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Operation Characteristics of a Closed-Field Unbalanced Dual-Magnetrons Plasma Sputtering System

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Abstract. In this work, a home-made closed-field unbalanced magnetron system for plasma sputtering purposes was constructed and operated. The effect of magnetrons was introduced by comparing the obtained Paschen's curve in existence of one or two magnetrons with no magnetron condition. Characterization of Paschen's curve as well as discharge current with gas pressure at different inter-electrode distances was introduced. These characterization results were effectively used to optimize the preparation of metal oxide films by plasma sputtering technique.

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1 Introduction

A glow discharge is simply produced by applying an electric potential on a gas sample between two electrodes placed inside a vacuum chamber [1]. This glow discharge is a common source of plasma that can be established through an avalanche like ionization of gas neutrals at specific conditions for gas pressure and applied voltage [2-3].

At low kinetic energies (energies between 0 and about 50 eV), the ion does not have sufficient energy to dislodge the target atoms and thus the ejection of target particles occurs only for very special collision geometries [4]. With moderate energies (between 50 and roughly 1 keV), the ions impact dislodge "knock-on" atoms into the target, which by their turn will dislodge other target atoms [5]. Several studies showed that the ion energies must exceed four times the binding energy of the atoms of the target surface to induce sputtering [6-9]. This induces a collision cascade that eject atoms, ions, electrons and neutrals from the first 10 to 50 Å of the surface of a target [7].

Initially existence of electrons is a requirement for this ionization process and such electrons, which may normally exist by cosmic radiation, are accelerated by the applied electric field towards the anode and consequently gained sufficient energy to collide with gas atoms and ionize them [8-9]. Hence, the number of electrons existing between the two electrodes will be multiplied at a rate described by the Townsend's first ionization coefficient (α), which represents the relative increase in electron flux (j_e) per unit path length as [10-12]

$$\frac{dj_e}{dx} = \alpha j_e \,. \tag{1}$$

This equation can be solved as

$$j_e\left(d\right) = j_e\left(0\right) e^{\alpha d} \,, \tag{2}$$

where $j_e(0)$ is the current density from electron current emitted from the cathode at $x = 0$.

The continuous electron production is required to sustain the discharge and provided by the production of secondary electrons induced during the ion impact at the cathode. The electron production can be described by the emission coefficient (γ_e) of the secondary electrons as:

$$j_e\left(0\right) = \gamma_e j_i\left(0\right) . \tag{3}$$

For the case of producing one ion in the cascade with each produced electron, we have

$$\begin{aligned} j_e\left(0\right) - j_i\left(d\right) &= j_e\left(d\right) - j_e\left(0\right) ; \\ j_e\left(d\right) - j_e\left(0\right) &= j_e\left(0\right)\left(e^{\alpha d} - 1\right) . \end{aligned} \tag{4}$$

Here, α is equivalent to the product of the net ionization probability per unit length and the probability of ion generation by the collision and can be written as [13]

$$\alpha = \frac{1}{\lambda} \exp\left(-\frac{U_i}{e\lambda E}\right) , \tag{5}$$

where λ is the collision mean free path and $e\lambda E$ is the energy gained by electrons between consecutive collisions

Knowing that the mean free path is inversely proportional to the gas pressure, the Townsend's coefficient can be given by

$$\alpha = Ap \exp\left(-B\frac{pd}{V}\right) , \tag{6}$$

where A and B are constants and their values are determined by the properties of the used gas, p is the gas pressure, d and V are the distance and the applied voltage between discharge electrodes as the electric field (E) is included by the ratio V/d.

When the electron multiplication gets very efficient and $j_e(d) \gg j_e(0)$, a breakdown condition is reached. If the term of the ion flux at the anode in Eq. (4) is neglected, then the following condition is obtained

$$\alpha d = \log\left(1 + \frac{1}{\gamma_e}\right). \tag{7}$$

By treating both equations (6) and (7) mathematically, the breakdown voltage is given by

$$V_B = \frac{pdB}{\log(pdA) - \log\left(\log\left(1 + \frac{1}{\gamma_e}\right)\right)}, \tag{8}$$

and this equation is known as Paschen's law.

The breakdown voltage (V_B) depends on the product of pressure (p) and electrode separation (d) as this product is denoted as "*pd*", while this voltage weakly depends on the cathode material that defines the emission coefficient of secondary electrons. As well, the breakdown voltage is proportional to the product *pd* at large values of this product and the electric field $(E = V/d)$ is scaled linearly with the pressure [14]. In case of small values of the product *pd*, only few collisions occur and higher voltage is applied to increase the probability of breakdown per collision. Hence, the minimum voltage required to ignite the discharge of a gas sample of pressure p over a distance d is defined at the minimum of Paschen's curve, where

$$pd|_{V_{\min}} = \frac{1}{A}\log\left(1 + \frac{1}{\gamma_e}\right). \tag{9}$$

If the pressure and/or separation distance is too large, ions generated in the gas are slowed by inelastic collisions so that they strike the cathode with insufficient energy to produce secondary electrons. In most sputtering glow discharges, the discharge starting voltage is relatively high.

Eventually, an avalanche occurs in which the ions striking the cathode release secondary electrons, which form more ions by collision with neutral gas atoms. These ions then return to the cathode, produce more electrons. When the number of electrons generated is just sufficient to produce enough electrons to regenerate the same number of electrons, the discharge is self-sustaining. The gas begins to glow, the voltage drops, and the current rises abruptly [15]. This is called the "normal glow". The color of this luminous region is characteristic of the excitation gas used. Since the secondary electron emission ratio of most materials is of the order of 0.1, more than one ion must strike a given area of the cathode to produce another secondary electron. The bombardment of the cathode in the normal glow region self-adjusts in the area to accomplish this. Initially, the bombardment is not uniform, but concentrated near the edges of the cathode or at other irregularities on the surface. As more power is supplied, the bombardment increasingly covers the cathode surface until a nearly-uniform current density is achieved [14].

A further increase in power produces both increased voltage and current density in the discharge. This abnormal glow is the mode used for sputtering [16]. If the cathode is not cooled, at a current density of approximately 0.1A/cm^2, thermionic electrons are emitted in addition to secondary electrons, followed by a further avalanche. The output impedance of the power supply limits the voltage and the low-voltage high-current arc discharge forms. The abnormal glow is dependent on the breakdown voltage V_B. This in turn is dependent on the mean-free-path of secondary electrons and the distance between the anode and the cathode. Each secondary electron must produce about 10-20 ions for the original avalanche to occur. If gas pressure is too low, or the cathode-anode separation too small, the secondary electrons cannot undergo a sufficient number of ionizing collisions before they strike the anode [17].

Secondary electrons are repelled at high velocity from the cathode and start to make collisions with neutral gas atoms at a distance away from the cathode corresponding to their mean free path. This leaves a dark space which is very well defined [18]. Since the electrons rapidly lose their energy by collisions, nearly all of the applied voltage appears across this dark space. The dark space is also the region in which positive ions are accelerated toward the cathode [19]. Since the mobility of ions is very much less than that of electrons, the predominant species in the dark space are ions. Acceleration of secondary electrons from the cathode results in ionizing collisions in the negative glow region [20].

2 Experiment

The main parts of the plasma sputtering system are shown in Figure 1 and the closed-field unbalanced magnetron (CFUBM) was employed at the cathode electrode. Electrodes (anode and cathode) were made of stainless steel and each was a disk of 8 cm in diameter and 4 mm in thickness. Two annular concentric magnets were placed behind each electrode to form the magnetron configuration, as shown in Figure 1. The outer diameters of the two magnets were 8 cm and 4 cm, while the inner diameters were 4 cm and 3.2, respectively. The electrodes were connected to a DC power supply to provide the electrical power required for discharge. The lower electrode (anode) could be move vertically with respect to the fixed upper electrode (cathode) to adjust the separation of the two electrodes from 1 to 8 cm.

Pure argon gas was used to produce the discharge plasma, as shown in Figure 1. A DC power supply up to 5 kV was used for electrical discharge between the

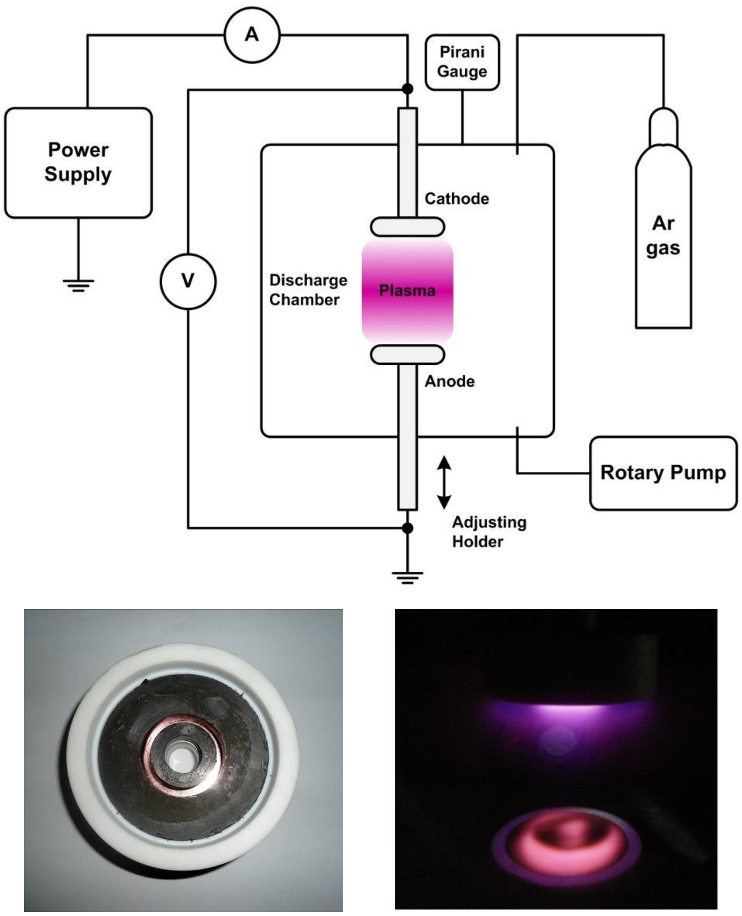

Figure 1. (Color on line) Schematic diagram of the system used in this work (above), a photograph of the magnetron employed at each electrode (bellow, left), and a photograph of the plasma produced between the two magnetrons (below, right).

electrodes and both breakdown voltage (up to 1 kV) and discharge current (up to 100 mA) were monitored by two digital voltmeter and ammeter, respectively. A current limiting resistor of 6.75 kW was connected in series to the discharge circuit in order to control the current flowing in the circuit. The discharge chamber was evacuated by a two-stage Leybold-Heraeus rotary pump and the vacuum inside chamber was measured by Pirani gauge connected to a vacuum controller from Balzers VWS 120. Argon gas was supplied to the chamber through a fine-controlled needle valve (0-160 ccm) to control the gas pressure inside the chamber.

3 Results and Discussion

Sputtering of a target atom is just one of the possible effects resulting from the surface ion bombardment. Aside from sputtering, the second important process is the emission of secondary electrons from the target surface, which play a fundamental role in keeping the sputtering process itself. Figure 2 shows Paschen's curve for both cases of using and not using the magnetron at the upper electrode (cathode). As clearly shown, the effect of using one magnetron lies in decreasing the breakdown voltage to about 15-17% of its value in absence of magnetron. However, Paschen's curves of both cases are identical and the minimum value of "$p.d$" product was 0.52 mbar.cm. However, it was expected that using magnetrons might cause the minimum point of $p.d$ to be shifted downward due the effect of magnetic field in trapping electrons near the electrode and hence a smaller amount of gas is required to reach breakdown point.

In dc sputtering, the electrons that are ejected from the cathode are accelerated away from the cathode and are not efficiently used for sustaining the discharge [4,19]. To avoid this effect, a magnetic field is added to the dc sputtering system that can deflect the electrons to near the target surface, and with appropriate arrangement of the magnets, the electrons can be made to circulate on a closed path on the target surface. This high current of electrons creates high-density plasma, from which ions can be extracted to sputter the target material, producing a magnetron sputter configuration [20].

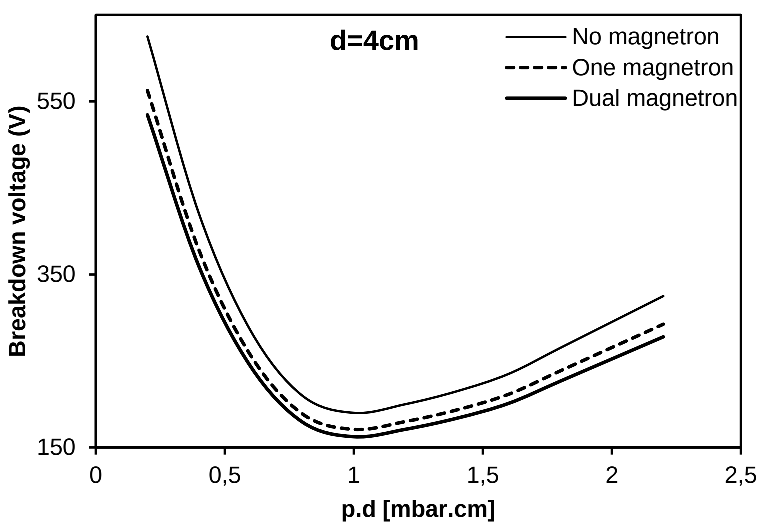

Figure 2. Effects of using one magnetron and two magnetrons on the Paschen's curve of the discharge plasma when compared to no magnetron case, the inter-electrode distance is 4 cm.

A disadvantage of the magnetron sputtering configuration is that the plasma is confined near the cathode and is not available to active reactive gases in the plasma near the substrate for reactive sputter deposition. This difficulty can be overcome using an unbalanced magnetron configuration, where the magnetic field is such that some electrons can escape from the cathode region [21]. An unbalanced magnetron (UBM) has a proper magnetic field configuration in which a finite degree of the field lines from the outer magnetic pole diverge to the substrate, though the rest of the lines finish on the inner pole behind the target. Sufficient plasma density and a positive ion current on a metallic substrate even at a large distance from the target can be achieved in the unbalanced magnetron as compared with the balanced one [22].

The Paschen's curves of the plasma sputtering system in this work were plotted at different inter-electrode distances (2-6 cm) in presence of the dual magnetrons as shown in Figure 3. These curves are identical with the minimum shifted upward on the $p.d$ axis as the minimum voltage required to ignite the electrical discharge of the gas sample between the electrodes is increased with increasing the inter-electrode distance (d).

Obviously, increasing the inter-electrode distance requires much more potential to be applied before the breakdown of the existing gas is reached. Consequently, the breakdown voltage is increased with increasing distance in accordance to equation (8).

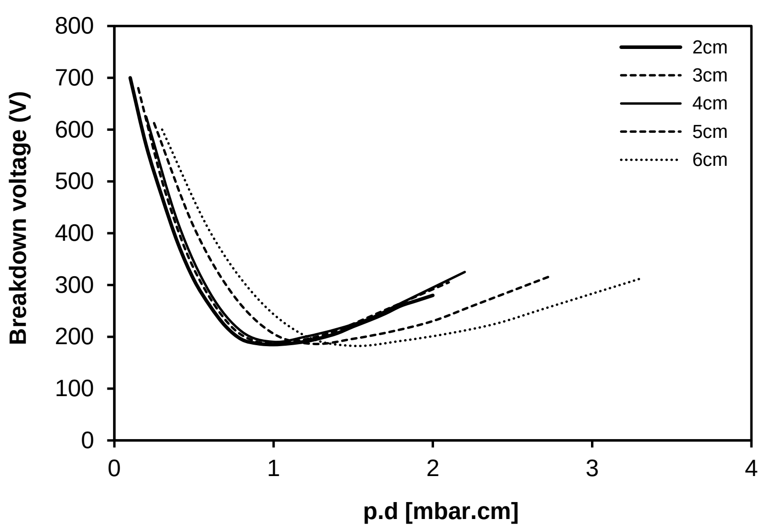

Figure 3. Paschen's curves of the discharge plasma at different inter-electrode distances (d) in case of using dual magnetrons.

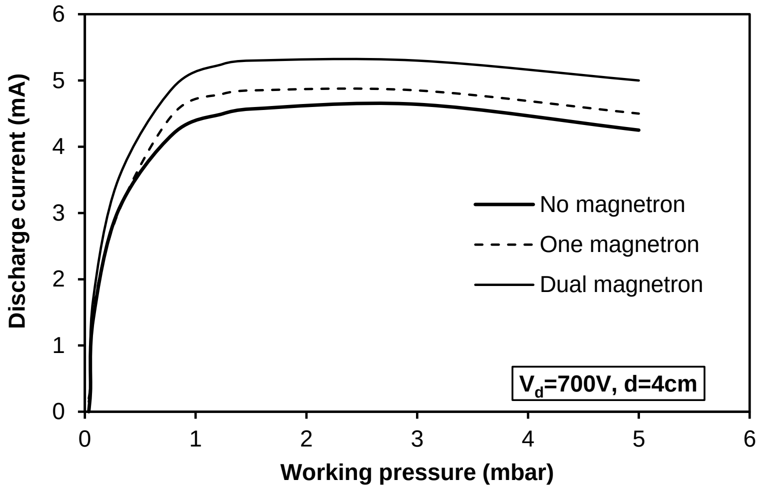

Figure 4. Effects of using one magnetron and two magnetrons on the variation of discharge current with gas pressure when compared to no magnetron case, the inter-electrode distance is 4 cm.

Using one magnetron at the cathode of the discharge configuration had a noticeable effect on the relation of discharge current with gas pressure, as shown in Figure 4 as the measured current was increased by 15% of its value when no magnetron was used. Also, using dual magnetrons caused the measured discharge current to increase by 5% of its value when only one magnetron was used. Such effects are attributed to the feature of magnetic field in trapping electrons and increasing the ionization rate and hence the production of charged particles (ions and electrons), which form the discharge current flowing between the electrodes. Increasing discharge current allows performing sputtering at lower voltages since the input power required for this process is simply the product of discharge voltage by the discharge current.

The plasma sputtering system was then characterized by the relation of discharge current to the gas pressure inside the chamber at different inter-electrode distances, as shown in Figure 5. Again, all curves are identical with the discharge current shifted upward on the vertical axis. According to Eq. (2), as the distance between the electrodes is decreased, the current density from electron current emitted from the cathode $j_e(0)$ is increased because less number of electrons are able to reach the anode and hence lower current flows. However, compensation is required between gas pressure and distance to work at a given discharge current before converting into decreasing current as saturation is reached.

Finally, the system considered in this work was used for deposition of metal oxide thin films (e.g., FeO, NiO, CuO, Sn_2O_3) on glass substrates and these films were featured by uniformity, good adhesion and large area when compared to

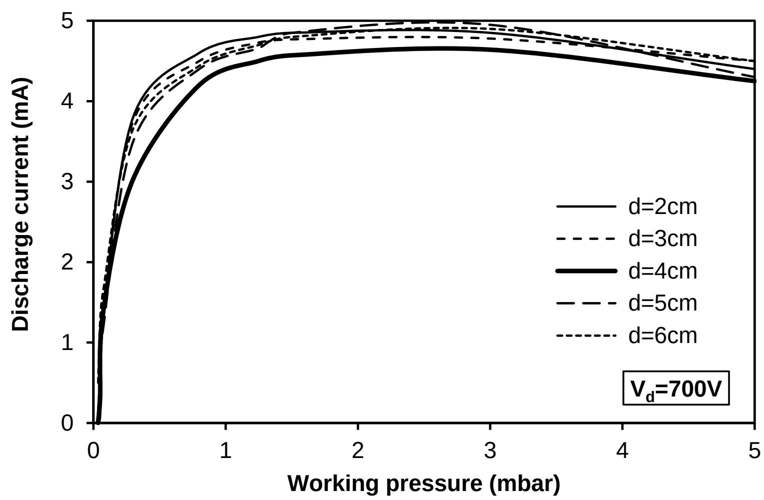

Figure 5. Variation of discharge current with gas pressure at different inter-electrode distances.

other deposition techniques available in the local research environment. Therefore, these films could be described as high quality structures. However, the results of deposition were not included in this work as they are presented in other studies carried out using the same system.

4 Conclusion

Referring to the results obtained from this work, the home-made dc magnetron plasma sputtering system was characterized to introduce its performance in accordance to Paschen's law and governing properties of such deposition systems. Results showed that using dual magnetrons has highly affected the relation of breakdown voltage to the gas pressure and distance product as the breakdown voltage was reasonably decreased. The characterization of Paschen's curve for this system was carried out at different inter-electrode distances and results showed that the minimum point of this curve was shifted upward on the $p.d$ product axis as the inter-electrode distance was increased. The effect of using magnetrons on the relation between discharge current and gas pressure was introduced as higher discharge current was measured when using dual magnetrons when compared to the one magnetron or no magnetron cases. As well, the effect of inter-electrode distance on this relation was seen as the measured current increased with increasing distance. As well, this system was found to satisfy the requirements for deposition of metal oxide thin films with good quality.

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