Diagnostics of dusty plasma properties in planar magnetron sputtering device

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Abstract

The effect of Al dust particles on glow discharge regions, discharge voltage, discharge current, plasma potential, floating potential, electron density and electron temperature in planar magnetron sputtering device has been studied experimentally. Four cylindrical Langmuir probes were employed to measure plasma parameters at different point on the radial axis of plasma column. The results shows the present of Al dust causes to increase the discharge voltage and reduce the discharge current. There are two electron groups in the present and absent of Al dust particles. The radial profiles of plasma parameters in the present of dust are non- uniform. The floating potential of probe becomes more negatively while the plasma potential becomes positive when the dust immersed into plasma region. The electron density increases in the present of dust particle which lead to decreases the electron temperature.

Keywords

Planar magnetron, Dusty Plasma, Al dusts grain, Electric Discharge, Longmuir probe.

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تشخيص خصائص البلازما المغبره في منظومه الترذيذ المغناطيسية ذات الابعاد المستوية

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الخلاصة

تم دراسة تجريبية لتأثير غبار الالمنيوم على كل من منطقة التفريغ المتوهج ،وفولتيه التفريغ، تيار التفريغ،جهد البلازما،الجهد العائم و درجة حرارة الالكترون في منظومة الترذيذ المغناطيسي٠فقد تم استخدام اربعة مجسات لانكمور اسطوانية لقياس معلمات البلازما لمختلف نقاط الاشعاعية على طول عمود البلازما ٠ فقد بينت النتائج في وجود غبار الالمنيوم تزداد فولتيه التفريغ وحدوث نقصان التيار التفريغ بالاضافة الى ذلك وجود مجموعتين من الالكترونات ذات طاقات مختلفة بوجود وعدم وجود الغبار الالمنيوم٠ وان التوزيع المحوري لمعلمات البلازما تكون غير منتظمة بوجود غبار الالمنيوم. وان الجهد العائم يصبح اكثر سالبيه بينما يصبح جهد البلازما موجب عند دخول الغبار الى منطقه البلازما وان الكثافة الإلكترونية تزداد بوجود الغبار مما تؤدي الى تقليل في درجة حرارة الالكترون٠

Introduction

Magnetron sputtering deposition techniques are widely applied both in industrial processes and in advanced material developments or treatment [1,2]. Magnetron device is classified into several types for practical application. The most common configurations are planar, cylindrical, and circular.Planar magnetron sputter is widely used as a plasma processing device. The field of application is sputter deposition, reactive sputter deposition, reactive ion etching, and coating of thin film [3].

In magnetron discharge, crossed electric and magnetic fields confine electrons in closed $E \times B$drift loops near a negatively biased cathode (i.e.

target). Theelectric field is providing by the plasma sheath and pre-sheath while the magnetic field is produced either by permanent magnets or current- carrying coils [4]. The applied magnetic field causes the magnetron sputter device operates at low pressure and low voltage [3].The confined electrons ionize neutral gas atom and creating a region of intense ionization adjacent to the cathode. Ions born in the electron trap region are then accelerated by the plasma sheath to the cathode target and impact there with several hundred electron volts of energy, sputtering atoms from the target, and causing secondary electron emission. The secondary electrons are accelerated back into themagnetic trap region helping to sustain the discharge [3,4]. According to this saturation the plasma media is often contaminated with particles or aerosols having sizes of tens to hundreds of micrometers. The particles can be generated within the plasma by nucleation, injected externally into the plasma or occur naturally. These particles may have varying degrees of conductivity, from metallic to classically dielectric [5].

The phenomenon of formation of dusty particles in plasmas has been known almost as long as the plasmas themselves, however the research of the "dusty plasma" has considerably lagged behind the general knowledge of plasmas. Since then, plasmas have proven to be indispensable tools in research, technological and industrial processes, where their use ranges from relatively benign and non-intrusive surface modification to thermonuclear fusion, encompassing technologies such as selective etching, cleaning of metallic surfaces, biomedical application such as improving bio-compatibility of prosthetics and sterilization, thin-film deposition, etc. Regardless of the application, one of the key requirements for the plasma was purity as too high a concentration of impurities would hinder the efficiency of the process, if not outright rendering it useless. In this context, the appearance of dusty particles in the plasma was a most undesired occurrence [6].

Dusty plasmas are ionized gases that contain particulates of condensed matter. These particles may have sizes ranging from tens of nanometers to hundreds of microns. They may be in the shape of spheres or rods or irregularly shaped pancakes. They may be composed of dielectric, e.g. SiO_2or Al_2O_3, or conducting materials. Although the particles are commonly solid, they might also be fluffy ice crystals or even liquid droplets. They are typically much more massive than the plasma electrons and ions [7- 9].

Dust particles frequently appear in industrial plasmas utilized for sputtering, deposition, etching, and so on due to reactive chemical or physical processes. The dust particles, charged by plasma electrons and ions, experience various forces such as gravity, electrostatic, and ion drag force. As a result of charging and force balancing, the dust particles are likely to be localized or trapped around the plasma-sheath boundary, which is regarded as the main scenario of plasma contamination in processing plasmas.1 For this reason, dust particle control is one of the important research issues because it can provide a way of alleviating dust contamination problem in many plasma-aided microelectronics fabrication processes. Recent studies reported that the shape of the particle trap and the collective motion of the particles could be manipulated by a static electric or magnetic field by simply changing electrode configurations [10].

Experimental device

Fig.1 illustrats the experimental device with a discharge circuit. The vacuum chamber of this device made from Pyrex cylindrical tube. This tube has two open ends closed by two stainless steel flange.One of it was connected to pumping systems, while the other was used to immerse the Argon gas (99.9% purity).Inside the chamber isconsisted from two disc aluminum electrodes (one of them used as cathode while the other used as the anode) 8 cm in diameter and 2 cm thickness. The inter distance between them is 8cm.

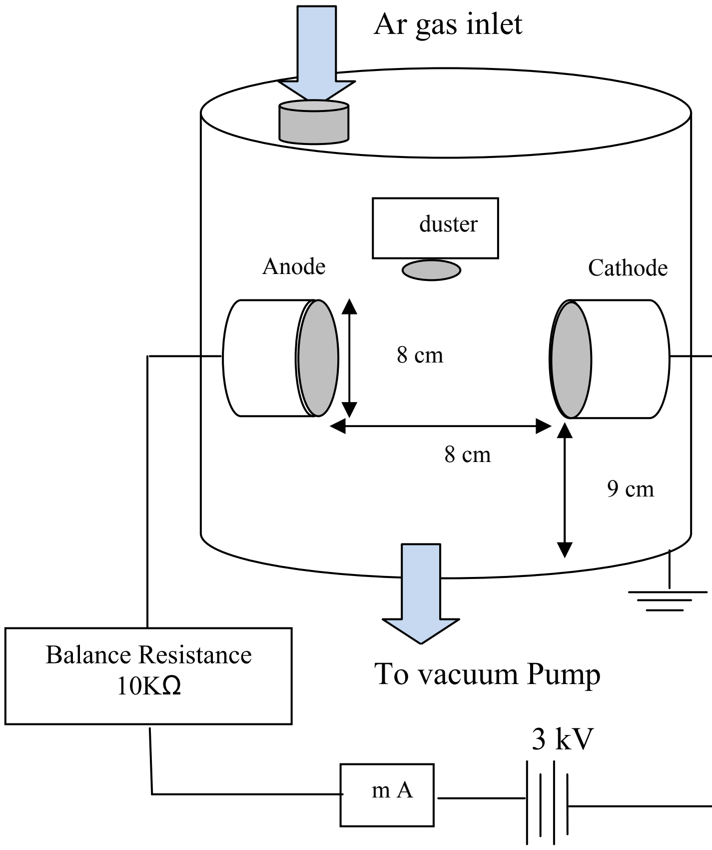

Fig. 1: Schematic the diagram of vacuum chamber with electric circuit.

To evacuatethe chamber which was evacuate by two stages rotary pump,CIT-ALCATEL Annacy,(made in France) to a base pressure 2×10^{-2} torr, after that it is pumped by diffusion pump,NRC - Oil Diffusion Pump,(made in France) to a base pressure of about 2×10^{-5} torr. Argon gas is fed to the plasma chamber with the help of a digital flow controller attached to the plasma chamber. Argon plasma is produced in the plasma chamber under pressure ranging from (0.1 –1)torr in order to study Paschen curve Aluminum dust particles ~180µm in size are dropped from the top of chamber into plasma by a dust dropper (i.e. duster). This dust dropper consists of dust container having mesh and 3V d.c motor.The electric motor works by remote control system. This motor gives two motions to the dust container which are rotation and vibration motions. The weight of the dust particles that immersed into the plasma is equal to 0.2gm as measured by electrical sensitive balance.

The glow discharge is formed between electrodes when a d.c.constant voltage of about 3 kV is applied between them. Therefore, the electrical breakdown is formed in argon gas at relative pressures, of about ≈ (0.1-1)Torr.

The magnetic field which used to confine the plasma particles is created by used two coaxial circular permanents magnets located behind the cathode. This field was measured by using a tesla-meter model. Fig. 2 illustrated the magnetic field distribution along the cathode surface and the figure non -symmetric . It should be remarked from this figure, the magnetic field distribution has two peaks located at positions -2.3cm and 2.3cm, while it has a minimum value at the center and the edge regions of the cathode surface.

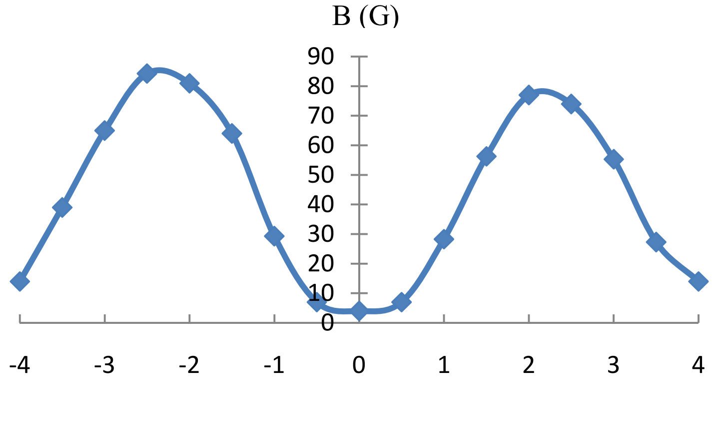

Fig.2: Radial distribution of magnetic field along cathodesurface.

Influence of Al dust particles on glow dischargeregions

In planar magnetron sputtering device the electric discharge is produced when a constant d.c. potential difference of about 3kV is applied between two electrodes cathode and anode. As a result of this applied potential, the electric field is generated and causes electrical breakdown. The gas pressure range of the discharge generation in this device is from 0.1torr to 1torr. Figs. 3 and 4 show the influence of gas pressure on the structure of discharge region in the absence and present of Al dust particles with present of magnetic field.One should observed from both figures, in the present or absent of Al dust particles, the fact that when pressure is increases the cathode fall are compressed, the negative glow becomes a thin layer of intense luminosity, while the positive column and anode fall are increasing.

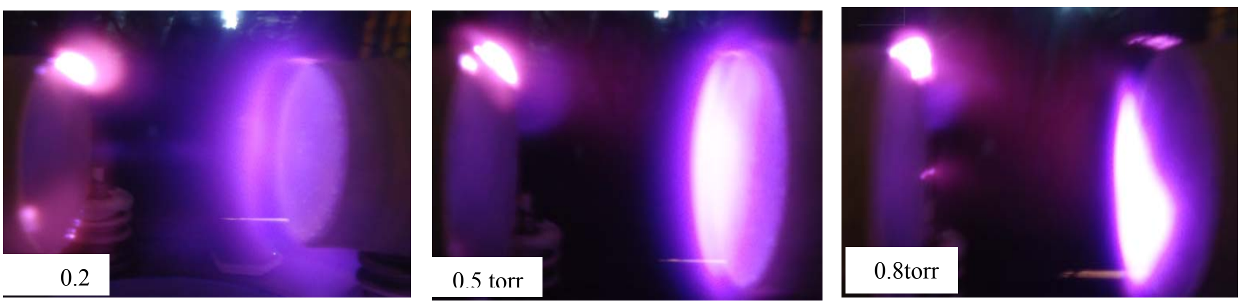

Fig. 3: Photographs of discharge regions at different pressures without Al dustparticles.

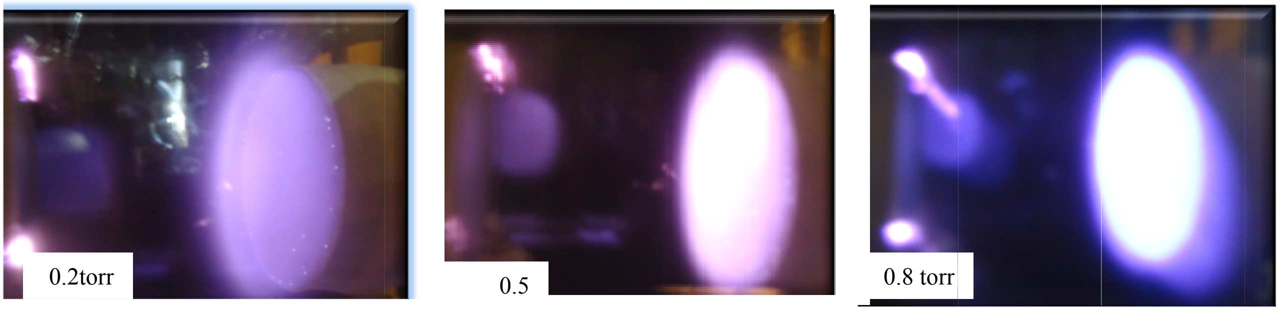

Fig.4: Photographs of discharge regions at different pressures in the present of al dust particles.

The change in the glow discharge structures in both figures with increasing of the pressure can be described as: since the mean free path of electrons is inversely proportional to the gas pressure, it follows that the distance required for an electron to travel before it has produced adequate ionization to sustain the glow would also be inversely proportional to the pressure. Then, the thickness of the cathode dark region decreases as the pressure is increases (i.e. the cathode fall is compressed). Consequently, the negative glow region becomes a thin layer of intense luminosity and the positive column region and anode fall increase.

Basic discharge Parameters

The discharge current and voltage as a function of gas pressure are presented in Figs. 5 and 6. The discharge voltage was decreased with increasing pressure of the working gas in the discharge tube while the plasma current was increases. This behavior is consequence of the increased loss of plasma electrons and ions in the presence of dust particles and is also the consequence of spatial redistributions of plasma components in the dc. glow discharge. These results mean that the electron losses cause quenching of glow discharge. In addition to that, we noted also, the presence of dust particles in the glow has no effect of the behavior of both curves of voltage and current when there is no dust presence. This behavior of voltage and current discharge can based on the assumption that, the presence of dust particles in glow discharge usually accumulated negative charge (due to high electron mobility). Therefore, as a result of this, the discharge current decreases but the discharge voltage increases. These results agree with results of Polyakov et al. [11].

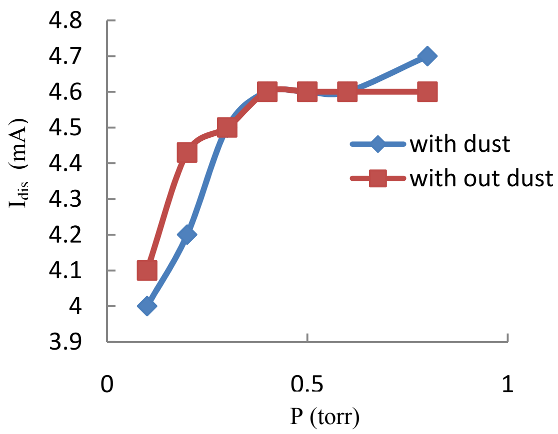

Fig.5: Variation of discharge current with gas discharge pressure in the present and absent of dust particles.

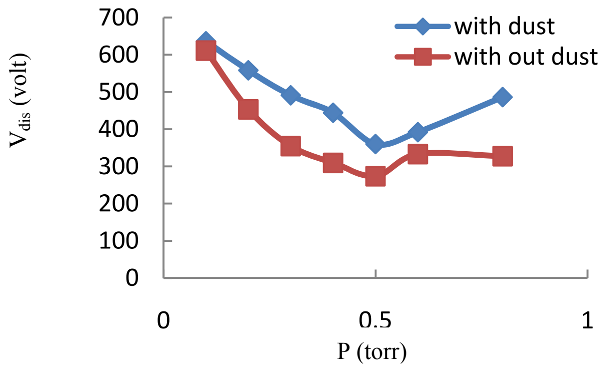

Fig.6: Schematic of the discharge voltage as a function of pressure at presence and absence ofdust particles.

Plasma parameters theory

This section describesthe basic aspects of Langmuir probe theory that are needed to construct a model probe for I-V characteristics. The methods that used in the calculation of plasma parameters such as electron density, electron temperature, plasma potential, and floating potential are review.

1.The transition region

In this region, the probe collects both ions and electrons. Fortunately, the ion current is much smaller than the electron current, because of the disparity in mass, so it can be subtracted out even if not accurately known. The probe then collects electrons moving against a repelling field. The electron temperature can be calculated as [12]:

$$dlnI_e(v) / dv = e / kT_e \qquad (1)$$

The above equation shows that, the slope of the ln (Ie)-V curve is exactly $1/T_{eV}$ and is a good measure of the electron temperature ek, T_e, and e, are Boltzmann constant, electron temperature, and electron charge. If Ln I_e is plotted against V, Eq. (1) predicts a straight lines if the distribution is Maxwellain.

In the case of two groups of electrons at different temperatures, the Ln I-V plot would be a broken line as shown in Fig. 7. The slopes of the two straight segments would give the temperatures of the two electron groups [12,13]. Therefore, the total electron temperature evaluated as [12]:

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

where, T_{ec}, T_{eh}, n_{ec}, n_{eh} and n_e are cold electron temperature(eV), hot electron temperature(eV), cold electron density(cm^{-3}), hot electron density(cm^{-3}) and electron density (cm^{-3}), respectively.

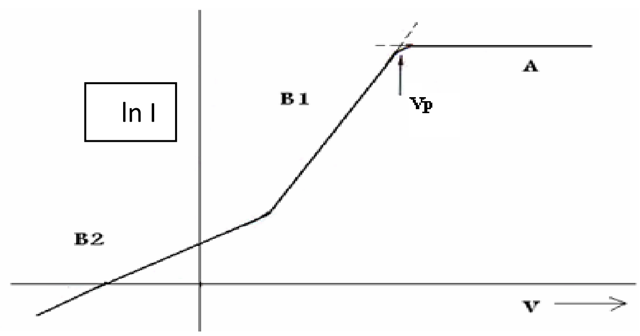

Fig.7: Schematic of ln I-V curve with a bend in the transition region, indicating the presence of two groups of electrons with different temperatures [13].

2. Electron density

Methods of calculating the electron density described as following: for positively biased of probe, the probe collects all the hot and cold electrons and repels all the ions. The electrons density calculated from [12]:

$$n_e = n_{ec} + n_{eh} \qquad (3)$$

and the electron density (n_e)is;

$$n_e = \frac{4\ I_{es}\sqrt{\pi m_e}}{eA_p(8\ KT_e)} \qquad (4)$$

where, A_p, K, $m_e I_{es}$ and e are probe surface area(m^2), Boltzmann constant, electron mass(kg), electron current saturation(A), and electron charge, respectively [13].

3.Floating potential

There are two methods to calculate the floating potential (V_f); the first one by use the definition as $I_i = I_e$, or I_i (V_f) +I_e (V_f) = 0. While the others by using the equation [12]:

$$V_f = V_p + \left(\frac{kT}{e}\right)\ln\left[0.6\left(\frac{2\pi m_e}{m_i}\right)^{1/2}\right] \qquad (5)$$

Where Vp plasma potential(volt) and mi ion mass(kg).

It is clear, from this equation that the floating potential depends, essentially, only on the electron temperature and the species of ions involved[13].

4. Plasma Potential

The plasma potential (V_p) corresponds to the bias voltage where the plasma and probe are at the same potential. The plasma potential defines the potential where the electron current changes from the electron repelling current to the electron saturation current. In the "electron saturation region" electrons experience an attracting potential whereas the probe delivers a repelling potential to the electrons in the "electron repelling region". The potential at point of change is defined as plasma potential and can easily be obtained by looking at the rate of change of the current with respect to the applied voltage. The maximum of the first derivative or the zero crossing of the second derivative of the probe current with respect to the voltage is the way to find the plasma potential. The floating potential can be calculated from the following equation, as the bias voltage at which Ii+Ie = 0.

Radial profile of plasma parameters

In this section, the redial profile of dusty plasma characteristics that are measured by using Langmuir probes at pressure of 0.5 torr will be evaluated and investigated. Four cylindrical Langmuir probes are used to give: the radial distributions of some of plasma parameters (which concluded plasma potential, electron density, electron temperature, and floating potential), and understanding the influence presence of Al dust particles on the characteristics of magnetized plasma in plasma region.

According to the experimental data of probes and according to definition of floating potential (It is the potential at which no net current is drawn), the influence of Al dust on radial profile of floating potential is plotted in Fig. 8. Theresults show that the floating potential increases negatively in all radial positions in the present of Al dust. As well as, the distribution of V_f in the present and absent of Al dust are non- uniform. The fluctuation of the radial profile of V_f in both casesare caused by fluctuation of discharge regions properties in radial direction.

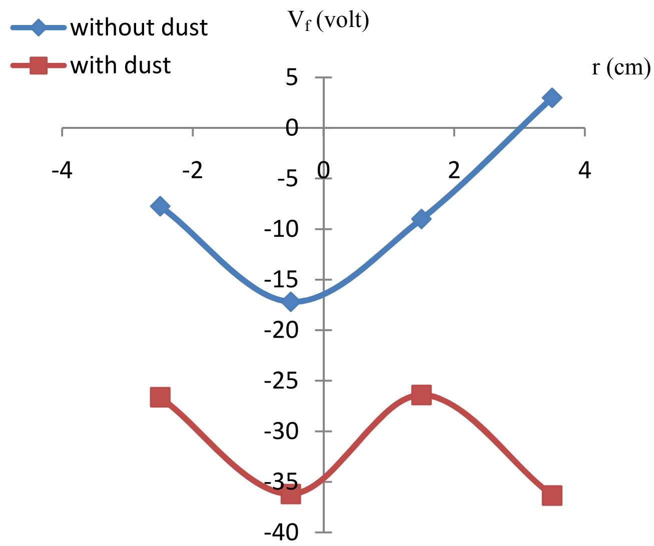

Fig.8:Radial profile of floating potential in the presence and absence of Al dust particles.

The radial profile of plasma potential with and without dust particles was indicated in Fig.9.There are many features can be noted in this figure, the radial profile of V_p in uniform without present of dust in plasma region. The values of V_p was negative value. When the Al dust entered the plasma region, the radial distribution of V_p becomes non- uniform and become positive. The capture of electrons from plasma region on the dust particles surface was responsible for positive value of Vp. The present of dust particles (grains) inside the plasma becomes either positively or negatively charged by different mechanisms such as primary electron and ion collection, the photoemission of electrons, electron and ion-induced secondary electron emission, thermionic emission, and electric field emission. Since the secondary electron emission from dust grains are small, the dust grains normally become negatively charged due to preferential capture of electrons [14]. Therefore, the behavior of V_p give evidence of the negatively charged of dust particles. This fact gives the evidence of the negative polarity of dust particles in the plasma region.

As a mentioned in the previous section, when there are two electron groups of the electrons which have a Maxwellian distribution, the straight line of the transition region is broken into two straight lines. This fact means that, there are two distinct Maxwellian distributions of electrons with different energies, cold and hot electrons with temperatures T_{ec} and T_{he}, respectively. The slopes of these two straight segments would give the temperatures of the two groups. Fig. 10 gives the influence of Al dust particles on the radial distribution of T_{ec} .

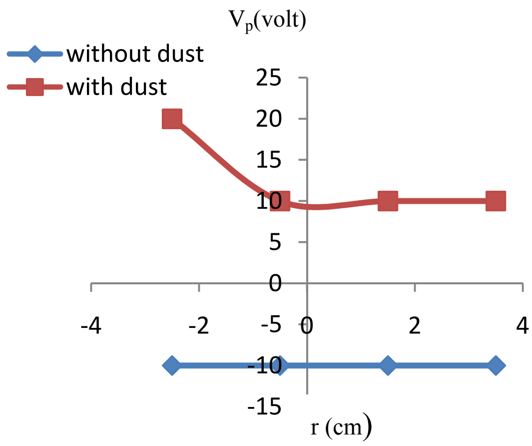

Fig. 9: Effect of al dust on radial profile of plasma potential.

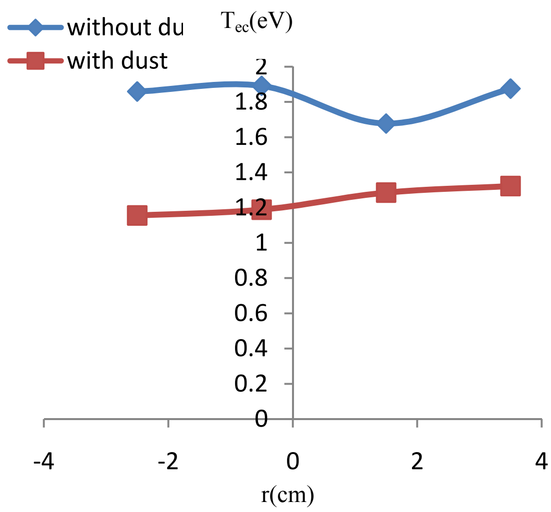

Fig. 10: Effect of Al dust on the radial profile of cold electron temperature.

It is explicit from this figure the facts that, the radial profile of T_{ec} in the present and absent of dust is non-uniform. In all radial position, T_{ec} was deceases when the dust immersed into plasma region.

Fig. 11 illustrated the variation of the radial profile T_{eh} with present of dust particles. It is clear the fact that, the hot temperature of electrons reduced in the present of dust particles.

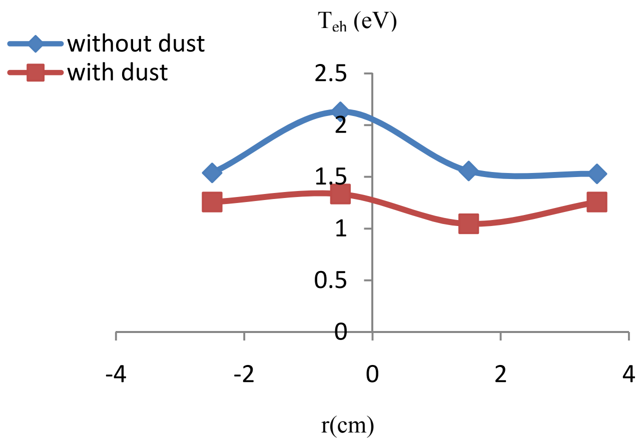

Fig.11: Influence of Al dust on the radial distribution of hot electron temperature.

Using Eq. (4) with experimental data that listed in Figs. 10 and 11, the cold and hot electron densities are calculated and plotted in Figs. 12 and 13, respectively. It is clear from both figures, the cold and hot electron densities are increases in the present of dust particles.

Consequently, according to experimental data shown in Figs. 12 and 13, the total electron density was calculated by using Eq. 3 and then demonstrated in Fig.15. One should observe from the figure that, the electron density increases after the Al dust introduction to the glow discharge. This observed increasing of electron density may be the result of a standard secondary electron release by ionic bombardment and the inability of electrons to reach the surface of charged particles in the afterglow [15].

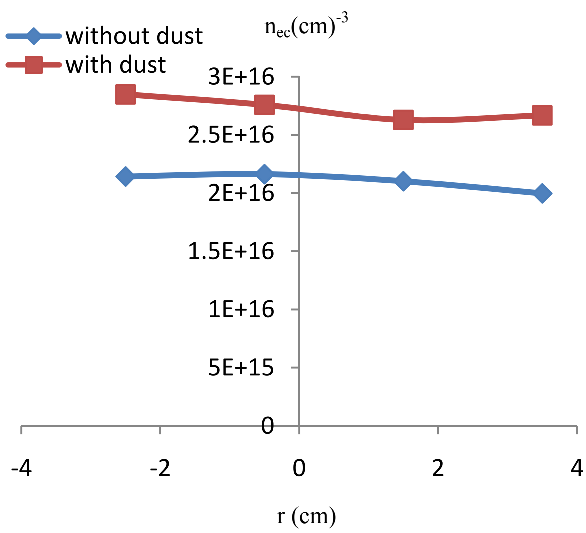

Fig. 12: Influence of Al dust on cold electron density.

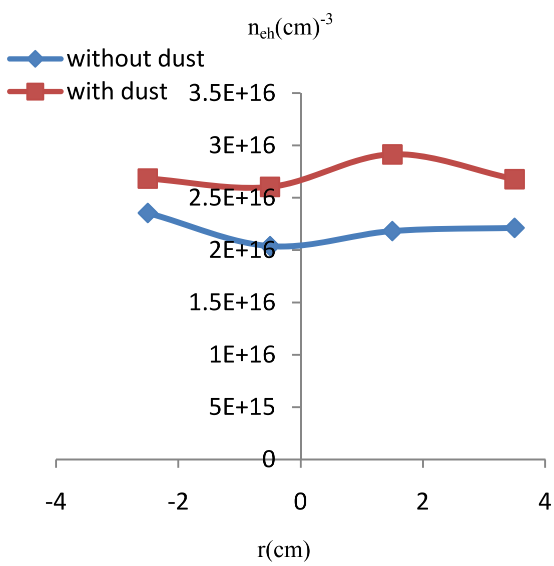

Fig. 13: Influence of Al dust on hot electron density.

The experimental data of electron temperature are computed by using Eq. (2) after substituting the experimental data from Figs. 10,11,12,13, and 14, the experimental data of T_e is drawn in Fig. 14. One should observe from this figure that the electron temperature decreases in the present of dust particles because the electrons energy reduced in the presence of Al dust. The presence of dust shows the energy of electrons approximately uniform.

This reduction in the electron temperature may attributed to increases in the electron density associated with enter of Al dust particles inside glow discharge.

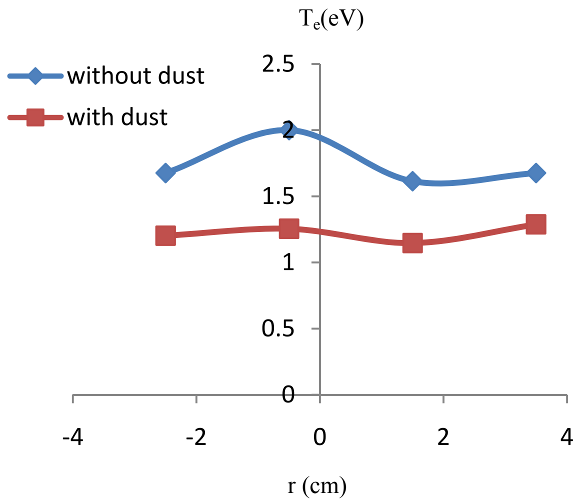

Fig. 14:Influence of Al dust on the radial profile of electron temperature.

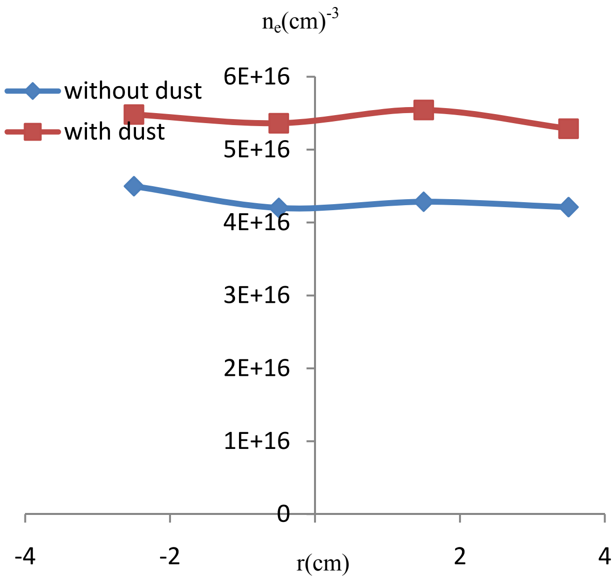

Fig. 15: Influence of Al dust on electron density.

Conclusions

Different radial profile of characters of argon plasmas in a planar magnetron sputtering tubes are studied experimentally via the Langmuir probe technique and results are compared with that in the present of Al dust. The effect of Al dust particles on voltage and current of discharge was investigated. The results confirm that because of present of dust particle in the plasma region, the number of electrons is reduced in this case which lead to increase in the discharge voltage and decreases in the discharge current.

The radial profile of plasma parameters in the plasma region indicated that the present of Al dust particles in the plasma region cause to fluctuate of these radial profiles of plasma parameters. In addition to that, the value of plasma potential becomes positive. While the value of floating potential of probes become negative. The electron density of both groups increases which leads to decrease of the temperature of both electron groups.

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