas practical plasma processes are usually done by a radiofrequency (RF) power source [3, 4].

The use of dc glow discharge for surface modifications and plasma polymerization has been reported in recent years, and high frequency glow discharges still seems to dominate the interest of investigators. In many studies on the corrosion protection of steel, plasma pretreatment of steel surfaces and subsequent in situ cathodic plasma polymerization were used in combination with the conventional electro-coating (E-coat) primer or vacuum deposited [5, 6].

It became clear that one of difficulties associated with the dc cathodic plasma processes is the nonuniform effect of plasma due to edge effect that is caused by the concentration of electric field near the edge of the cathode [7-9].

Different tools and techniques can be employed to characterize the discharge plasmas but the electrostatic probes are considered to be the most powerful and experimentally simple technique for plasma characterization over a wide range of plasma densities because they did not require the assumption that the plasmas should be in local thermodynamic equilibrium. Multi-tip probes are found to have negligible influence on tested plasmas and yield accurate data while investigating different plasma parameters [10, 11]. Therefore using a double Langmuir probe method, the spatial distribution of electron temperature T_e and number of electron N_e (especially for the cathode fall region C.F.) are investigated and results are presented in this article in the presence and in the absence of the magnetic field.

2- EXPERIMENTAL SETUP

Experimental procedures and the apparatus used are identical to our previous study that was carried out with DC discharges system. In this study a dc power source was used exclusively, and the hollow permanent magnet around the cathode in order to study the magnetic field effect on the electron density and temperature .The magnetic field strength was measured, and more details about the dc circuit and the strength of the permanent magnet was discussed before.

The double probe consists of two identical cylindrical electrodes. Each electrode is 2 mm long and 0.8 mm diameter and made of tungsten wire. The separation distance between the two electrodes centers was about 3 mm. The separation distance was large enough to avoid the interference of the sheaths around each electrode, the quantity λ_D called Debye length which is a measure of the shielding distance or thickness of the sheath, where the values of the Debye length calculated from the following equation (1):-

$$\lambda_D = 740\,(KT/n)^{1/2} \quad \text{Cm} \qquad KT \text{ in eV} \qquad (1)$$

At the temperature equal to 10 eV and the density equal to 7×10^8 cm^{-3}, the Debye length is about 0.08844 cm. Then the distance between the two electrode is larger than double of Debye length, the electron temperature using the double probe method [16-18], can be calculated using relation (2):-

$$T_e = \frac{1}{4}.\Delta V_a.F(\frac{S}{X}) \qquad (2)$$

Where ΔV_a is the voltage difference. The correction factor F(S/X) was introduced since the ideal double probe characteristic is extremely difficult to obtain (experimentally) because of the sheath formation around the probe surface**.** The correction factor is given by (3):-

$$F(\frac{S}{X}) = \frac{1-0.85(S/X)}{1+0.5(S/X)} \qquad (3)$$

Where S and X are slopes].

The plasma density N_e was measured using the double probe I-V characteristic curve for each region in the glow discharge. N_e was calculated using formula (4),

$$N_e = \frac{I_i}{e\left(2kT_e/m_i\right)^{1/2}.A_p} \qquad (4)$$

Where I_i is the ion current, A_p is the area of the probe and T_e is the electron temperature which was determined previously by equation (2).

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3- RESULTS AND DISCUSSION

Since our major interest is determine the distributions of electron density and electron temperature in magnetized discharge, to be able treat the surface of a substrate used as a cathode[12], or inactivate microbes in a Petri dish over the cathode [13], or etch a sample over a cathode [14] .

From our previous study, the radial distribution of the magnetic field B as measured by using the Hall probe across the diameter of the cathode surface from one edge to the other. The magnetic field B is maximum at the two cathode edges and minimum at its center (the center of the hollow magnets also). Furthermore the axial distribution of B along the discharge tube from the edge of the cathode to the edge of the anode. The magnetic field B is maximum at the edge of the cathode fall region then it decreased toward the anode passing through the negative glow region.

Glow discharge is characterized by the appearance of several luminous zones. The relative size of these zones varies with pressure and the distance between the electrodes, and glow intensity depends on the density and energy of the exciting electrons [15]

The glow shape as well as the distribution of the electron density and energy were distorted when a magnetron was paired around the cathode. The shape and the intensity of glow are correlated to the density and the energy of the electrons for in the present of magnetic field (CM-A)mode [strong permanent magnet was placed around the cathode] and in the absence of the magnetic field (C-A)mode

3-1. The I-V characteristic of the double probe for C-A mode and for CM-A mode

Typical examples of the double probe (I-V) characteristic curves for Ar, at different pressures for C.F. region specially (where it is the place of the treatment samples), are shown in Fig.(1) to Fig.(4), in the absence and in presence of the magnetic field, at the edge and at the center of C.F. region.

In the glow discharge and the measurements which carried out in the pressure range of (1-2.5-4) mbar, The figures show that the ion saturation current of the probe is increased by increasing the gas pressure. Since at low pressure, the probability of electron ionizing collisions with atoms will decrease (i.e. the mean free path will increase) , large value 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.

In the presence of the magnetic field for CM-A mode, with the same condition discussed for C-A mode, beside a condense and thin ring of plasma near to the cathode was observed. The main effects of the magnetic field on the present measurements are summarized in the following:-

1- When the magnetic field is applied, the diffusion coefficient of the electron is reduced due to the equation $D_\perp = D_C / (1+ \omega^2 \tau^2)$. Then the rate of plasma loss by diffusion can be decreased by a magnetic field [19,20], then the current and current density increase in the presence of the magnetic field as shown in Fig. (2) at center and Fig. (4) for Ar at edge, comparing with Figures(1) and (3) at center and edge respectively , because of if the magnetic field increase by B=100 gauss, then the diffusion $D_\perp$ decrease sharply by $\cong 10^4$ times).
2- In the absence and under the influence of the magnetic field. The probe was moved radially from the center to the edge of the cathode (i.e. its direction perpendicular to the direction of the electric field lines), at different pressures ranges and for different discharge regions to investigate the radial distribution. Moreover the probe move axially from cathode fall region until reach to the positive column region.

3-2 The temperature and density measurements in the C-A mode and CM-A mode

Figures (5a and 5b) show the distribution profile of T_e between the two electrodes space in the absence and in the presence of the magnetic field. Moreover Figures (6a and 6b) show the distribution profile of N_e between the two electrodes space in the absence and in the presence of the magnetic field.

As discussed before, as the magnetic field is applied, the diffusion coefficient of the electron is reduced. Thus the electric field required to maintain ambipolar flow is rapidly reduced as B is increased. The magnetic field reduces the electron temperature from the value given in the absence of the magnetic field Further increase in the magnetic field resulted in the reduction of the electron temperature through its influence on the ambipolar diffusion coefficient D_a .

$$D_a = \frac{D_e D_+ (T_+ + T_e)}{D_e T_+ + D_+ T_e} \cong D_+ \frac{T_e}{T_+}$$

The decrement of the temperature is marked at the edge than at the center this is related to the maximum of the magnetic field strength at the edge as shown in Fig.(5b). Moreover Magnetic field acts to increase the plasma density as shown in Fig.(6b), where we note that the electric field distribution increase in the presence of the magnetic field, then more excitation and ionization processes occur in a small region (i.e. in a confinement region), so the plasma density increased in the C.F. to the edge of the negative glow region, except in the positive column region, the density began to decease sharply due to the electron capture by the anode in the positive column.

3-3 The Radial Distribution Of The Electron Temperature And Density

Figure (5a) show the radial distribution of T_e in the absence of the magnetic field, temperatures have slightly the same values, in the same discharge region, except at the edge. This may be related to the difficulties which associated with the dc cathodic plasma processes, i.e. nonuniform effect of plasma due to the ″edge effect ” that caused by the concentration of the electric field near the edge of the cathode [21].

Figure (5b) show Increasing of N_e radial distribution from cathode to anode in the absence of the magnetic field, may be attributed to the fact that the number of electrons N_e is low near the cathode and does not increase while electrons are accelerated in the dark space and the electron temperature is increasing [22]. When the electrons gain enough energy to ionize the gas atoms, ionization occurs. At the onset of ionization, electrons lose their energy and the number of the electrons increases. this situation is clearly seen in the distribution profiles of T_e and N_e , where the decrease of T_e is observed, N_e increases. N_e continuous to increase toward the anode (i.e. The increase of N_e from cathode to anode may be due to the electron movement from the cathode to anode and also to the occurrence of the electron impact ionization in this region)[23]

The influence of the magnetic field on T_e and N_e is shown in Figures (6a) and (6b) for all the discharge regions, where the radial distributions of the electron density has its highest value at the edge whereas the magnetic field is maximum. The electron temperature changes very little. The density begins to increases also from the cathode fall region ,at the edge, to the negative glow region and then it began to decrease sharply at the positive column region . This may be related to the distribution of the magnetic field, where the plasma is very intense in the cathode fall region (very thin bright ring), and very brighter and sharp in the negative glow region (extends several mm from the cathode fall region). But in the positive column, the density begins to decrease due to the electron capture by the anode in the positive column [23, 24]**.**

Figures [5(a , b) and 6(a , b)] are clearly seen in the distribution profiles of T_e , where T_e is decreased, N_e continues to increase toward the anode, as shown for all the discharge regions:- cathode fall region, negative glow region, and positive column region, respectively. There is clearly a general trend that values of T_e and N_e are inversely proportional (T_e x N_e = constant); the maximum value of one is found where the minimum value of the other **.**

4- CONCLUSION

The main effects of the magnetic field on the present measurements are summarized in the following :-

- The basic effect of the magnetic field is it cause helical paths for charged particles around the lines of magnetic force . The radius of the helix decreases with increasing magnetic field . In most circumstances only the paths of electrons are altered, the ions being virtually unaffected . The electrons thus move a much longer total distance in the gas in the order to move a given distance in the direction of the electric field . They hit gas atoms more often and thus have a greater chance of ionization . In this way the presence of a magnetic field acts like an increase in gas pressure
- 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 , 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, which satisfy a good medium for etching process and inactivation of microorganisms process .
- The magnetic field strength is maximum at the edge of the cathode , thus the density increases sharply at the edge in the presence of the magnetic field than those in the absence of the magnetic field. Where at the center of the cathode it changed very little .

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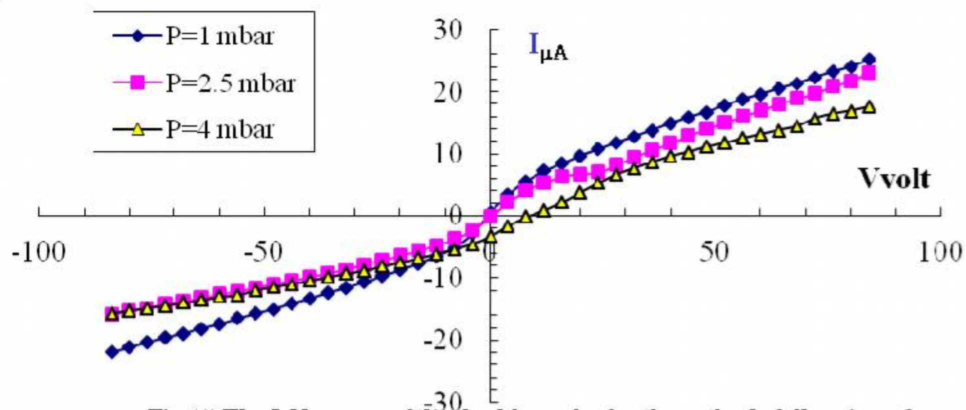

Fig.(1) The I-V curves of the double probe for the cathode fall region of Ar discharge of different pressure in the absence of the magnetic field (at center)

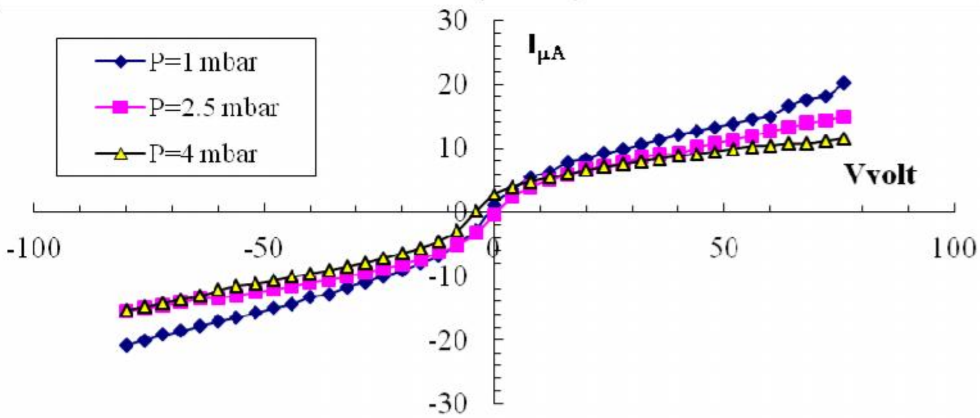

Fig.(2) The I-V curves of the double probe for the cathode fall region of Ar discharge of different pressure in the presence of the magnetic field (at center)

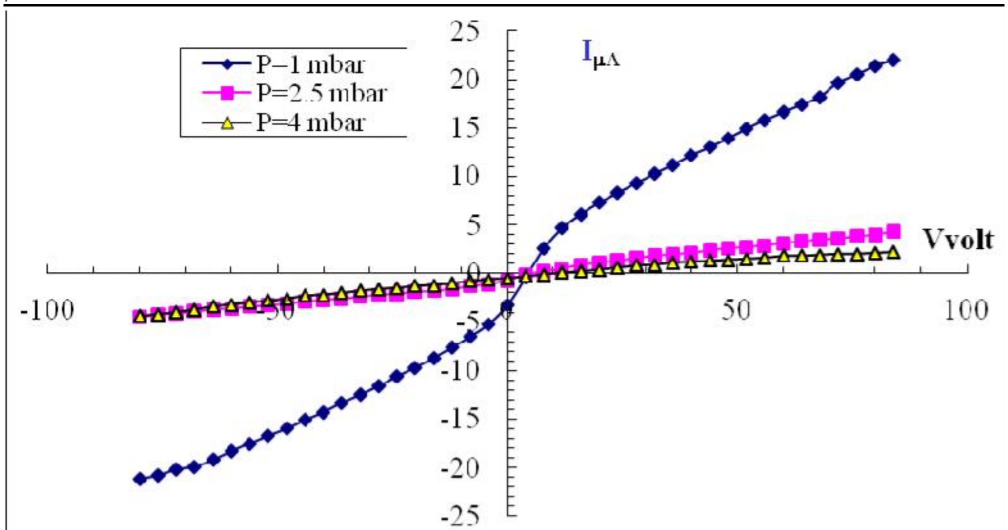

Fig.(3) The I-V curves of the double probe for the cathode fall region of Ar discharge of different pressure in the absence of the magnetic field (at edge)

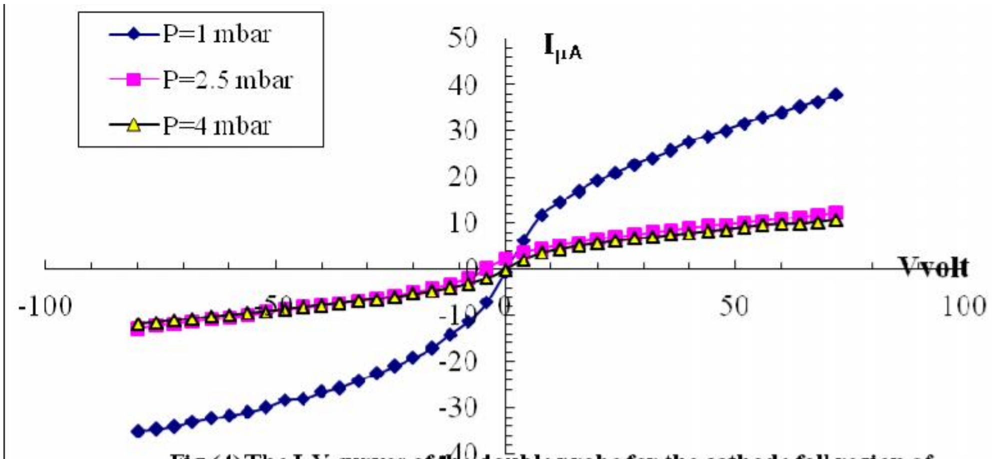

Fig.(4) The I-V curves of the double probe for the cathode fall region of Ar discharge of different pressure in the presence of the magnetic field (at edge)

Fig.(5 a) The distribution profile of T_e between the two electrodes space in the absence of the magnetic field

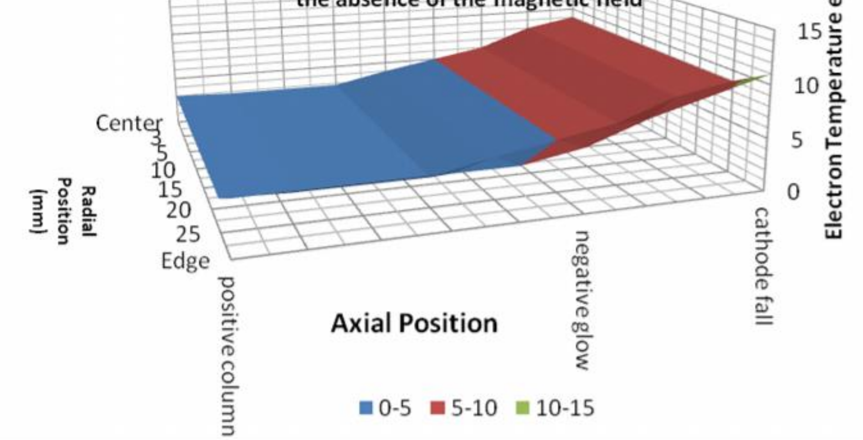

Fig.(5b) The distribution profile of T_e between the two electrodes space in the presence of the magnetic field

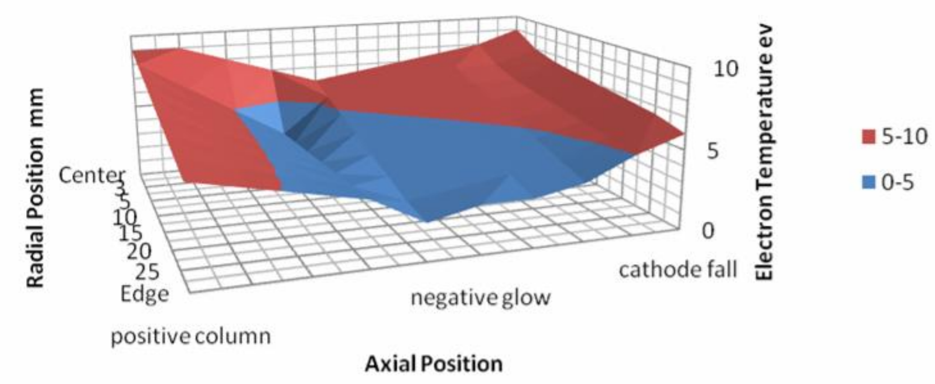

Fig.(6 a) The distribution profile of N_e between the two electrodes space in the absence of the magnetic field

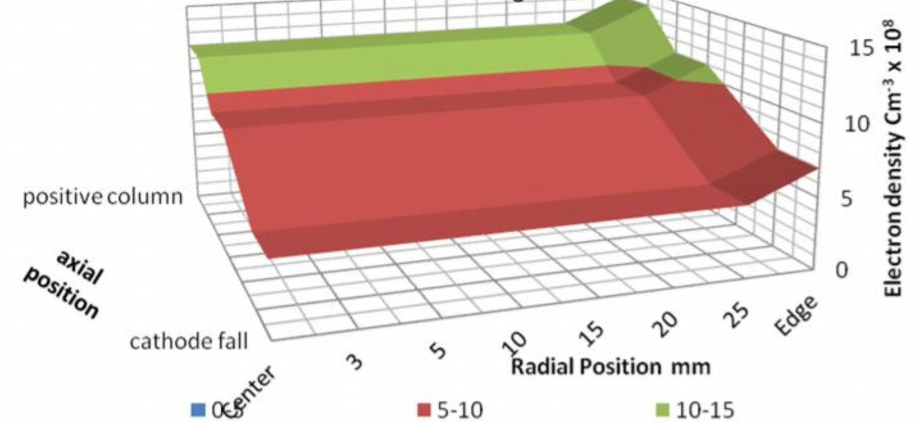

Fig.(6b) The distribution profile of N_e between the two electrodes space in the Presence of the magnetic field