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Preparation of Cu thin film by cylindrical magnetron sputtering device

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Abstract

In the present work, a D.C. magnetron sputtering system was designed and fabricated. This chamber of this system includes two coaxial cylinders made from copper .the inner one used as a cathode while the outer one used as a node. The magnetic coils located on the outer cylinder (anode) .The profile of magnetic field for various coil current (from 2Amp to 14Amp) are shown. The effect of different magnetic field on the Cu thin films thickness at constant pressure of $7x10^{-5}$mbar is investigated. The result shown that, the electrical behavior of the discharge strongly depends on the values of the magnetic field and shows an optimum value at which the power absorbed by the plasma is maximum. Furthermore, the plasma characterization was also measured by Planar Langmuir probe to given information bout the behavior of plasma through the sputtering process.

Keywords
cylindrical Magnetron sputtering.
D C sputtering, abnormal glow discharge.

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تحضير الاغشية النحاسية بواسطة منظومة الترذيذ المغناطيسي ذات الابعاد الاسطوانية

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الخلاصة:

في هذا البحث , تم تصميم و بناء منظومة الترذيذ المغناطيسي ذات التيار المستمر. ان حجرة هذه المنظومة تتكون من أسطوانتين نحاسيتين متداخلتين. الداخلية منها تستعمل كقطب سالب بينما الخارجية منها تستعمل كقطب موجب. حيث ان ملف المغناطيسي موضوع على السطح الخارجي للاسطوانة الخارجية (القطب الموجب). أن توزيع المجال المعناطيسي لمختلف التيارات المارة بالملف من 2 أمبير الى 14 أمبير قد وثقت. تم دراسة تأثير المجال المغناطيسي على أسماك الاغشية النحاسية المحضرة تحت ضغط ثابت مقداره $7x10^{-5}$ ملي بار. ان نتائج هذا البحث قد بينت بان سلوك التفريغ الكهربائي يعتمد على قيم المجال المغناطيسي حيث لوحظ بان المجال المعناطيسي يمتلك افضل قيمة عندما تكون القدرة الممتصة من قبل البلازما أعظم مايمكن. بالاضافة الى ذلك أن خصائص البلازما قد قيست بأستخدام مجس لانجمور المستوي لغرض معرفة سلوك البلازما خلال عملية الترذيذ.

Introduction

Magnetron sputtering deposition techniques are widely applied both in industrial processes and in advanced material developments or treatment [1, 2]. The first paper on the magnetron was reported in 1960s, but the physical basis originates back to the later [3]. Since then, magnetrons have known a continuous development in various industrial fields, especially microelectronic, surface processing and widely used for thin film deposition [4]. As well as, the field of applications is sputter deposition, reactive sputter deposition, reactive ion etching, and coating of thin films. Taking the advantage of magnetic field, magnetron sputter operates at a low pressure and low voltage [3]. Since then, magnetrons have known a continuous development in various industrial fields, especially microelectronic, surface processing and widely used for thin film deposition [4]. Basically, magnetrons utilize an external magnetic field parallel to the cathode (target). The component of this field parallel to target traps energetic electrons in their travel from the cathode to the anode leading to an amplification of gas ionization and form high density plasma near the cathode surface [3,4]. Ions produced by these electrons are accelerated toward cathode surface with high energy. This bombardment of ions not only sputters out target material, but also produces secondary electrons which maintain discharge [5].

Magnetron systems take the same philosophy one step further and attempt to trap electron near the cathode so as to increases their ionizing effect [6]. This is achieved with electric and magnetic fields that are generally Perpendicular.

There are three stages in the glow discharge sputtering system [6]:

1- Acceleration of gas ions and generation of the energetic neutral gas particles in cathode dark region, giving rise to a flux of energetic particles that bombard the cathode,

2- The sputtering of cathode particles and the reflect ion of the gas particle at the cathode,

3- Transport and thermalization through the plasma of particles emitted from the cathode, until they reach the substrate.

Within the cathode dark space region the generation of energetic fluxes that bombard the cathode, which corresponds to the first stage, is dominated by inelastic process such as ionization or charge exchange. However, elastic events prevail both in the sputtering and backscattering processes that take place during the second stage, and also are responsible for the energy degradation of the particles. Whereas, during the third stage, they travel through the plasma until reach the substrate.

Experimental Setup

A Dc cylindrical magnetron sputtering is designed and fabricated. The chamber of this system is consisting of two copper coaxial cylinders the inner one used as a cathode and the outer one used as anode. The diameters of the inner and outer cylinder are 1.9cm and 9.8cm respectively and 22cm length. This system is shown in figure (1).

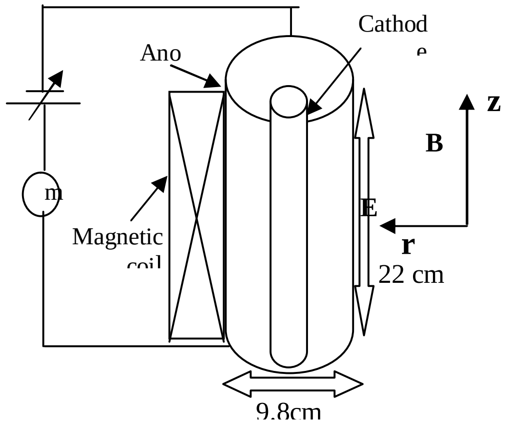

Figure (1): Schematics of cylindrical

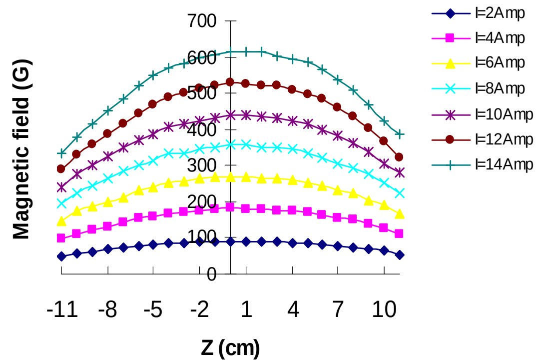

Figure (2): The experimental magnetic field profile as a function of coil current.

Basic Magnetron parameters

In this paper, the abnormal glow discharge was used to preparation of Cu thin film. Where the abnormal glow was established when we applied a D.C. constant potential about 1.6kV between coaxial cylinder electrodes. The deposition pressure associated with preparation of Cu thin film is approximately of $7x10^{-5}$mbar after argon gas puffing. A rectangular shape (25.4mmx76.2mm) pieces of flat glassing is chosen as substrate and located at Z=0 (where Z=0 refer to 11cm high from the bottom of cylinders) on the anode surface as shown in figure (1). The period of sputtering process for deposition of Cu thin film was 30 minutes.

Nevertheless, the environment substrate locations surrounding a cylindrical-post magnetron is considerably different from that of planar magnetron by two facts [7]. First, the substrate is not in direct contact with the intense plasma. Where the substrate are generally located at radii beyond the virtual anode where the charged particle density due to escaping ions is typically 1/50 to 1/100 that in the discharge. Second, the important difference is the wide range of working gas pressure that is possible with magnetrons. Magnetrons can be effectively operated at such low pressures that the mean free path of both the working gas and the sputtered atoms is of the same order of magnitude as be effectively used to define deposition areas.

Figure (3) indicted the influence of increasing the magnetic fields that associated with increasing coil current on discharge voltage. One should remarked that, the discharge voltage decreases with increasing of coil current until 4Amp and then increasing progressively with increasing of coil current above 4Amp. This behavior can be explained as, when the coil current increased, the magnetic field was then established. A present magnetic field perpendicular to the electric field increases the path length of electron and ensures a sufficiently high ionization rate. Thus, the ion formed and most of these ions are bombardment the cathode, causing atoms of the cathode material to be sputtered and secondary electrons to be emitted. These secondary electrons enter the trapping region and cause sufficient ionization to maintain the discharge. Therefore, the discharge current increases and consequently the discharge voltage decreased. This happened for coil current less than 4Amp. Moreover, when the coil current increases above 4Amp, the electron gyro radius would decreases and therefore the probability of the electrons to make collisions with neutral atoms to generate ion bombardment of the cathode was decreases. So that, the discharge current decreases and discharge voltage increases.

The power of the system for different current of coil (corresponding to magnitude of magnetic field) is measured in figure (4). It can be seen that, there is a peak power when the current coil is 4 Amp (corresponding to magnetic field 181.33 G). This behavior can be described as, when the magnetic field is too high compare to applied voltage, the electron cannot reach to the anode. Therefore, the current of discharge decreased and this fact leads to power reduction. On other hand, in low magnetic field, the degree of ionization is low and therefore the current of discharge decreased.

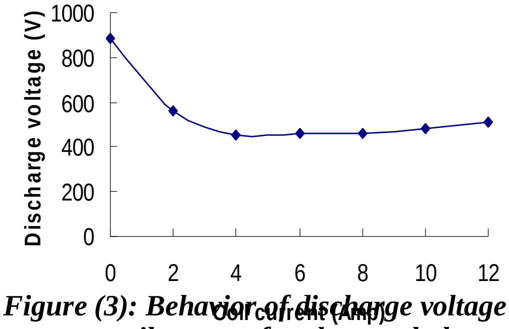

Figure (3): Behavior of discharge voltage versus coil current for abnormal glow discharge region at pressure of 7x10^{-5} mbar.

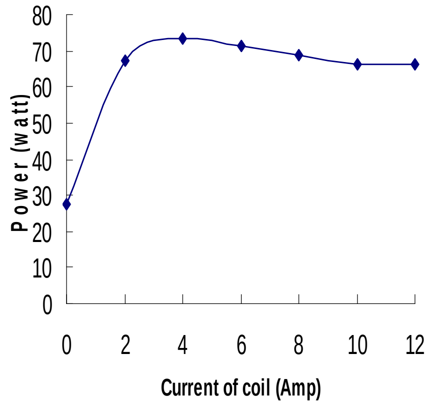

Figure (4): Curve of power of the system versus Current of coil at pressure of 7x10^{-5} mbar.

However, figure (5) shows the thickness of film as a function of coil current at constant Argon pressure of 7x10^{-5}mbar. One can observe from this figure, the thin film thickness increasing with increasing the coil current until it reach to optimum value 4Amp then decreased. This behavior attributed to the variation of the behavior of power with coil current which was mentioned above (see figure (4)).

Anyway, most of the above observation leads us to believe that any understanding of the sputter process would require the analysis of the plasma properties in such process.

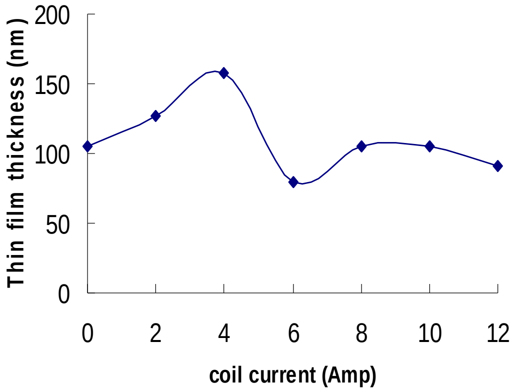

Figure (5): Thin film thickness versus current of Coil at constant pressure of 7x10^{-5} mbar.

Analysis of Plasma Characteristics in Abnormal Glow Discharge Region

Two 2.2mm diameter tungsten planar probes located at different radial positions were used to measure of plasma characteristic in center region (i.e. Z=0 cm). These probes located at a radial distance 1cm and 2cm from the cathode surface with axial parallel to the cathode (in the direction of magnetic field lines).

According to the experimental data of these probes, Ln I_e-V curves for different magnetic field strengths were plotted in figure (6). It is clear from this figure, the straight line of transition region of these curves dividing into two straight lines. Therefore, two Maxwellian electron groups with different energy are presents (i.e. hot and cold electrons groups are present). The slopes of two straight segments would give the temperatures of the two groups.

Figure (7) shows the effect of magnetic field on the hot electron temperature at different radial positions from the cathode. The comparison of both curves showed that, the values of hot electron temperature at a distance 1cm less than its values at distance 2cm with and without the magnetic field strength except at 530G. This behavior was due to the electron in the vicinity of the cathode was suffer many collisions with argon atoms to generate ion bombardment that could reduce the electron temperature in the vicinity of the cathode. The upper curve shown to appear of two peaks at 181.33G and 457.83G (corresponding to I_{coil}= 4Amp and 10Amp) which has values 46eV and 31eV respectively. In contrast to this behavior, the hot electron behavior at distance 1 cm showed two bottoms at these magnetic fields. We could expect from these results, the deposition rate increased at these field values.

The variation of cold electron temperature via increasing of magnetic field strength at different radial positions was shown in figure (8). It is clear from this figure, the cold electron temperature shown approximately the same behavior for different radial positions. Moreover, the cold electron temperature value at a distance 1cm is less than from its value at distance 2cm. The cold electron temperature increases from 2eV to 5eV and 6eV to 8eV at distance 1cm and 2cm respectively when the magnetic field increases from 0G to become 90.76G. Further increase in the magnetic field above 90.76G the cold electron temperature rapidly reduced to minimum value in both curves at the power peak before starts slightly increase and then decreases with increase of magnetic field strength. The decreasing of cold electron temperature may be attributed to; the electric field near the cathode was reduced with increasing of magnetic field caused by the decreasing of the cathode fall. While at distance 2cm, the decreases of cold electron temperature are due to collision of electron with deposition atoms through traveling cross the plasma.

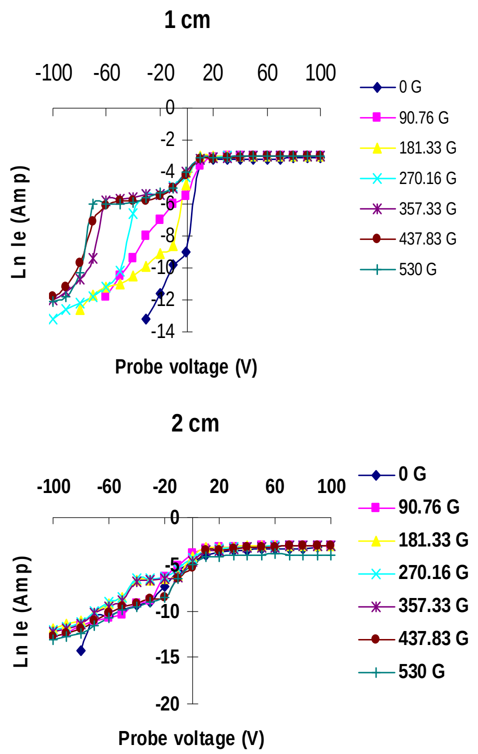

Figure (6): Ln I_e-V curves at different radial Positions versus magnetic field strength.

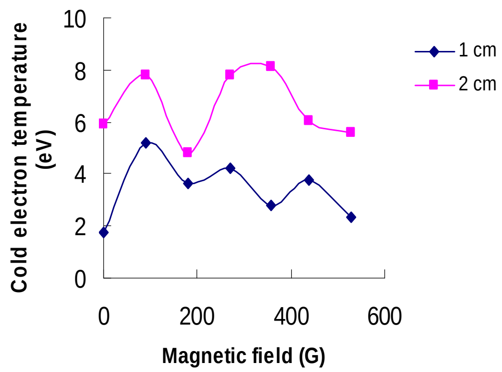

Figure (8): the variation of cold electron temperature with magnetic field strength at different radial positions.

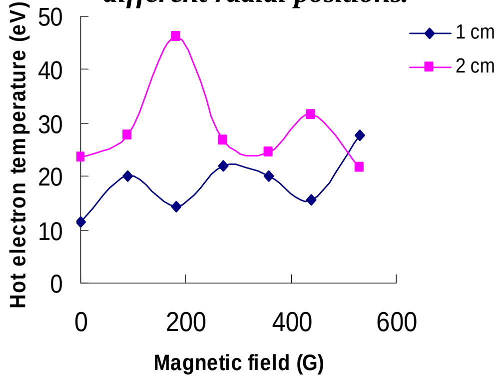

Figure (7): variation of the hot electron temperature with magnetic field strength at different radial positions.

However, the electron saturation current as function of the increasing of magnetic field strength at 1cm and 2cm from the cathode surface was illustrated in figure (9). This figure depicted several features, when there is no magnetic field applied the electron saturation current at radial distance 1cm greater than at radial position 2cm. The comparison between the electron saturation currents curves illustrated that, the electron saturation current is approximately constant and has the same values in both distances except little reduction above 357.33G in radial position 2cm. These behaviors of both curves may be due to, in the planar probe the electron current that collected by the probe (with and without magnetic field) are coming from only one direction. As well as, the magnetic field restricted the electron to move only in the direction of magnetic field. So that, the electron saturation current is approximately constant. While the reduction in the electron saturation current at a radial distance 2cm above 357.83G are due to, the electron cannot reach to the anode when the magnetic field is too high compare to applied voltage. Therefore, the electron saturation current decreased at radial distance 2cm.

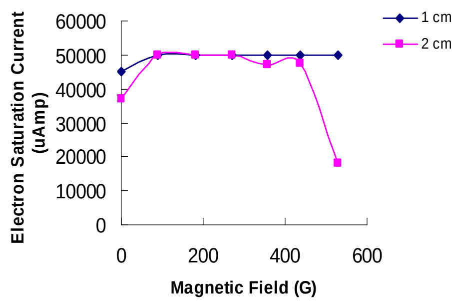

Figure (9): The influence of the magnetic field on the electron saturation current at different radial positions.

Beside of the above parameters, the effect of magnetic field on the plasma potential in the center region was obtained. Figure (10) remarked the influence of the magnetic field on the plasma potential at different radial positions from cathode surface. One should observed from this figure, the plasma potential has a positive value in the absent of magnetic field. Because of the electron has thermal velocity greater than that for ion, the electron then tend to leave plasma toward the wall. When the magnetic field was applied, the positive plasma potential reduced to minimum positive values when the magnetic field increased until 181.33 G. This behavior was noted in both curves. Further increase of the magnetic field above 181.33G field (associated with I_{coil}= 4Amp), the plasma potential become more negative at both radial distance expect radial distance 2cm, where the plasma potential after become negative starts to increase rapidly to become positive again. This occur when the B field greater than 437.83G. The effect of magnetic field on plasma potential can be explained as; the magnetic field parallel to the cathode surface would confine a layer of secondary electrons near its surface. This fact means that, the magnetic field increases the electron density. So that, the plasma potential becomes negative. Further increase in the magnetic field the electron density increased near the cathode and then the ion becomes greater than electron in plasma center. Consequently, the plasma potential becomes positive in plasma center. Thus we can conclude that, the PSC mode was established when the magnetic field has a range from 0G to the 181.33G (corresponding to coil current change from 0Amp to 4Amp) while the NSC mode formed greater than 181.33G.

However, the hot and cold electron densities are evaluated by [8, 9]:

$$I_{es} = \frac{1}{4} e n_e v_{e,th} A_{probe} \qquad (1)$$

where n_e is the electron density, $v_{e,th} = \sqrt{8kT_e/\pi m_e}$ is the average electron thermal speed, A_{probe} is the probe tip area, and m_e is the electron mass. By taking the experimental value of I_{es} (from figure (9)) and T_{eh} and T_{ec} (from figures (7) and (8)), the results of this equation are plotted figures (11) and (12). Figure (11) illustrated the influence of the magnetic field strength on the cold electron density at different radial positions. This figure is recapitulating that, the cold electron density in the vicinity of the cathode has magnitude greater than its values in the plasma center for all magnetic filed strengths. These behaviors of cold electron density due to the magnetic field parallel to the cathode surface would confined a layer of secondary electrons near its surface and reduce it in the center of plasma. Thus, the density of cold electron increased with increasing of magnetic field at a distance 1cm and decreased in the plasma center.

The variation of hot electron density with increasing of the magnetic field strength at two different radial positions from the cathode was illustrated in figure (12). There are many features could be noted from this figure, the hot electron density at a distance 1cm is greater than at 2cm. Two bottoms and peaks appear in the hot electron density at radial position 1 cm and 2cm respectively when magnetic field has values 181.33G and 437.83G (corresponding to coil current 4Amp and 10Amp respectively). The reason of these behaviors is attributed to the behavior of hot electron temperature (since the electron density escapes from the magnetic field lines and motion in normal direction when it has higher temperature).

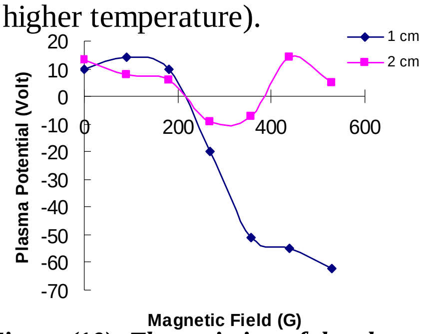

Figure (10): The variation of the plasma potential with increasing of magnetic field strengths for different radial position from the cathode.

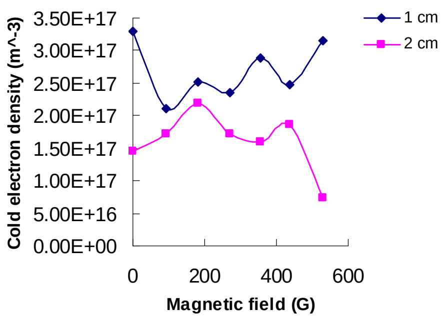

Figure (11): the influence of the magnetic field strengths on the cold electron density at different radial position from the cathode.

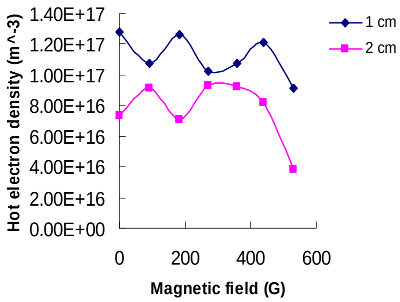

Figure (12): the influence of the magnetic field strengths on the hot electron density at different radial positions from the cathode.

The electron temperature in the case of apparent of two groups with different energy, can estimated as [9]:

$$\frac{1}{T_e}=\left(\frac{n_{ec}}{n_e}\right)\frac{1}{T_{ec}}+\left(\frac{n_{eh}}{n_e}\right)\frac{1}{T_{eh}} \tag{2}$$

Now, by taking the values of n_{ec} and n_{eh} from figures (11) and (12) and T_{he} and T_{ec} from figures (7) and (8), the result of equation (2) are plotted in figure (13). The variation of T_e versus the influence of magnetic field strength for different radial positions was shown in figure (13). It is interesting to observe that, the electron temperature curve at radial position 2cm is greater than from that in distance 1cm. At distance 1cm, the electron temperature is shown rapidly increase when the magnetic field increase to become 90.76G before starts to gradually decreases with increasing of magnetic field strength. On the other hand, the electron temperature profile in 2cm radial position shows two peaks at 90.76G and 270.16G before decreasing to minimum value. The maximum electron temperature at distance 1cm and 2cm is approximately 7eV and 10.5eV respectively.

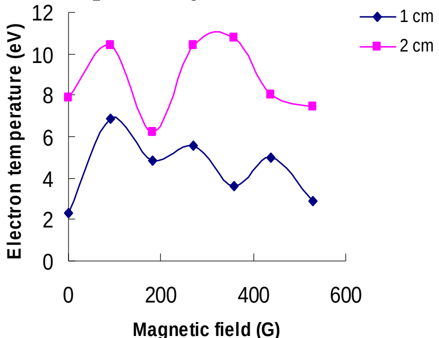

Figure (13): the influence of the magnetic field strengths on the electron temperature at different radial positions from the cathode.

Nevertheless, the behavior of T_e for both curves can be understanding based on the assumption that the magnetic field parallel to the cathode surface would confined a layer of secondary electrons near its surface. This forming virtual cathode. Moderate magnetic field will not alter significantly the incident ions trajectory nor the work function of the target [8]. Therefore, suppression would be achieved through the reduction of the local electric field near the target surface by this virtual cathode. Consequently, the electron temperature decreased near the cathode. The minimum values of electron temperature at plasma center corresponding to the field strength 181.33G. This minimum value could be associated to the fact that, the electron temperature decreases caused by the collision with the Cu atoms through passing cross the plasma.

Figure (14) shown the influence of magnetic field strength on the electron density at different radial positions from the cathode surface. Both curves in this figure shown that, the electron density near the cathode surface was greater than its values in the plasma center. The electron density at distance 1cm increasing with increasing of magnetic field strength. This fact are caused by, the magnetic field will traps the electrons near the cathode surface. While the electron density behavior at radial position 2cm shown the electron density increasing slightly with increasing of magnetic field until 181.33G before starts to decrease to minimum value. The decreasing of the electron density may be due to the electron cannot reach to the anode when the magnetic field become larger.

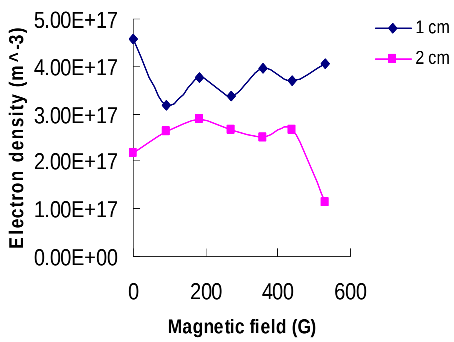

Figure (14): the influence of the magnetic field strengths on the electron density at different radial position from the cathode.

Finally, the influence of magnetic field strength on the Debye length at different radial positions was estimated in figure (15). It is interesting to observed from this figure, the formation of virtual cathode decreased the electron temperature and increased the electron density near the cathode, therefore the Debye length decreased near the cathode compare with its values in the plasma center. The Debye length profile has the similar behavior to that for electron temperature. Consequently, the sheath will expand.

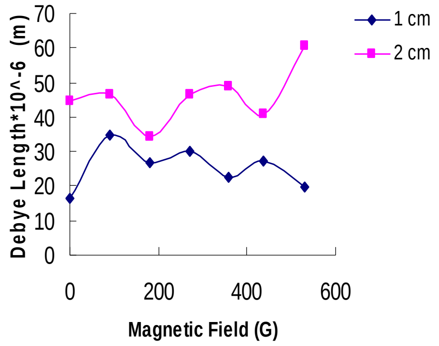

Figure (15): the influence of the magnetic fieldstrength on the Debye Length at different radial positions from the cathode.

Conclusion:

The effect of magnetic field on copper thin film thickness that perpetrated at abnormal glow discharge region at constant pressure of $7x10^{-5}$mbar was studied. The plasma characteristics in central region at radial positions 1cm and 2cm were evaluated. These characteristics illustrated that, there are two electron groups with different energy obey to the Maxwellian distribution. The magnetic field has optimum values at 181.33G that associated to 4Amp current of coil. According to this peak, the Cu thin film thickness has a maximum value. The PSC mode appears at magnetic field range 0G to 181.33G. While NSC mode appears for magnetic field above 181.33G. The PSC mode is more suitable for sputtering from the NSC mode in the sputtering device.

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