

On the Plasma Parameters in Co- Sputtering Discharge

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ABSTRACT

In this work, a DC planar sputtering system has been successfully designed, manufactured and assembled. The glow discharge plasma chamber was made of stainless steel with a length of 40.5 cm and a diameter of 28 cm. This chamber consists of two Co- planar sputtering magnetrons adapted with copper and Aluminum targets each of diameter of 4.8 cm. The systems have been tested with the pressure of 6×10^{-5} mbar. The plasma parameters like electron temperature T_e , electrons density n_e , ions density n_i , plasma potential V_p and floating potential V_F were measured using single Langmuir probe with different gas pressures and distances between the electrodes. It is found that the electron temperature decreases and electron density increased with increasing the argon gas pressure and varying distance between electrodes.

Keyword: Co-sputtering, Plasma diagnostics, Langmuir probe, DC sputtering.

1-Introduction:

Co-sputtering of materials offers an important alternative to complex and sometimes impossible alloying of metallic materials for a single sputtering target [1]. It is possible to configure a sputtering system such that two different target materials are sputtered, with the power to each of the targets controlled independently. Co-sputtering of two different materials has typically been accomplished with ion beam sputtering or the use of RF or DC supplies to deliver power to sputtering targets in diode or magnetron configuration [1, 2]. For alloys a sputtering system with two angled targets facing the same substrate may be used. If the two targets are simultaneously used during a single sputtering process, alloy films can be prepared using co-sputtering and the composition of alloy films can be simply controlled by adjusting the ratio of the powers applied to the two targets [3].

Plasma diagnostics are used to deduce information about the state of the plasma from observations of physical processes and their effects. The information is used to verify performance of the experiment and for control of the plasma volume regarding its topology and boundary. This is done in terms of a number of plasma parameters [4, 5]. Among various electrical diagnostics, Langmuir probe is the most widely used, because it provides a simple and relatively cheap technique for measuring plasma parameters in low-pressure plasmas. The probe characteristics help to obtain information about the electron and ion number densities, electron temperature and the plasma potential [6, 7].

Langmuir probe is a single electrode where one conductor is inserted into the plasma. The probe is a conducting wire typically made out of a high temperature metal such as tungsten or nickel, and is surrounded by an insulating sleeve, usually made out of a ceramic such as alumina. The conductor extends out of the insulator some distance to form the probe area. Low pressure plasma is defined as one in which a probe of sufficiently small diameter produces a negligible disturbance to the carrier concentration and in which the great majority of the applied probe to plasma

potential is developed across a region that is much thinner than the carrier mean free path [8].

Plasma parameter can be calculated using I–V characteristic curve obtained by applying various probe biasing voltage to the probe tip and recording their corresponding current. Langmuir probes provide reliable electron temperature and density measurement in relatively cool, low-density plasmas [9].

Child's Langmuir law can be applied to calculate probe current corresponding to the various values of probe potential [10, 11].

$$I_p = I_o e^{-eV_a/kT} \quad (1)$$

Where V_a is applied biasing voltage, I_p is probe current at any biasing voltage, T is temperature, k is Boltzmann constant, e is the electron charge and I_o is probe current at zero biasing voltage.

The inverse slope of the logarithmic plot of the electron retarding regime provides the electron temperature using [10]:

$$\frac{d \ln I}{dV} = \frac{e}{kT_e} \quad (2)$$

where I is probe current and V is probe voltage

The electron temperature (T_e) is calculated as [10,12]:

$$T_e = \left(\frac{eV_a}{k} \right) * \left(\frac{1}{\ln \left(\frac{I_p}{I_o} \right)} \right) \quad (3)$$

Electron density (n_e) can be calculated by the relation given below [9]:

$$n_e = \left(\frac{I_o}{A_p e} \right) * \left(\sqrt{\frac{m_e}{2\epsilon_o k T}} \right) \quad (4)$$

where A_p is the area of the probe tip inside the plasma, ϵ_o is the Free Space Permittivity and m_e is the mass of electron.

Debye's length (λ_D) can be calculated from the formula [10,12]:

$$\lambda_D = \left(\frac{\epsilon_o k T_e}{n_e e^2} \right)^{1/2} \quad (5)$$

The number of charged particle N_D within the Debye sphere must be large so that collection interactions dominate at the mean interparticle separation distance. The number of particles (N_D) in air as well as under vacuum is calculated by the formula [12]:

$$N_D = \frac{4\pi}{3} n_e \lambda_D^3 \quad (6)$$

The relatively fast electron frequency ω_{pe} (the ions do not participate in these oscillations because of their high mass) is the most important and references to the plasma frequency. Plasma oscillations will only be observed if the plasma system is studied over the periods τ longer than the $\tau = 1/\omega_{pe}$ and if external actions change the system at a rate no faster than ω_{pe} . Plasma frequency (ω_{pe}) can be calculated as [10, 13]:

$$\omega_{pe} = \sqrt{\frac{e^2 n_e}{\epsilon_0 m_e}} \quad (7)$$

Also, the ion plasma frequency (ω_{pi}) given by:

$$\omega_{pi} = \sqrt{\frac{e^2 n_i}{\epsilon_0 m_i}} \quad (8)$$

2-Experimental technique

The chamber is made up of stainless-steel with 28 cm in diameter, 40.5 cm in height and 0.4 cm thickness and designed in a cylindrical shape with one open ends. The chamber has a hole in the medial with dimension 0.5 cm width and 0.5 cm depth with O-ring. It contained three Pyrex windows with thickness of about 3 cm and diameter of about 10 cm in different levels (the dimension of the chamber and base is shown in fig.1).

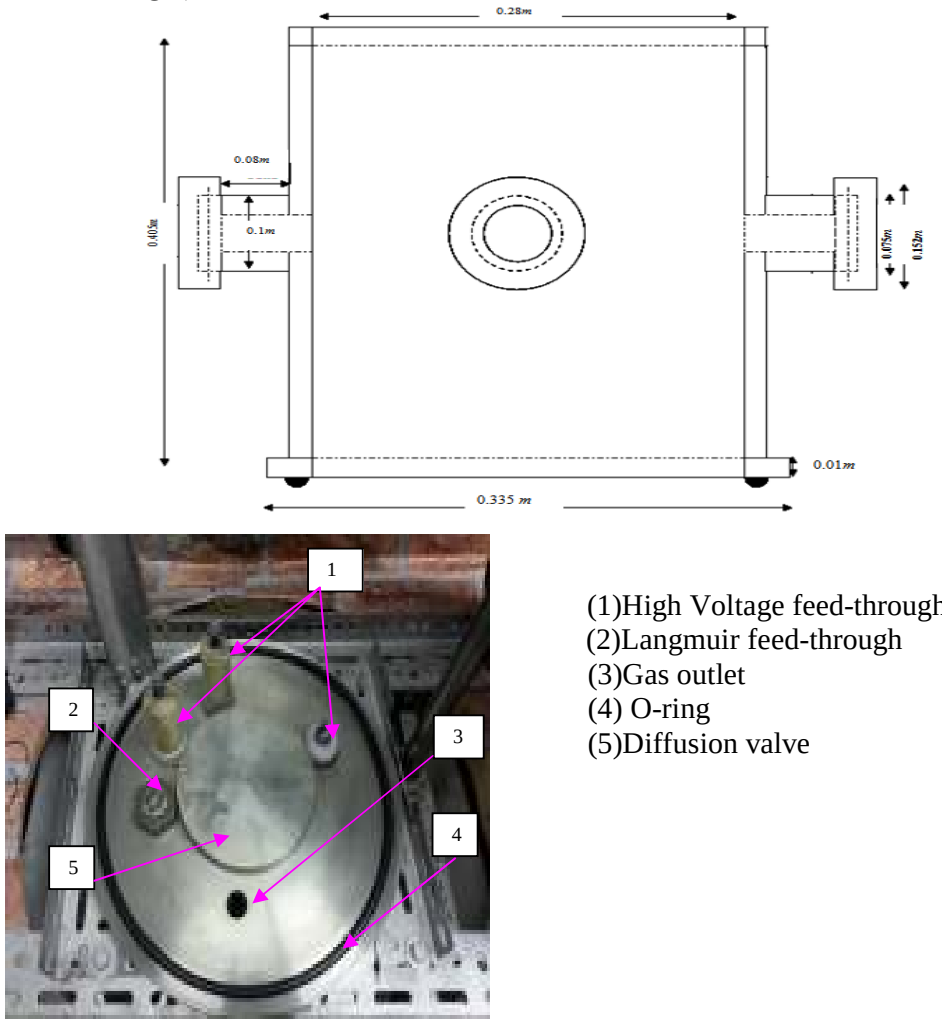


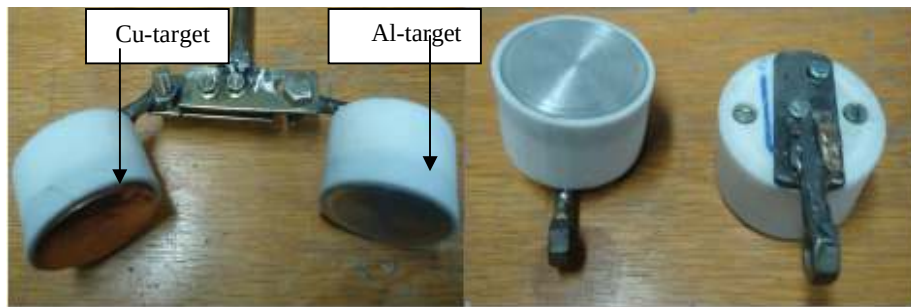
Fig.(1) The chamber and base diagram.

The targets were designed and constructed from aluminum and copper metal with diameter 4.8 cm and thickness 1 cm for each target (but normally the thickness of the

targets are equivalent to 0.3175 and 0.635 mm approximately) .Targets carried on the platform of variable angles as shown in Fig.2.



(a)



(b)

Fig. 2 photograph of (a) targets parts and (b) variable-angles stage

The Teflon was used as a cover with thickness of 4 cm and 5 cm diameter. Fig.3 show the Teflon target diagram.

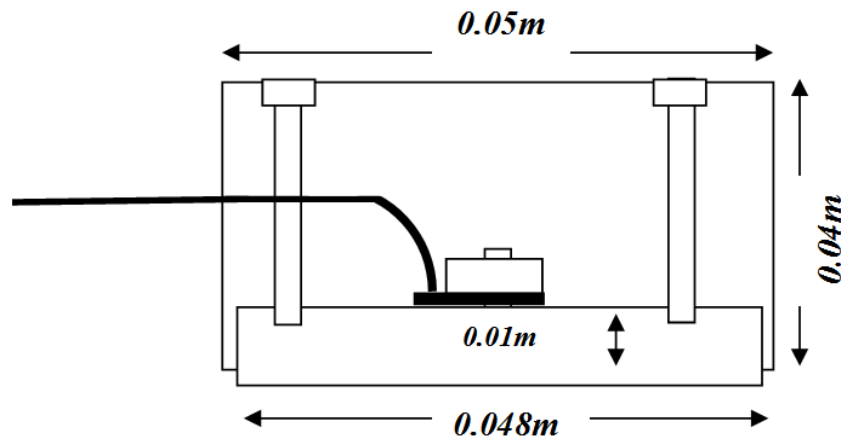


Fig.3. The target diagram

The probe consist of a tungsten wire of 4 mm in length and 0.5 mm in diameter, which are covered by a thin glass tube with outer diameter of (5mm) to insulate it from the plasma expect for a short length of exposed tip . Special designed are made for Langmuir probe to moving in 2D for plasma diagnostic. Fig.4 show (a) Langmuir probe with its stand and (b) Langmuir probe setup in system.



Fig.(4) (a) Langmuir probe with its stand and (b) Langmuir probe setup in system.

Chamber was pumped down by two- stage, rotary Vane Vacuum pump (model Varian DC302) to a base pressure of about 10^{-3} mbar, after which it was pumped by oil diffusion pump to a base pressure of 10^{-5} mbar.

3-Results and discussion

One of the assumptions made in probe theory is that the plasma is homogenous and large in dimensions compared to the mean-free path of the electrons. The mean-free path of electrons is inversely proportional to the mean collision probability for electrons. In the low-pressure (< 0.2 mbar) plasma investigated here, that the mean free path of electrons has to be reasonably long but shorter than the distance between the electrode while the transverse dimension of our reactor is 5cm .

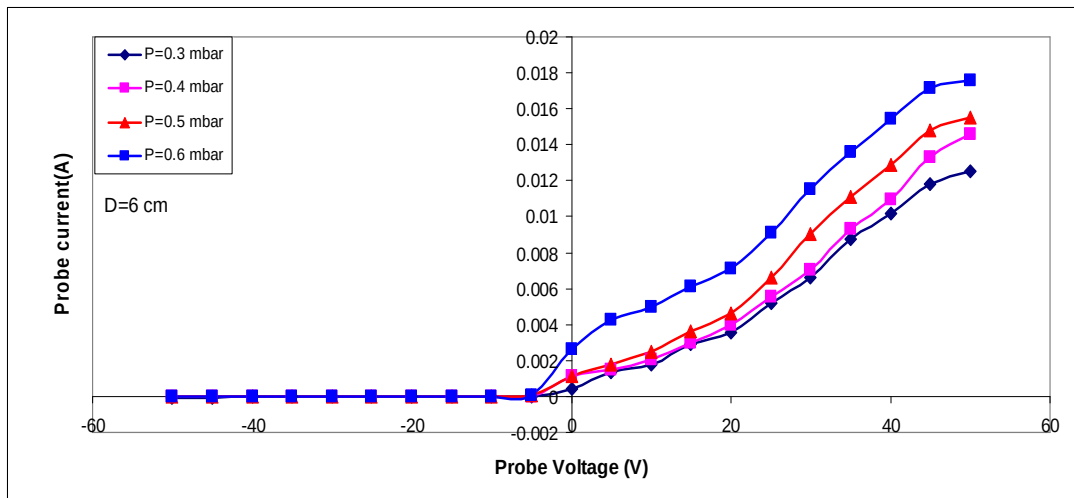
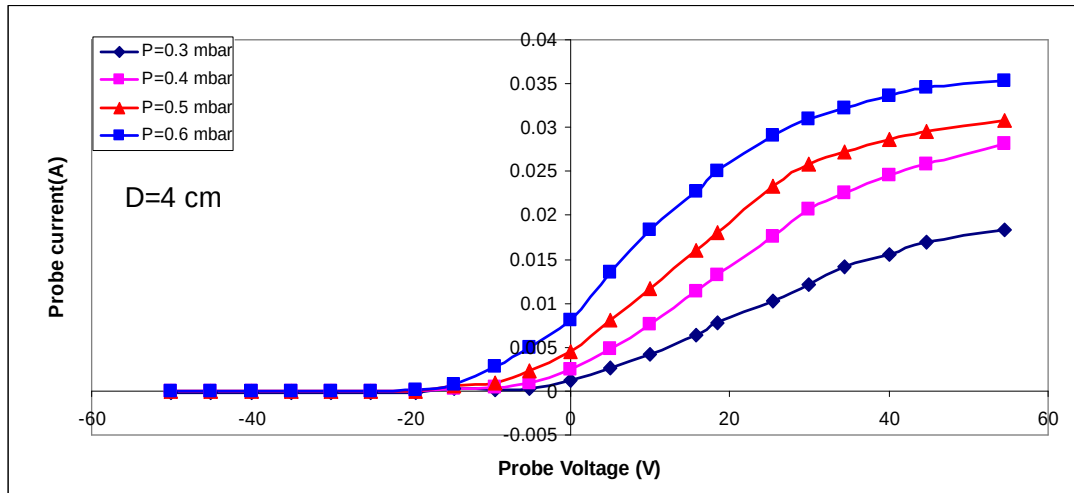
From Langmuir probe I-V characteristics we can calculate the variation of electron temperature, electron density, floating potential, and plasma potential as a function of argon gas pressure and distance between the electrodes. The probe current was calculated using equation 1. It was observed that probe current decreases with the decrease of biasing voltage. This may be due to the fact that positive sheath of ions is reduced as more electrons reach the probe tip, thus neutralizing the ions. In this way, the peak for electrons increased because new primary electrons are further producing electrons. Thus multiplication of electrons occurs. Also an increase in the biasing potential causes an increase in the number of electrons collected by the probe tip which may also be one of the reasons of increase in the probe potential.

3-1 Current – Voltage Characteristics

Figures (5,6 and 7) shows the variation of probe current I_e (A) as a function of probe voltage(V) at different Argon gas pressures and distance for Aluminum (Al) , Copper (Cu) and Al-Cu targets.

From the Figures it is observed that at weak electric fields the I-V curves are approximately symmetric, but by increasing the field strength they become asymmetric. The lack of ion saturation is slowly increasing due to an expansion of sheath thickness as the probe goes increasingly negative with respect to the plasma. The probe potential decreases with the decrease in biasing potential. This may be due to the fact that positive sheath of ions is reduced as more electrons reach the probe tip,

thus neutralizing the ions. In this way, the peak for electrons increased because new primary electrons are further producing electrons. Thus multiplication of electrons occurs. Also an increase in the biasing potential causes an increase in the number of electrons collected by the probe tip which may also be one of the reasons of increase in the probe potential. From Figures (5,6 and 7) we can show the electron current increases with increases the gas pressure and decreases with increases the distance. For Al-target the electron current will increase more than Cu-target and Al-Cu region.



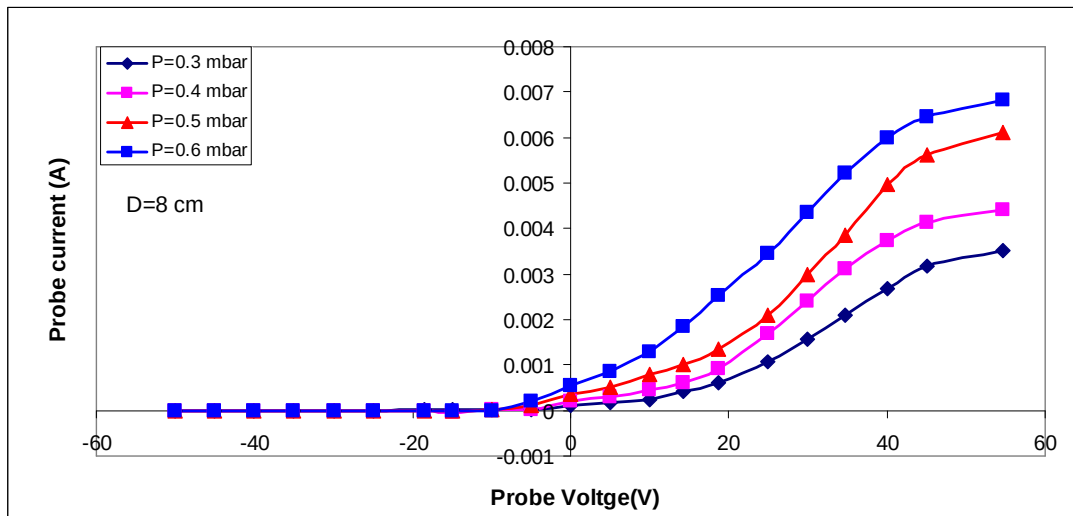
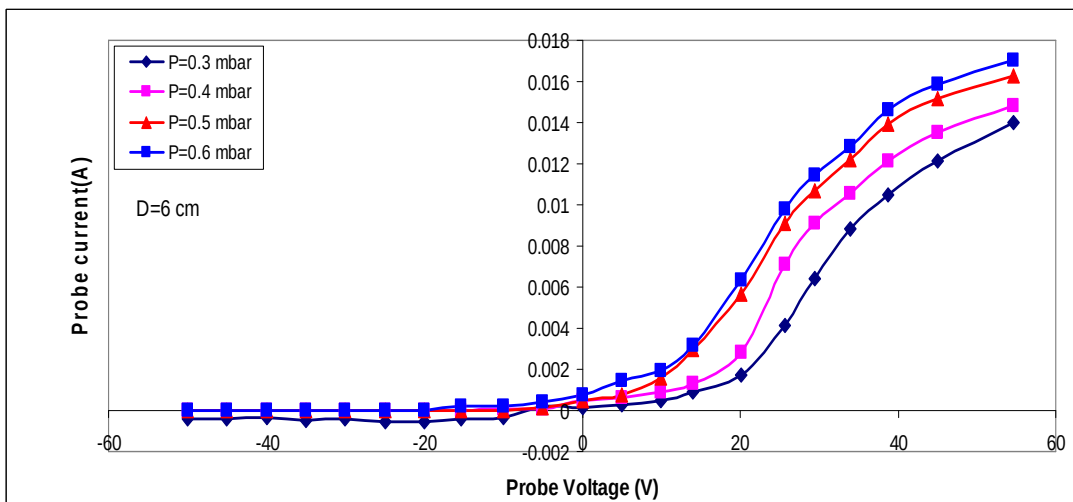
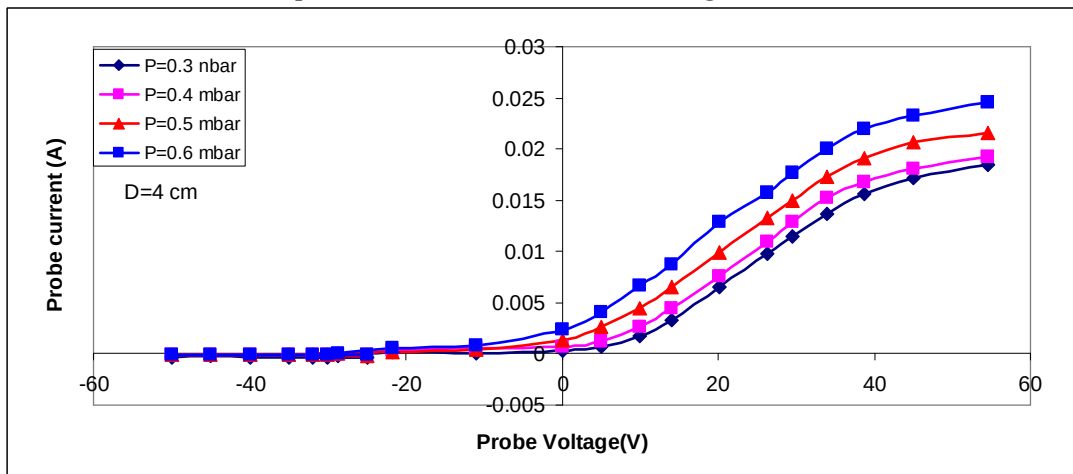


Fig.(5) The variation of I_e as a function of probe voltage at different Argon gas pressures and distances for Al target.



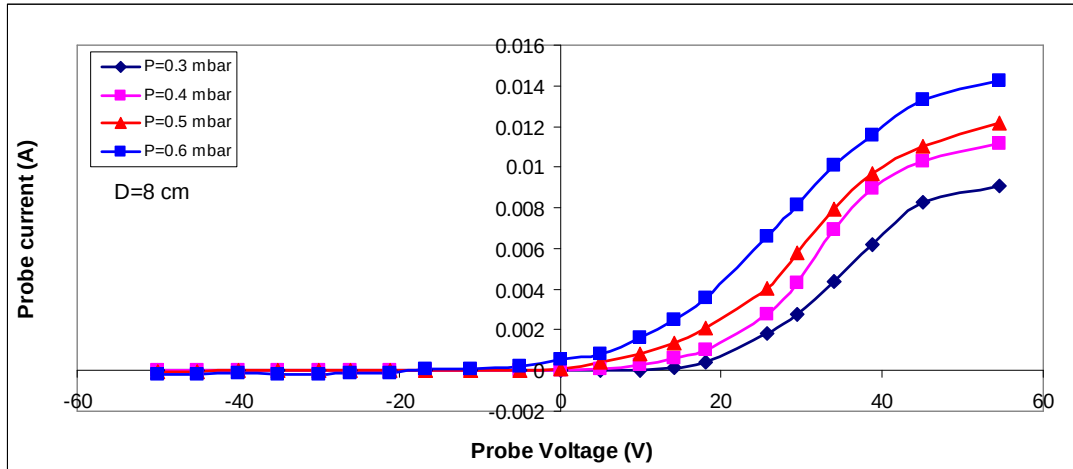
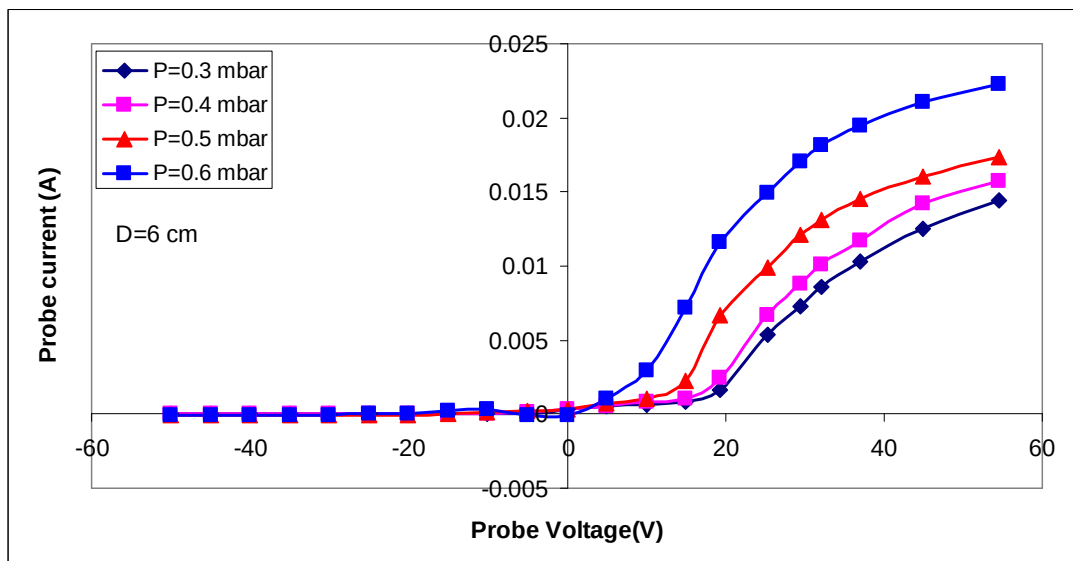
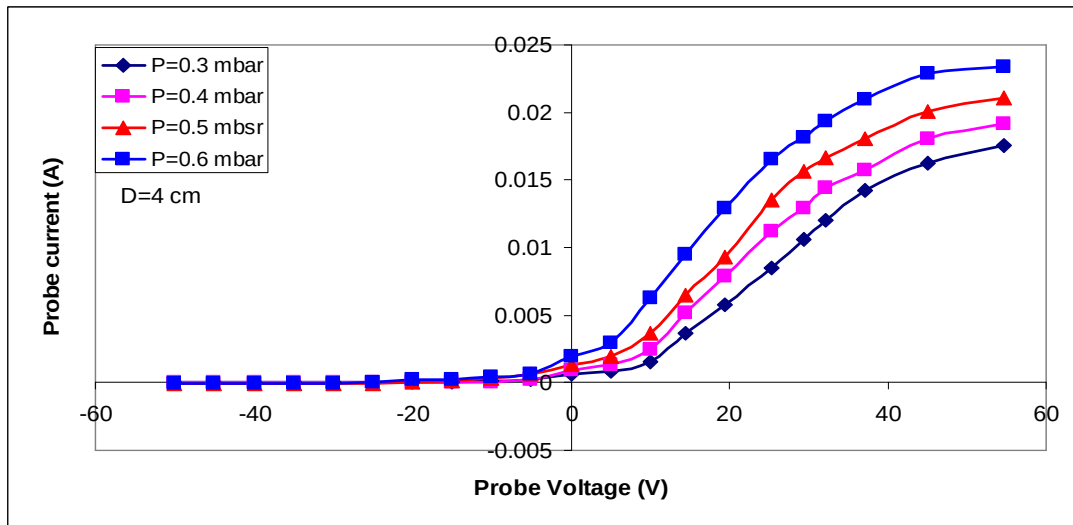


Fig.(6) The variation of I_e as a function of probe voltage at different Argon gas pressures and distances for Cu targets



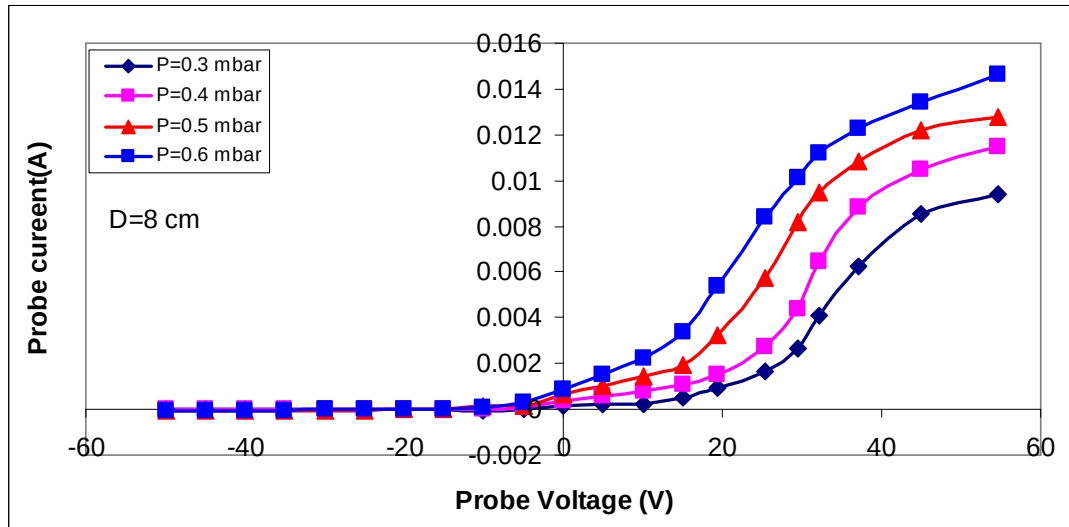


Fig.(7) The variation of I_e as a function of probe voltage at different Argon gas pressures and distances for Al-Cu targets.

The glow discharge of plasma for Cu-Al target is shown in figure 8.



Fig.8 The glow discharge plasma for Cu-Al target

3-2 Electron temperature and electron density

The variation of $\ln I_e$ as a function of probe voltage at different gas pressures and distance between electrodes for Cu, Al and Cu-Al target are shown in Figs.(9,10 and 11) respectively.

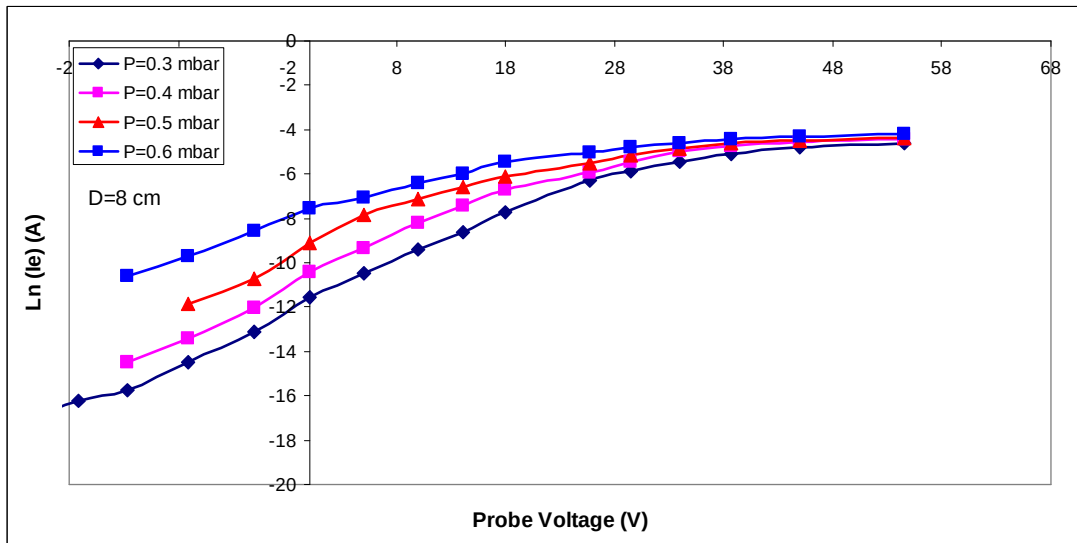
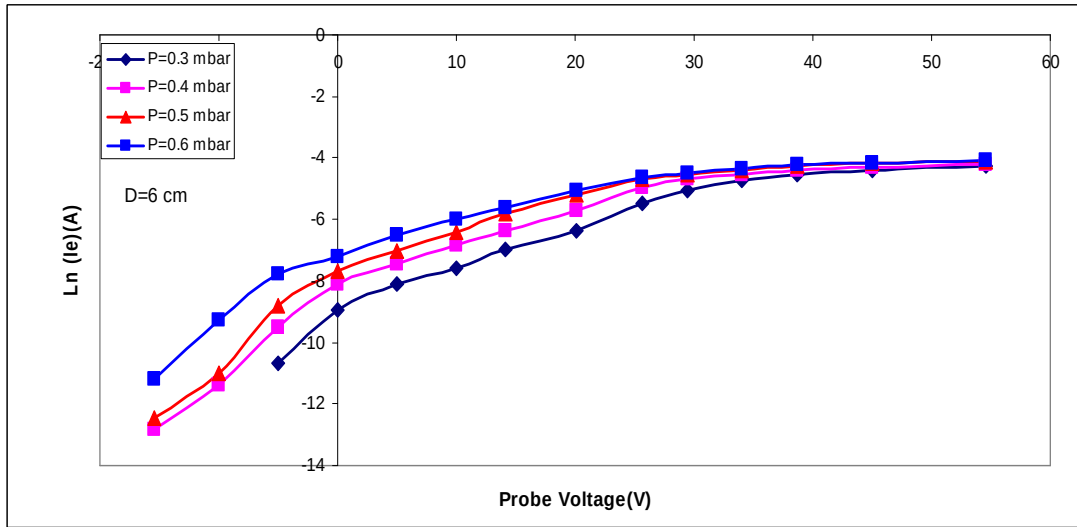
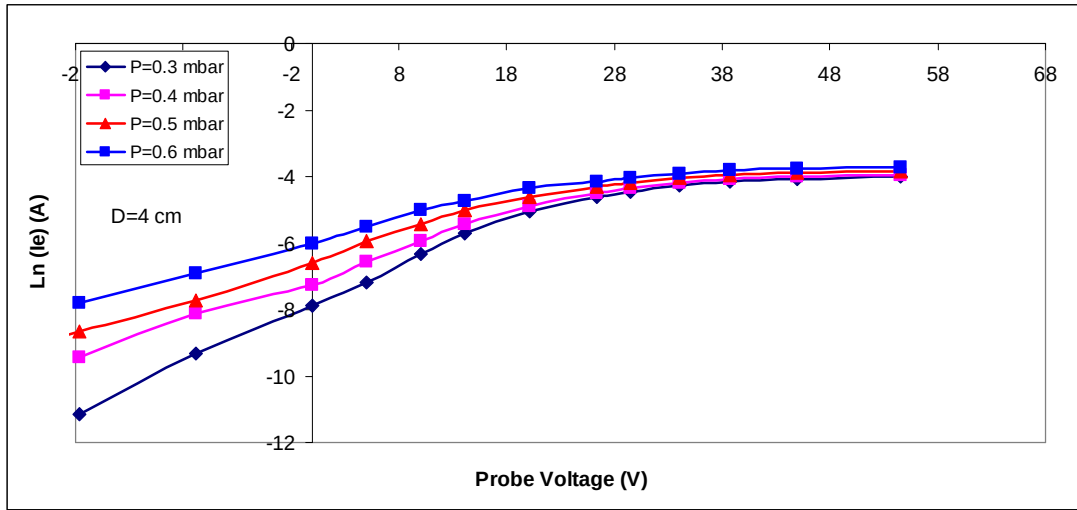


Fig.(9) the variation of $\ln(I_e)$ as a function probe voltage at different Argon gas pressures and distances for Cu target

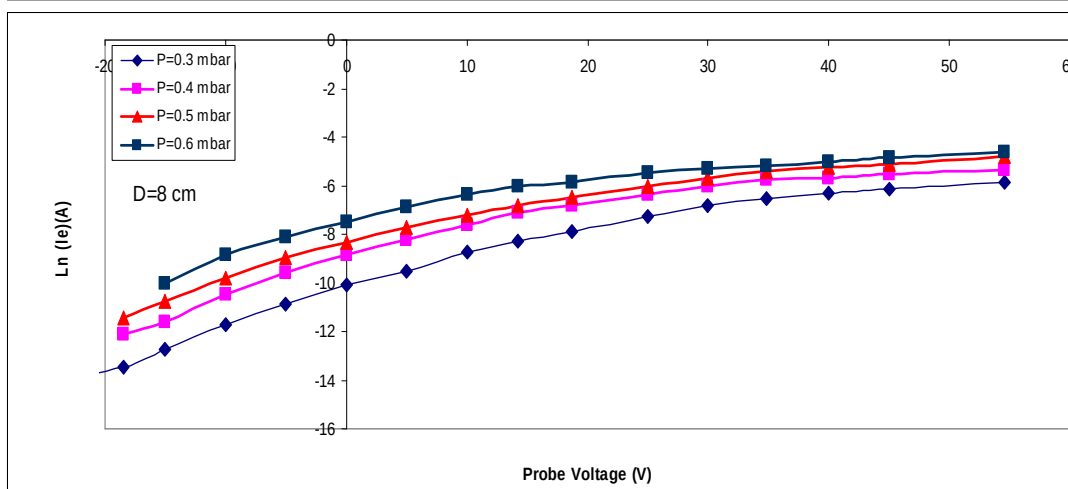
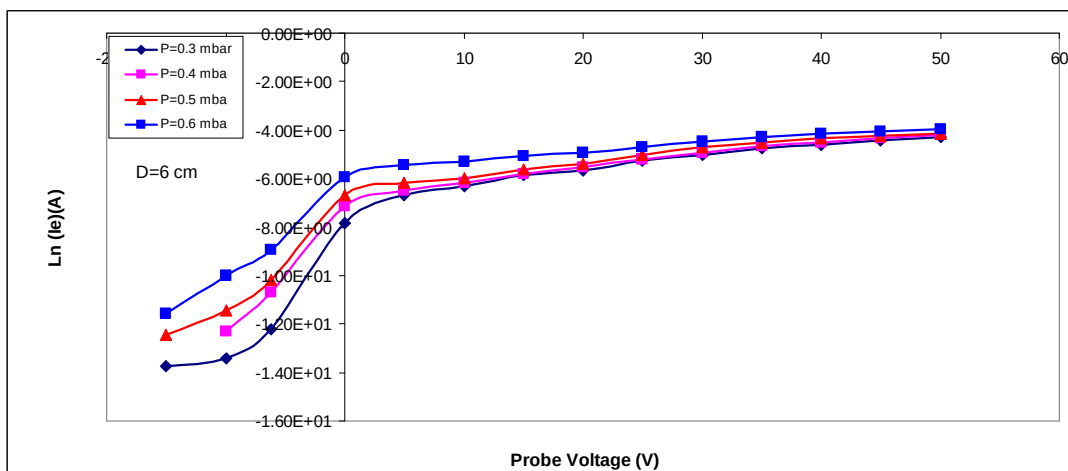
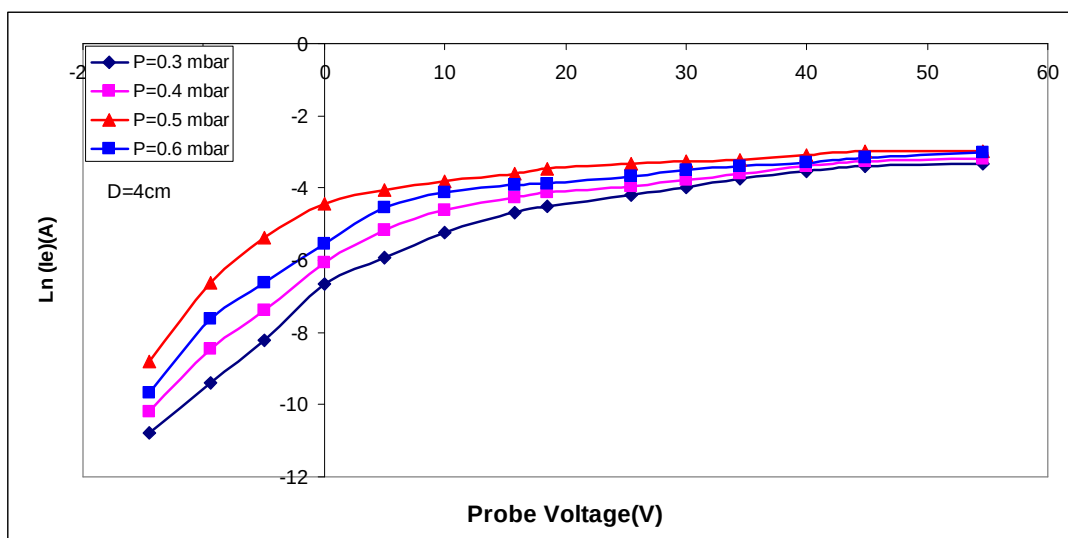


Fig.(10) the variation of $\ln(I_e)$ as a function probe voltage at different Argon gas pressures and distances for Al target

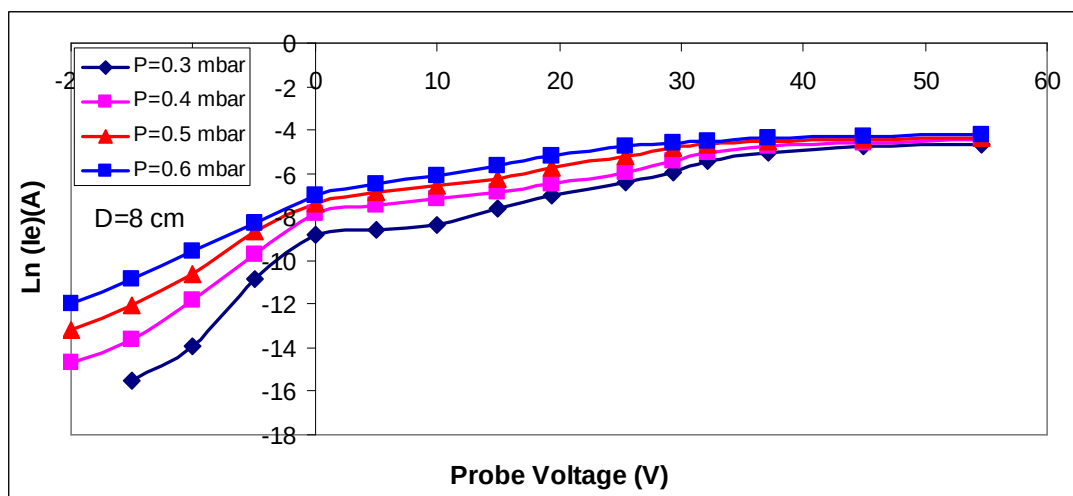
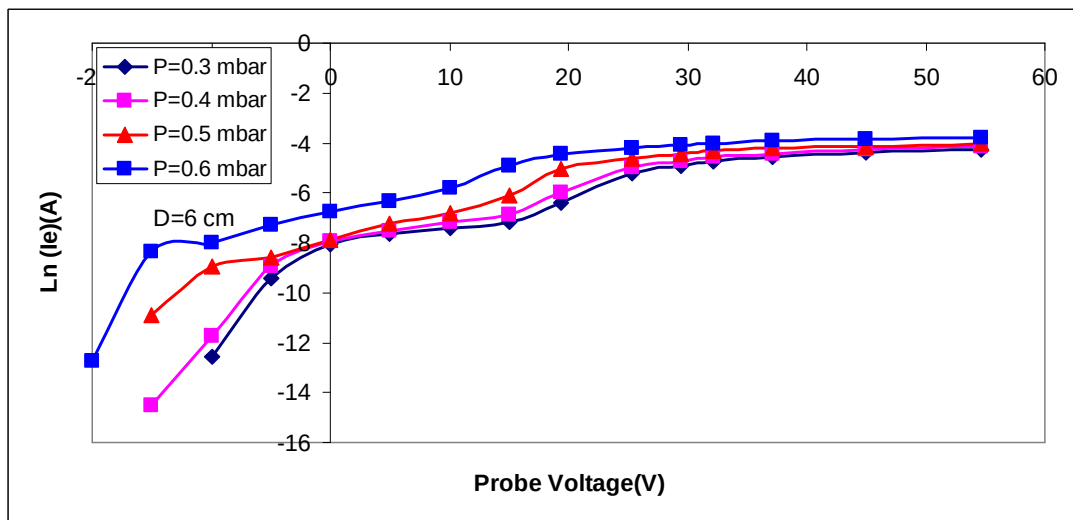
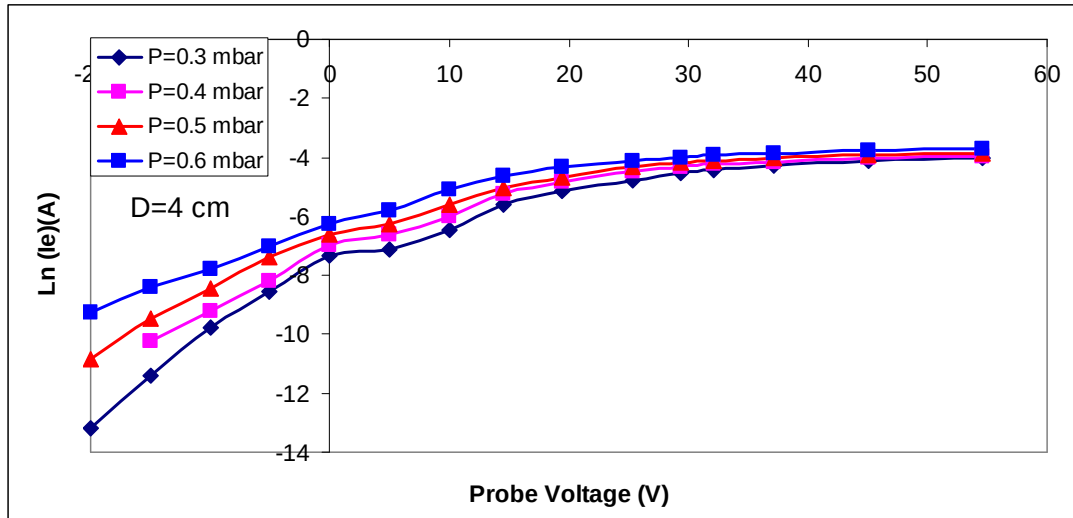


Fig.(11) the variation of $\ln(I_e)$ as a function probe voltage at different Argon gas pressures and distances for Al-Cu target

The slope of the $\ln I_e$ vs V curve in its linear region gives the electron temperature according to Equation (3). The variation of Electron temperature T_e and Electron Density n_e as a function of different gas pressures and distance between electrodes were shown in Table (1). It can be found that the electron temperature decreases with the increase of gas pressure from (0.3 -0.6) mbar. With the increase of gas pressure, electrons mean free path will become short. This will result in increased electronic inelastic collision and make the electron energy loss [14, 15]. It can be noticed that the electron density increases with increasing the pressure as shown in table (1).

Table (1) The variation of Electron Density with different gas Pressures & distances .

Distance (cm)	Pressure (mbar)	Electron Density n_e (m^{-3})			Electron Temperature (eV)		
		Al-target ($\times 10^{10}$)	Cu-target ($\times 10^{10}$)	Al-Cu region ($\times 10^{10}$)	Al-target	Cu- target	Al-Cu region
4	0.3	5.43	2.76	2.45	3.75	6.25	5.50
	0.4	9.32	3.30	4.30	3.00	5.10	3.75
	0.5	12.1	4.80	7.02	2.22	3.60	3.33
	0.6	14.4	6.20	13.0	2.08	2.80	3.07
6	0.3	4.04	3.09	4.26	3.75	5.00	2.50
	0.4	5.03	4.05	6.46	2.91	4.20	1.74
	0.5	6.39	4.70	7.70	2.18	3.65	1.42
	0.6	7.39	6.49	8.70	2.14	2.33	1.25
8	0.3	0.415	1.05	1.51	6.25	5.83	4.20
	0.4	0.650	1.59	2.20	6.00	5.0	3.75
	0.5	0.850	1.78	3.14	5.00	4.80	2.20
	0.6	1.25	2.39	4.40	4.70	4.50	1.30

It is well known that the gas pressure has a major effect on the discharge plasma parameters. When the pressure increases, there are more neutrals present, hence the distance between collisions (mean free path) decreases and less energy is gained between collisions and consequently the increase in the number of collisions means the frequency of ionization will increase leading to an increase in the density [16]. Also it can be say that at a higher gas pressure the plasma density becomes greater and more electrons can be confined. At the same time plasma density increases as pressure increases that is related to increase of discharge current. This working pressure effect on plasma density can be explained in term of the electron temperature [17].

3-3 Ion Density

When the bias voltage V_B , on the probe is sufficiently negative with respect to the plasma potential V_p , the probe collects the ion saturation current (I_{is}). Positive ions continue to be collected by the probe until the bias voltage reaches V_p , at that point, ions begin to be repelled by the probe. For $V_B \gg V_p$, all positive ions are repelled, and the ion current to the probe vanishes, $I_i = 0$. The ion density in Ar plasma can be calculated corresponding to orbital motion limit theory. Ion density was calculated by plotting the I_{ions}^2 vs. probe voltage curve for the ion collection range. The slope of the linear region of these I_p^2 vs V_B curves was used to calculate the ion density. The variation of ion density as a function of gas pressure across the glow discharge chamber shown in Fig. (12).

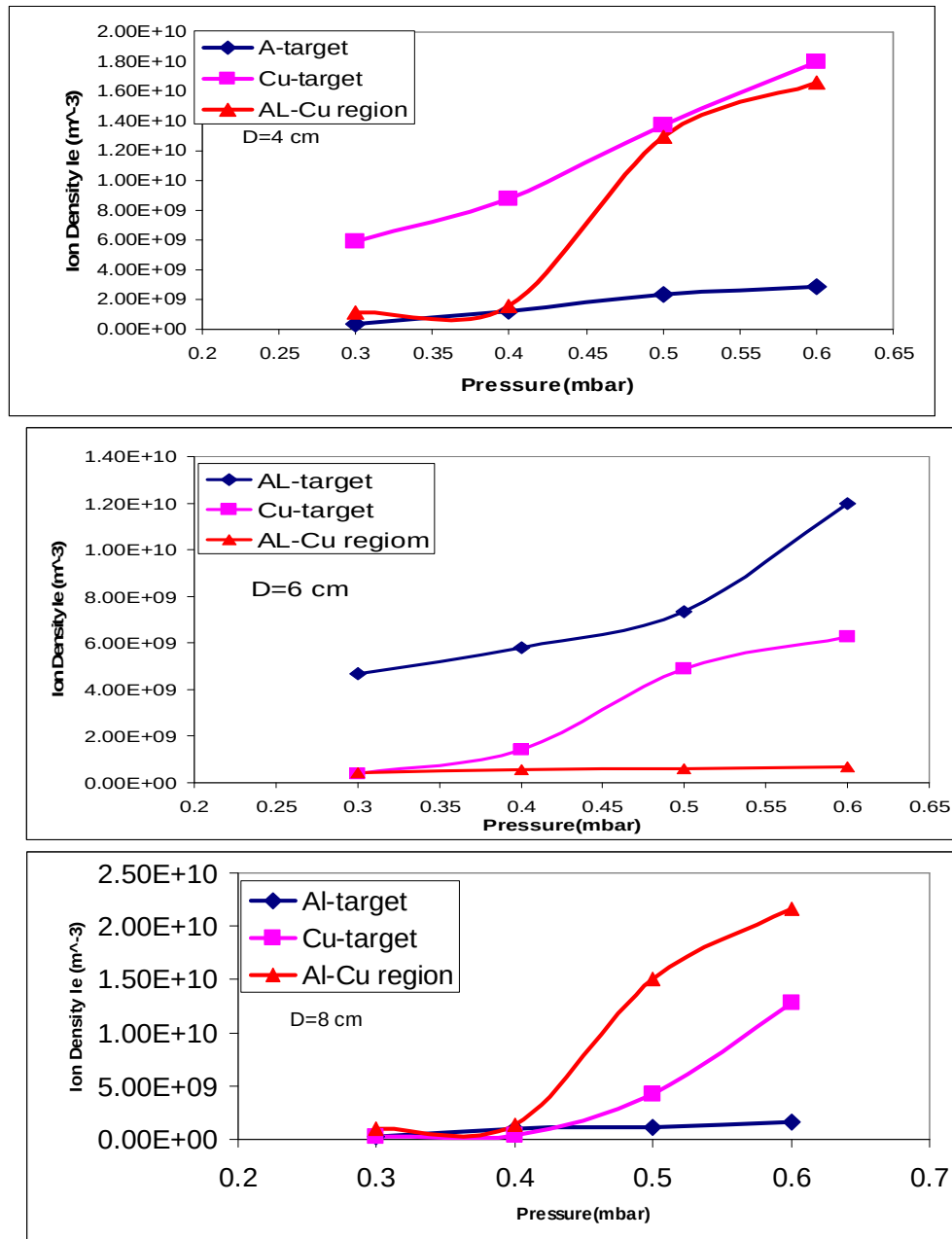


Fig.(12) The variation of Ion Density as a function of Argon gas pressures & distance.

Table 2 indicates that the ion density was increased with increasing of gas pressure. This is due to the frequency of collisions become higher where the electrons suffer collisions with neutral particles, then ionizing them. They lose their energy and accelerated according to the electron field therefore they gaining again energy and producing ionization [18].

Table (2) The variation of Ion Density with different gas Pressures & distances.

Distance (cm)	Pressure (mbar)	Ion Density n_i (m^{-3})		
		Al-target ($\times 10^9$)	Cu-target ($\times 10^9$)	Al-Cu region ($\times 10^9$)
4	0.3	0.390	5.90	1.10
	0.4	1.21	8.77	1.60
	0.5	2.37	13.7	13
	0.6	2.83	18	16.6
6	0.3	4.70	0.407	0.440
	0.4	5.80	1.41	0.54
	0.5	7.33	4.90	0.613
	0.6	12	6.29	0.681
8	0.3	0.247	0.28	0.99
	0.4	0.935	0.415	1.34
	0.5	1.16	4.24	15
	0.6	1.60	12.8	21.7

3-4 Debye length and Number of particles (N_D) in a Debye sphere

The Debye length λ_D is the measure of the penetration depth of the external electrostatic fields, i.e, the thickness of the boundary sheath over which charge neutrality may not be maintained. The applied electrical potential will therefor develop mostly near the surfaces, over a distance λ_D which is a function of the electron and ion temperature and plasma density.

Debye length is evaluated by substituting the experimental data of T_e and n_e into equation 5. The Number of particles (N_D) in a Debye sphere calculated using Equation 6. Debye length increases with the increase of the electron temperature. Debye length and N_D decreases with increases gas pressure at different distance as shown in Table (3).

Table (3) The variation Debye length λ_D with Number of particles (N_D) in a Debye sphere at different gas Pressures and distances.

Distance (cm)	Pressure (mbar)	Al-target		Cu-target		Al-Cu region	
		No. of particles N_D	λ_D (cm) $\times 10^{-3}$	No. of particles N_D	λ_D (cm) $\times 10^{-3}$	No. of particles N_D	λ_D (cm) $\times 10^{-3}$
4	0.3	5.32	0.661	16.0	1.11	14.0	1.10

	0.4	2.90	0.42	10.8	0.919	5.90	0.69
	0.5	1.61	0.316	5.29	0.638	4.58	0.59
	0.6	1.35	0.28	3.21	0.490	1.10	0.15
6	0.3	6.16	0.713	10.8	0.9 42	3.26	0.56
	0.4	3.77	0.56	7.30	0.755	1.54	0.38
	0.5	2.18	0.43	5.49	0.650	1.03	0.317
	0.6	1.90	0.39	2.38	0.440	1.02	0.280
8	0.3	41.4	2.80	23.0	1.70	23.0	1.23
	0.4	30.9	2.20	15.0	1.31	15.0	9.60
	0.5	20.7	1.70	13.4	1.21	13.4	6.20
	0.6	15.0	1.40	10.5	1.01	10.5	4.00

3-5 plasma frequency (ω_p)

For the first look at plasmas, when designing an experiment, the electron plasma frequency is of higher importance, so that it is often only referred to as the plasma frequency. Any electric field applied with a frequency below the plasma frequency has no chance of penetrating into the bulk plasma, as the electrons move fast enough to immediately shield it out. The behavior of the medium will be dominated by collective plasma phenomena, the basic plasma length and time scales. According to Equation 7 and 8 it can be noted that the electron plasma frequency (ω_{pe}) increases with increase gas pressure and its value greater than ion frequency (ω_{pi}) as shown in Table (4).

Table (4) The variation of plasma frequency (ω_{pe}) and Ion plasma frequency (ω_{pi}) at different gas Pressures and distances.

Distance (cm)	Pressure (mbar)	frequency					
		Al-target		Cu-target		Al-Cu region	
		(ω_{pe}) ($\times 10^7$)	(ω_{pi}) ($\times 10^4$)	(ω_{pe}) ($\times 10^7$)	(ω_{pi}) ($\times 10^4$)	(ω_{pe}) ($\times 10^7$)	(ω_{pi}) ($\times 10^4$)
4	0.3	1.31	4.88	0.938	3.48	0.884	3.28
	0.4	1.72	6.39	1.02	3.81	1.17	4.35
	0.5	1.96	7.37	1.24	4.61	1.20	4.73
	0.6	2.13	7.94	1.40	5.21	4.60	1.74
6	0.3	1.13	4.21	0.991	3.68	1.16	4.32
	0.4	1.26	4.70	1.13	4.21	1.43	5.32
	0.5	1.42	5.29	1.22	4.54	1.56	5.82
	0.6	1.50	5.69	1.40	5.33	1.66	6.20
8	0.3	0.363	1.35	0.578	2.15	0.695	2.58
	0.4	0.458	1.70	0.713	2.65	0.837	3.11
	0.5	0.520	1.93	0.574	2.80	1.01	3.71
	0.6	0.630	2.34	0.872	3.24	1.18	4.41

3-6 Floating Potential and Plasma Potential

Plasma potential (V_p) is one of the most important plasma parameters which indicate the incident energy of ions upon substrate. A low V_p will lead to low substrate temperature and weak ion bombardment damage to deposited films. The variation of plasma potential with gas working pressure for argon gas is shown in table 5. The plasma potential decreases with increasing argon pressure, while it can be observed from this figure that the floating potential increases with increasing of gas pressure, this result is good agreement with previous studies [15]. For a high gas pressure the plasma density becomes greater and more electrons can be confined, so V_p will decrease more as show in Table (5).

Table (5) The variation of Plasma Potentials (V) as a function of Argon gas pressures and distance

Distance(cm)	Pressure(mbar)	Plasma Potentials (volt)		
		Al-target	Cu-target	Al-Cu region
4	0.3	46	39	40
	0.4	43.5	36.5	36
	0.5	39.75	36	34
	0.6	38.2	34	32
6	0.3	51	48	48
	0.4	50	47	47
	0.5	49	45	46.5
	0.6	48	42.5	42
8	0.3	45	43.5	41.75
	0.4	41	41.75	38
	0.5	38	39.5	34
	0.6	36	41	32

The floating potential V_f is defined by $I_i = I_e$. It can be observed from these table that the plasma and the floating potentials decreases with increasing gas pressure and distance between two electrodes and the reason, is that the increase of the magnetic field will cause an increase of number of electrons compared with that of ions. When the electrons are accumulation the number of electrons on the surface decreases, this will lead to the decrease of plasma floating potential and then the decrease of plasma potential.

4 conclusions

A comparative investigation was carried out of the discharge characteristics(current-voltage characteristic and dependence of the running voltage on the gas pressure at constant discharge current, as well as of some plasma parameter (like electron temperature T_e , electrons density n_e ,ions density n_i , plasma potential V_p and floating potential V_F) were measured using single Langmuir probe with different gas pressures at different distance between the electrodes in Argon a cylindrical systems for Co-sputtering with Al-Cu targets. It was found that the electron

temperature, plasma potential decreases and electron density, ion density and plasma frequency increased with increasing the argon gas pressure. The value of plasma frequency greater than ion frequency (ω_{pi})

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