Hassan et al. Iraqi Journal of Science, 2021, Vol. 62, No. 11(Special Issue), pp: 4353-4363
DOI: 10.24996/ijs.2021.62.11(SI).16

ISSN: 0067-2904

Electrical Properties and Optimum Conditions of A Home-Made Magnetron Plasma Sputtering System

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Received: 16/1/2021 Accepted: 23/7/2021

Abstract

In this work, the electrical properties and optimum conditions of the plasma sputtering system have been studied. The electrical properties such as Paschen's curve, current-voltage, current pressure relations, the strength of magnetic field as a function of inter-electrode distance, the influence of gas working pressure and argon-oxygen ratio on the electrical characterization were studied to determine the basic optimum condition of the system operation. the discharge current as a function of discharge voltage showed high discharge current at 2.5 cm. These parameters represent the basic conditions to operate any plasma sputtering system which are the right behavior to build up and design the discharge an electrode. The ideal conditions of these homemade systems were qualified to prepare the various nanostructure thin films. The two electrodes were made of copper because of its good conductivity, and to avoid the power dissipation inside discharge chamber.

Keywords: I-V characteristics, Paschen's curve, Sputtering, Sputtering magnetro

الخصائص الكهربائية والشروط المثلى لمنظومة بلازما الترذيذ المغنطروني المصنعة محليا

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الخلاصة

في هذا العمل تم دراسة الخصائص الكهربائية والظروف المثلى لنظام بلازما الترذيذ. تمت دراسة الخواص الكهربائية مثل منحنى باشن ، منحني التيار– الجهد، علاقات التيار –الضغط ، شدة المجال المغناطيسي

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كدالة للمسافة بين الأقطاب ، وتأثير ضغط الغاز ونسبة الأرجون إلى الأكسجين على الخصائص الكهربائية التي درست لتحديد الحالة المثلى الأساسية لتشغيل المنظومة. لقد اظهر تيار التفريغ كدالة لجهد التفريغ ان اقصى تيار تفريغ يكون عند 2.5 سم. تمثل هذه المعلمات الشروط الأساسية لتشغيل أي نظام رش بالبلازما وهو السلوك الصحيح لبناء وتصميم قطب تفريغ. كانت الظروف المثالية لهذه الأنظمة محلية الصنع مؤهلة لإعداد الأغشية الرقيقة ذات البنية النانوية المختلفة. تم استخدام النحاس في صنع قطبين بسبب موصليته الجيدة ، ولتجنب تشتت الطاقة داخل حجرة التفريغ.

1. Introduction

Industry has relied on magnetrons in many applications, particularly the deposition of various such as nitrides, minerals and oxides [1]. Discharge electrodes with magnetrons include an electric loop field and direct magnetic field, these fields cause the electrons to be trapped around to the cathode. The magnetron gives the electrons sufficient energy so as to be able to ionize the gas atoms, thus enhancing the sputtering yield of the target as compared with non-magnetron discharge electrodes . Therefore, by pressure determination, it can effect on the thermal state of the sputtered atoms, finally it control on the films properties [2].

Dual magnetron configuration has applications to enhance the process of coating, where it can switch and control the power between two electrodes (cathode and anode) to gain the same material. In the present sputtering systems are use of magnetic field effects through the magnets. The results from an enhanced magnetic confinement between two electrodes (target and substrate) leads to more satisfactory deposition and allows increased cathode (target) to anode (substrate) distances to be used[3-7]. The anode (substrate) is placed perpendicularly on target zone to finish substrate bombardment with high energy types. The combination of physical sputtering and chemical reactions on a target or substrate in a plasma environment is called reactive sputtering. Because of the many parameters involved , some simplifications should be done [8, 9]. Using one or two sources like metals or semiconductors in an argon-oxygen or another effective gas for deposition purposes is usually chosen to increase the sputtering yield (flexibility) with respect to the chemical structure components that can be returned [10]. This flexibility leads to low cost, especially with reactive gas in magnetron sputtering. In fact, both electrodes will interact based on adding a gas that has e a more reactive feature. This increases the yield of sputter atoms form the target. The inter-electrode distance and gas pressure are very important factors for the production the breakdown voltage. While it has low dependability on the electrode material that describes the freedom of secondary electrons. The electric field changes linearly with pressure (E =V/d) [11-13]. Therefore, the minimum of Paschen's curve is known when the minimum value of breakdown voltage is equal to the discharge of gas pressure p times the distance d:

$$pd|_{\mathrm{Vmin}} = \frac{1}{A}\log\left(1+\frac{1}{\gamma_{\ e}}\right) \tag{1}$$

where A is the saturation ionization in the gas at a particular (electric field/pressure),V_{min} is the minimum breakdown voltage in volts and γ_e is the secondary-electron-emission coefficient (the number of secondary electrons produced per incident positive ion),

When the value of (p) or/and (d) is very large, the released ions in a gas are slowed because of critical collisions thus, it hits the target having not enough energy to generate secondary electrons emission. Most discharges of sputtering voltage are relatively large, producing large number of ions due to collisions with the gas atoms [14, 15]. All the ions returns to the electrode (cathode) and free up more electrons. After the pre-formed electrons are enough to release the electrons required regenerating the same number of electrons, and with that the gas will glow, the voltage drips, and the value of current increases sharply [16]. The process is called the normal glow. The discharge gas used is excited and its color is characteristic of luminous region. In the same time, the emission ratio of secondary electron of the material is around 0.1. More so, the one ion must hit the region of the cathode to release another

secondary electron. So, the normal glow region that witnesses the cathode bombardment to found achieves it. Firstly, the bombardments are not humongous, but focused nearby the electrode edges or at other abnormalities into the surfaces. Generally, when the power sources are available; the bombardment progressively shields the electrode (cathode) surface until a closely uniform the (current density) J is realized [17]. So, the voltage value and the current density in discharge process increases with the increase of power produced . The abnormal glow discharges is used for sputtering [18].
If un-cooled of the target (cathode), both thermal and secondary?????? are emitted when the value of current density around $0.1A/cm^2$; the value resulted (impedance) Z of power supply bounds the voltage, also the low voltage and high current discharge I forms. The abnormal glow rely on (VB) the breakdown voltage. It depends on the average mean free path of the distance between the electrodes and secondary electrons emission. Each secondary electron needs to produce around ten to twenty ions for the novel avalanche to arise. When the gas pressure is low, the secondary electrons cannot undertake adequate number of collisions ion in advance they hit an electrode anode [19]. At the high velocity from the cathode the secondary electrons are repelled and began to do more collisions with the neutral gas of atoms apart from an electrode (cathode) parallel to their free path. Also, Kelly and Arnell defined the dark space is very well [20]. The collisions cause the electrons to promptly lose their energy, closely wholly of a fitted voltage seems through the dark space. The region (dark) in which the acceleration of positive ions in the direction of the (electrode) [21]. Meanwhile the movement of ions is slow as compared to the movement of electrons, and the dark space containing an ion. The secondary electrons are accelerated from the cathode caused to collision ions in the region [21]. In fact, this work aims to characterize of home-made magnetron sputtering system and employ and optimize the magnetron configuration, electrical characteristics, Paschen's curve and operation conditions. To prepare new molecular phases of films and nanostructures at optimum conditions.

2.Experimental Setup

The main components of the home-made magnetron dc sputtering system are shown in Figure 1. Two concentric magnetrons (permanent ring shaped magnets) at the cathode and anode electrodes were tested , The strength of the magnetic field of these magnets was determined with a digital Gaussmeter of high resolution (0.1 gauss at 200 G range).

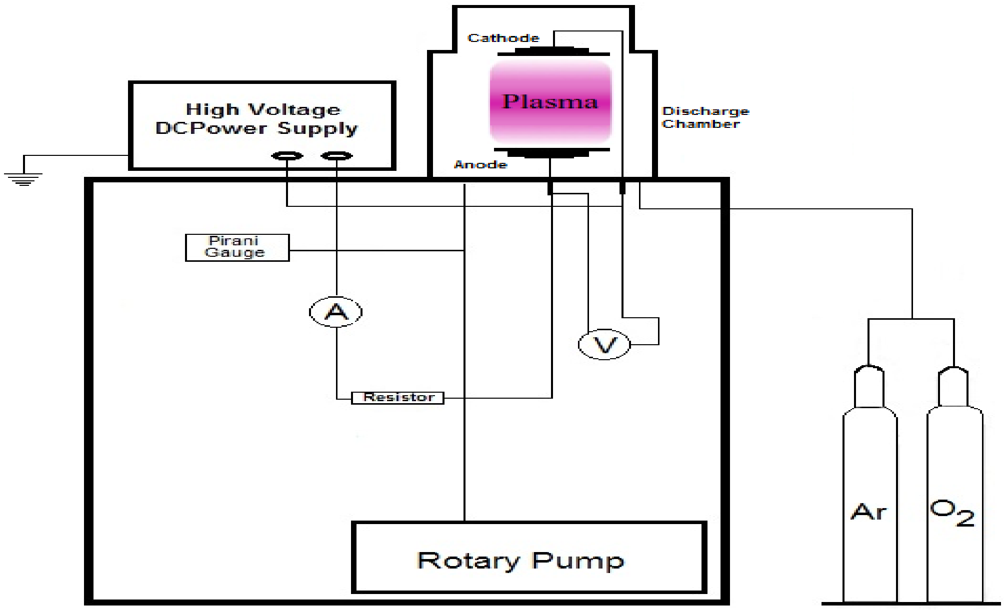
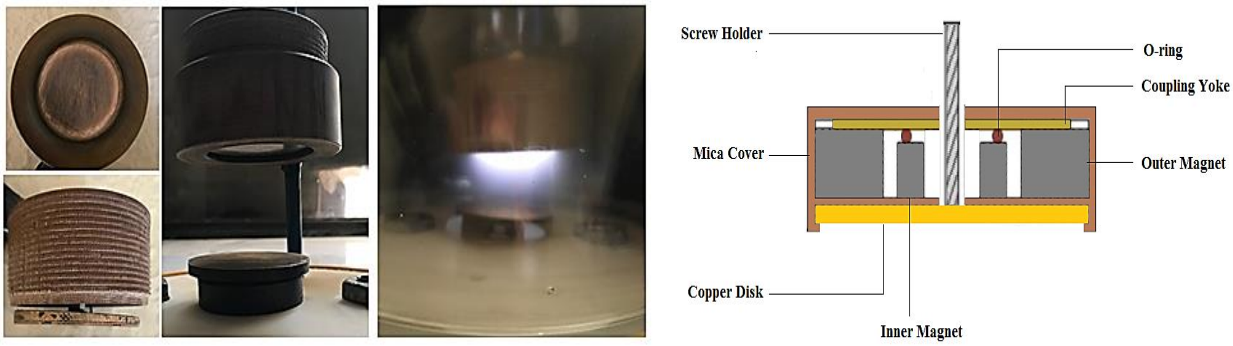


Figure 1-Schematic diagram of the sputtering system.

Figure 2 shows the design of the electrodes used in this work. The electrodes (cathode and anode)are disc shaped,the diameter and thickness of each are 6 cm and 3 mm, respectively, and are made of copper because of its high conductivity and its easy fabrication . Con-centric magnets were fixed behind each electrode to create the final magnetron structure. The inner and outer diameters of the magnets are 2 and 5 cm, respectively. Both the anode and the cathode were connected to a (DC) power supply to provide the discharge power . The anode was fixed perpendicularly as the lower electrode, while the cathode was the movable upper electrode .the spacing between the two electrodes was varied between 1 and 6 cm.



(a) (b)

Figure 2-shows: (a) Design of discharge electrode used in the work and (b) a photograph of the magnetron at each electrode, and the plasma produced between the two magnetrons.

Argon (discharge gas) was supplied to create the plasma and oxygen gas was used as the reactive gas in field. (DC) power supply (up to 1 kV, the transformer was joined feedback to gain high voltage around 1800 volt) was employed for the discharge between the cathode and the anode, A millimeter and a voltmeter were connected to the circuit to register the current,,which was 1.27A and the breakdown voltage, respectively. A limiting resistance (500Ω) was connected in series in the discharge circuit in order to control the current flowing in the circuit. The discharge region was evacuated with a two-stage Edowrds rotary pump; vacuum was recorded with Pirani gauge connected to a vacuum controller from Edowrds (starting from atmosphere10^3 to ultimate pressure 10^{-3} mbar). Argon gas (vacuum gas) was provided inside the glass container over a micro-control needle valve (0-160 cc) to control the gas pressure inside the chamber.

3.Results and Discussion

In order to get high homogeneity of the generated plasma, its electrical characteristics should be determined . The discharge currents (I), for two values of O_2 percentage in (Ar/O_2) gas mixture , were determined for different values of the discharge voltage V at different anode – cathode distance of d = 2, 2.5, 3, 3.5, 4 and 4.5 cm. The relationship between voltage (V) and the discharge current (I) across the plasma chamber, was extremely nonlinear,as seen in Figure 3. , This result helps in the adjustment of discharge electrodes as suitable and acceptable with the behavior of Ohmic and non-Ohmic materials such as copper [22].

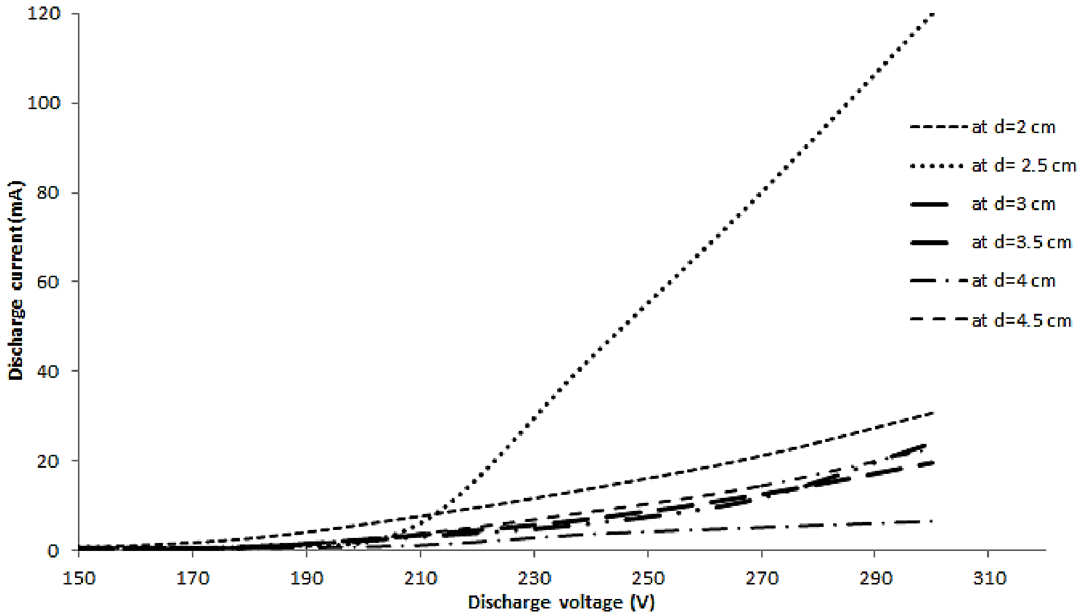


Figure 3-the discharge current as a function of discharge voltage (I-V characteristics) at different inter-electrode distances from 2 to 4.5cm at a gas pressure of 0.15 mbar

For discharge voltage from 150 to 190, the discharge current was zero. Above this value the current starts to increase with the increase of the voltage. as the breakdown voltage is extended. Clearly, *I* at lesser inter-electrode distance as the (electron) has to pass smaller distance to move from cathode to anode. The change of the discharge current as the distance between the electrodes was changed for different values of discharge voltage is shown in Figure 4. The discharge current is very small, nearly zero, at short distances and for small values of discharge voltage.. The relation between I and V is usually nonlinear [23]. At *d* equal 2.5 cm, (I) rises with increasing V. The ionization of oxygen molecules is less than that of argon [24]. In addition, since the electron affinity of oxygen, discharges in oxygen consist of the negative ions, which results in the growth of plasma resistance due to decrease of electron density and thus the discharge current losses.

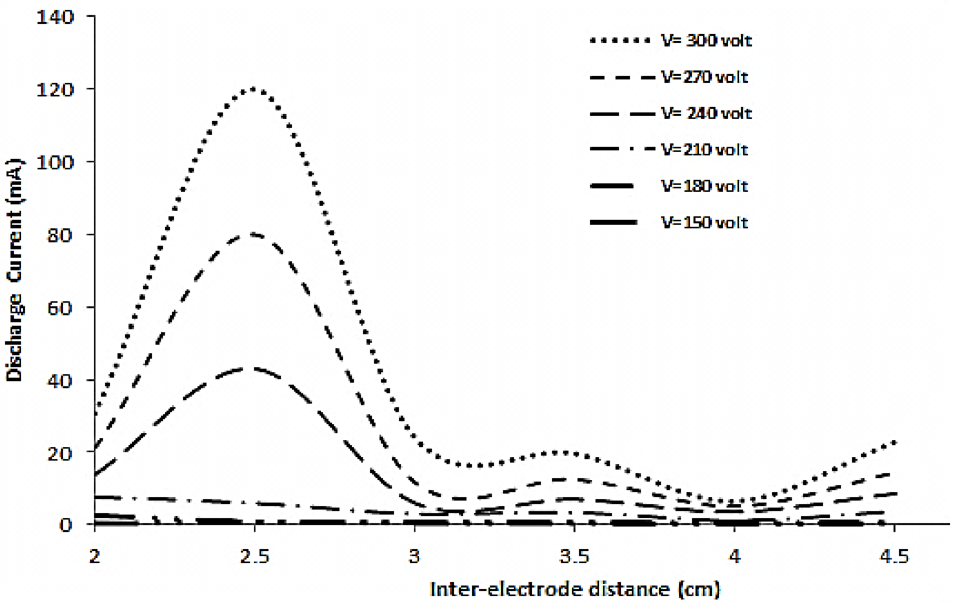


Figure 4-The discharge current *I* as a function of inter-electrode distance d with different discharge voltages V.

At low voltages <240 V, the changes in the *I* values with the changes of *d* are small. While, at (300V), the discharge current (I) increases as the inter-electrode distance (d) increases . At low voltages <240 Vthe changes in the I values with the change of d are small The (cathode and anode) are fully shielded via the discharge and the rise of (I) leads to an increase in the electrode collapse. Thus, the applied voltage between cathode and anode increases abruptly. Maximum discharge current was detected at inter-electrode distance of 2.5cm. This behavior is recognized to the mobility limited version of (Child-Langmuir equation), where the discharge current is proportional to ($V^{3/2}/d^2$) [24].

The plasma generated by the presence of O_2 gas only is not suitable for the synthesis of any nanostructure oxides. One promising way to enhance the dissociation of O_2 in plasma is to introduce an inert gas such as argon.

So argon with oxygen were introduce inside the chamber to provide the reactive gas required for the synthesis. For two mixing ratios of Ar:O_2 , the IV characteristics for different *d* were studied (Figure 5 and 6). For 1:1 Ar:O_2 ratio , an increase in the discharge current was detected with the increase of voltage and as the distance between the electrodes was increased. It is obvious from the figure that high voltage is needed at large inter-electrode distance to support the current.

Whereas (as shown in Figure 6), at 2:1 Ar:O_2 ratio, the discharge current is high at inter-electrode distance of 2.5cm.. There are very small differences in current at low discharge voltages from 250 to 300 volt, because of the major contribution of oxygen molecules for the ionization of primary electrons. At high discharge voltages more than 350V, the differences are clearly observed, because the high electric field accelerates the secondary electrons (V/d) and the ionization of oxygen molecules is observed via collisions with electrons [24].

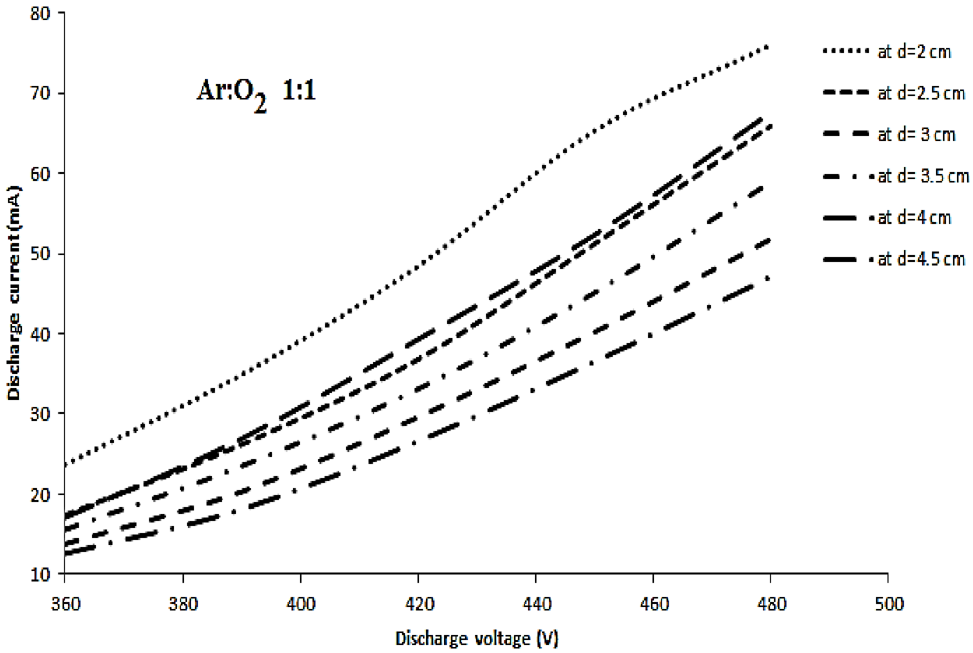


Figure 5- Discharge current-voltage characteristics for Ar: O_2 1:1, at pressure gas of 0.15 mbar with different d (inter-electrode distance)

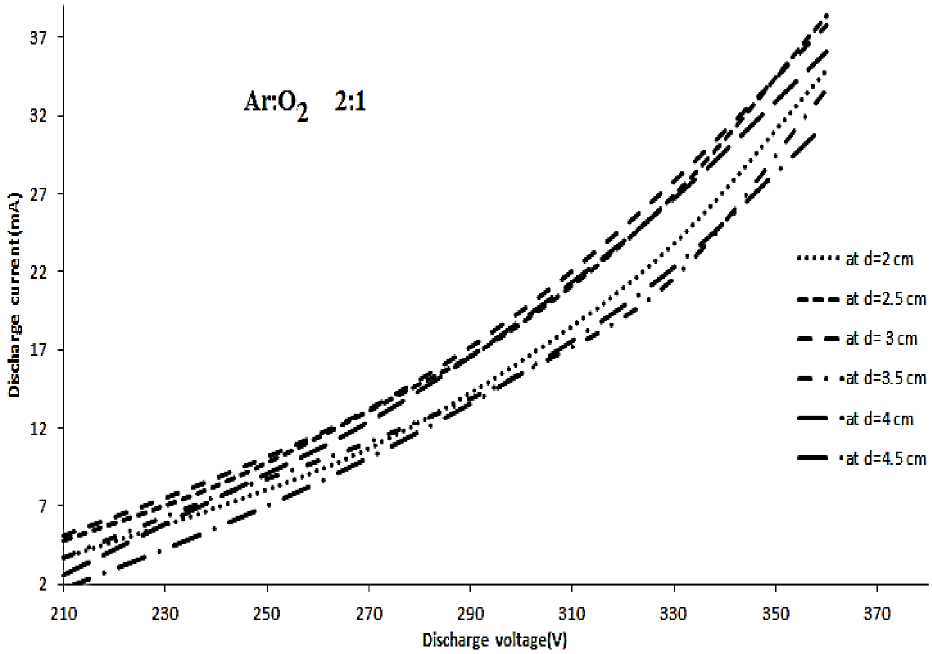


Figure 6-Discharge current-voltage characteristics at Ar: O_2 2:1, at gas pressure of 0.15 mbar with different *d* (inter-electrode distance)

Glow discharge is used in several applications for example thin films deposition. The breakdown of gas is a very difficult operation which commonly happens at the electronic destruction. A gas in its standard state is practically an ideal isolator. When a voltage is applied, gaseous dielectrics are exposed to many phenomena . At low voltage, the minor discharge currents flowing between cathode and anode ends and the isolation retains its electrical charges. Alternatively, the current flows through the isolation and increases very sharply when the applied voltages are huge, thus electrical breakdown occurs .

The breakdown curves of discharge are defined according to Paschen's law VB=f(pd); that is the breakdown voltage(VB) depends on inter-electrode distance *(d)* and gas pressure *(p)* [22]. Figure 7 shows Paschen curve of Ar gas with magnetrons for different *(d)* from 2 to 4.5cm. The shift of the curves to higher breakdown voltages (pressure times inter-electrode distance) with the rise of *(d)* is related to the growing of the charged particles losses on the adjacent walls of the discharge electrode. This can be explained as being due to decline in collisions. When the pressure is low, the electron mean free path is longer and the probability of collision is smaller than that at high pressure. So, electrons need more energy to ionize the neutral atoms. At *d* equals 2 and 2.5cm, their Paschen curves are of similar behavior and the minimum of (*p.d)* product is (1 mbar.cm), when discharge voltage equals 235 and 190 volt, respectivly. At *d* equals 3 and 4.5cm, the minimum points of the curves were shifted towards higher values of (*p.d)* product of 1.15V and 1.5mbar.cm, at discharge voltage equals 200 and 180 V, respectively [25].

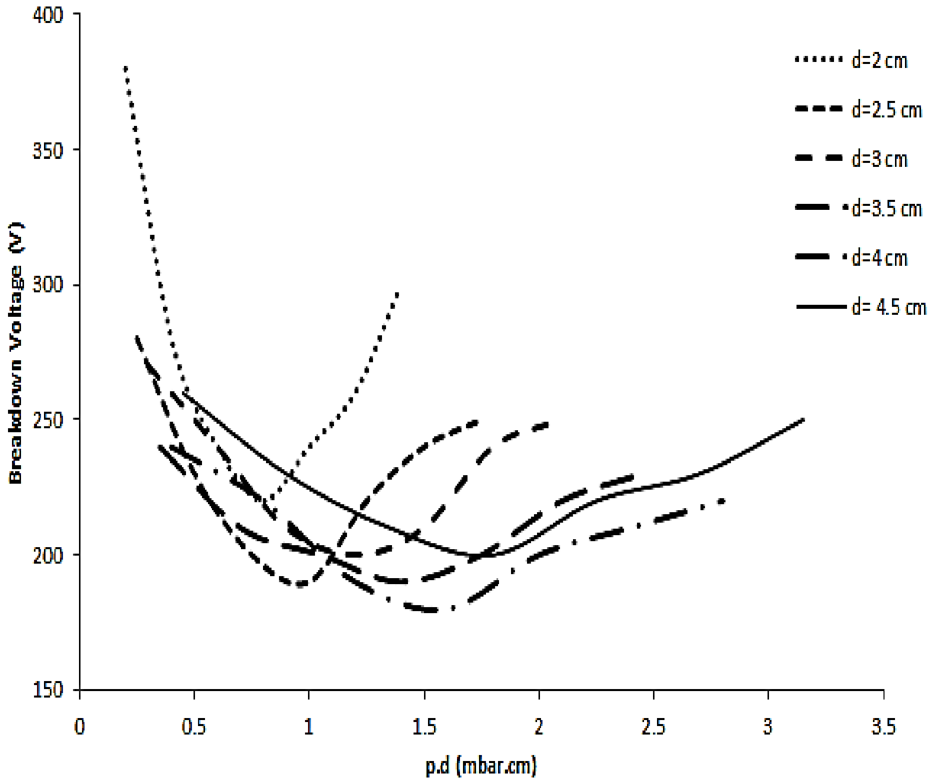


Figure7- Paschen curves gives the breakdown voltage as a function of inter-electrode distance using argon gas discharge at different d from 2 to 4.5cm.

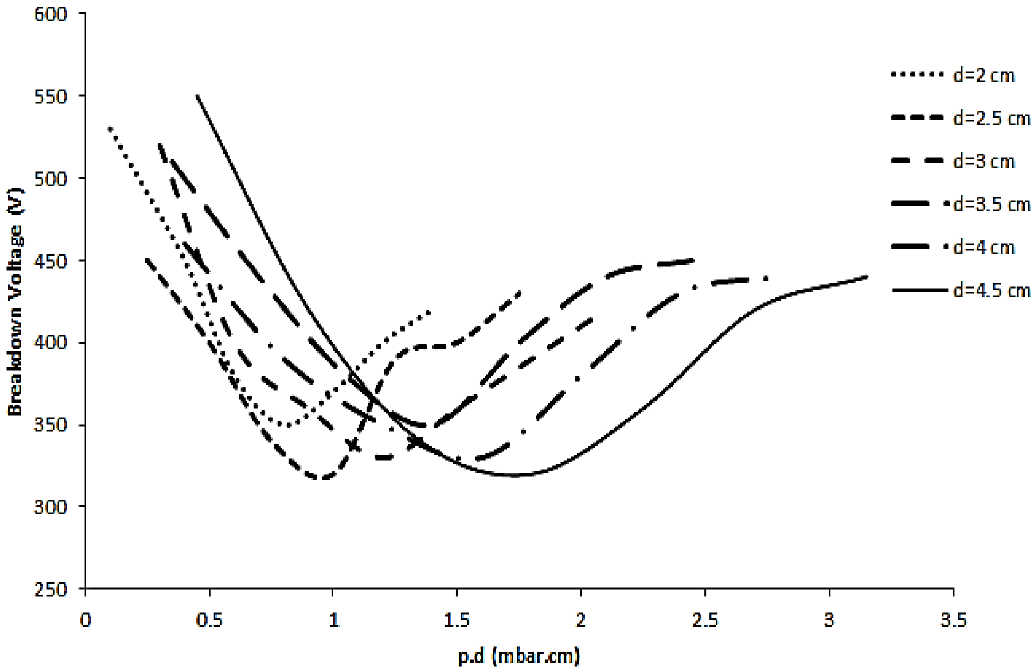


Figure 8-Paschen curves presents the breakdown voltage VB as a function of p.d using 2:1 argon to oxygen ratio at different d from 2.5 to 7.5cm.

To determine the optimum condition of inter-electrode(anode-cathode) distance of magnetrons, the strength of magnetic field was determined at the surface of the electrodes at different distances between the two magnetrons from 2 to 4.5 cm on the edges of the electrodes(Figure 9).

The highest value was observed to be at 4.5 cm, while the lowest value was at 2 cm. where probe diameter was around 0.8 cm, so, the minimum distance was 2 cm. Considering.
the interference between magnetic field lines, high interference occurred at the midpoint of separation distance of 2 cm . This interference decreased when the electrodes were moved apart reaching the “no interference” conditions at $d \geq 5$ cm. The electrons are accelerated by both electric and magnetic fields to greater drift velocities that the probe could not attract them from their paths between the discharging electrodes [26].

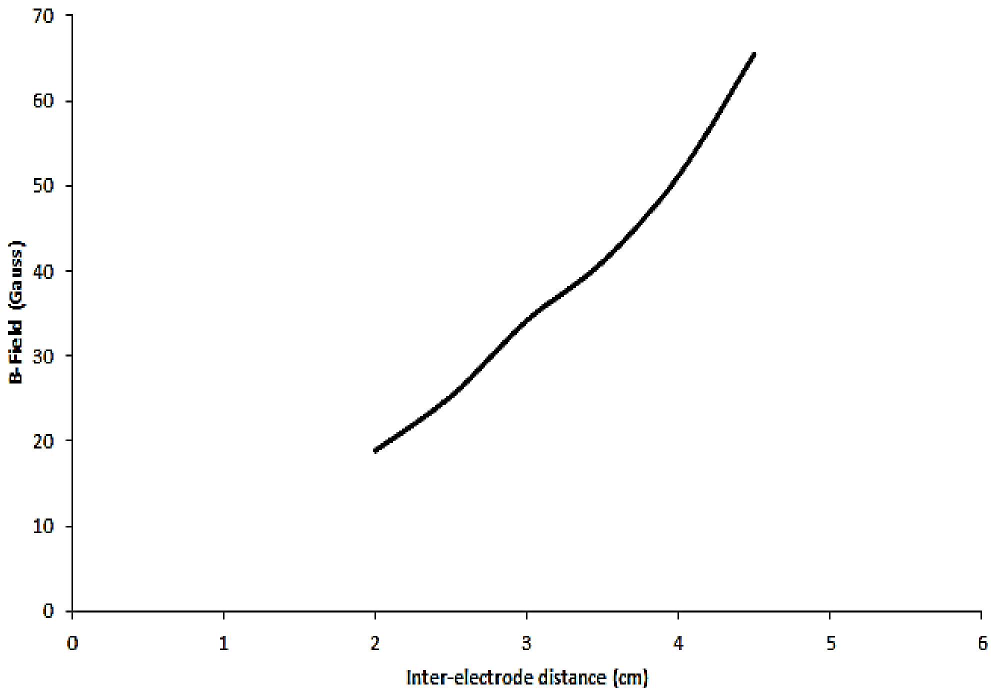


Figure 9-The magnetic field intensity as a function of inter-electrode distance.

Figure 10 shows that the breakdown voltage as a function of VB (p.d) for different inter-electrode spacing for 1:1 argon to oxygen ratio.. For the left-hand side bend, VB increases as the gas pressure and inter-electrode spacing decreases. This result may be explained as to be due to decrease in the collisions. The mean free path of electrons was extended at low gas pressure and the probability of collisions were lower than that when the pressure was high, accordingly that a rare collision. Herein lies a low probability that the secondary electrons emitted will collide with neutral atoms during the journey from the cathode to the anode. As for the right-hand side, VB increases gradually with increasing the gas pressure i.e., increasing the ionization cross-section and also a rise of p.d. Therefore, electrons need more energy to ionize the atomsoms.

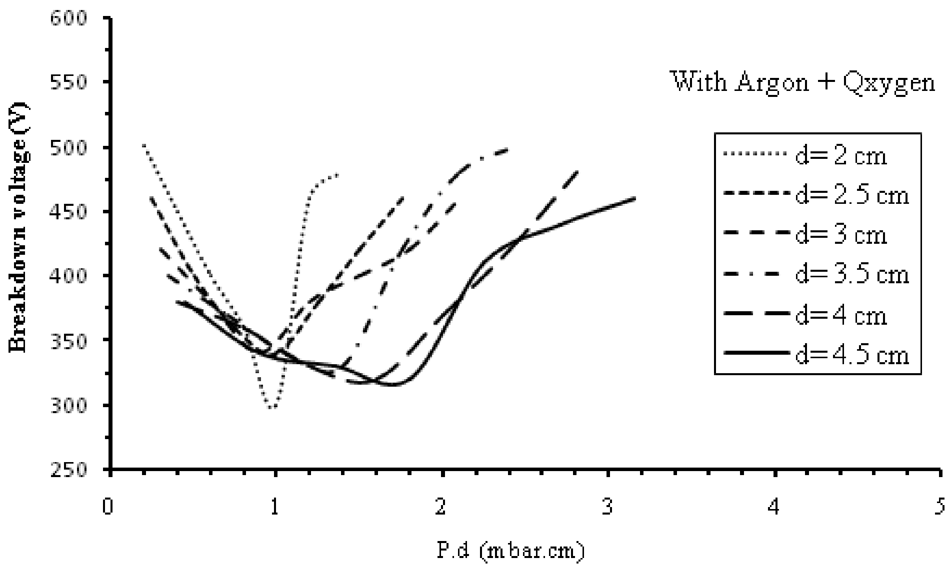


Figure 10-Paschen curves as function of inter –electrode spacing for 1:1 Ar /O_2 gas ratio.
Table 1 explain the minimum breakdown voltage $(VB)_{min}$ for different inter-electrode distances when gases (Ar and O_2) are mixed together. By this table, Argon gas contains less than min (VB) of oxygen gas. This outcome relies on the collision of particles which is related to secondary-electron parameter and oxygen electro-negativity, as it was found that the collision cross-section would increase when the size of the atoms/molecules increased.

Table 1- The Breakdown voltage (VB) with pd parameter for argon and oxygen gas mixture.

Inter-electrode distance	d= 2 cm	d= 2.5 cm	d= 3 cm	d= 3.5 cm	d= 4 cm	d=4.5 cm
Breakdown voltage (VB)min (volt)	300	340	340	330	320	320
P.d min (mbar.cm)	1.09	1	0.9	1.4	1.6	1.8

4. Conclusions

This work describes the characteristics of magnetron sputtering system, employs and optimizes the magnetron configuration at different operation conditions . The discharge electrodes and the home-made system presented achieved good indication of intensity of magnetic field (magnetic field distribution), electrical characterization and Paschen law to employ the results for preparing any films. Using magnetrons at the cathode and anode has influenced this characterization as the breakdown voltage was reduced. This home-made system has been found to satisfy the conditions for the deposition of highly pure thin films from diverse targets and achieve this out come to prepare different nanomaterials devices, because of the design of cathode have more flexibility to fix any target (foil or sheet) to obtain the films.

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