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Influence of Inter-Electrode Distance, Gas Mixing, Magnetic Field and Cathode Material on Breakdown Voltage of Lab-Made DC Magnetron Sputtering Device

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In this paper, the effect of inter-electrode distance, gas mixing, magnetic field and cathode materials on breakdown voltage in DC glow discharge of argon and argon-oxygen plasma is presented. The results showed an increased breakdown voltage when inter-electrode distance and oxygen percentage in (Ar/O_2) gas mixture increased. At lower pressure, the breakdown voltage decreases by increasing the magnetic field, while at higher pressure, the breakdown voltage becomes less sensitive to the magnetic field. Moreover, the lower breakdown voltages are associated with smaller work function of the cathode material.

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1. Introduction

Glow discharges are used in various applications such as deposition of thin films, and modification of surfaces in semiconductor industry and materials technology [1]. Therefore the research into the conditions of the glow discharge breakdown is of considerable interest. Gas discharge breakdown is a complex process which generally begins at electronic avalanche. A gas in its normal state is almost a perfect isolator. Various phenomena occur in gaseous dielectrics when a voltage is applied. When the applied voltage is low, small currents flow between the electrodes and the insulation retains its electrical properties. On the other hand, if the applied voltages are large, the current flowing through the insulation increases very sharply, and an electrical breakdown occurs [2]. As far as it is known, the breakdown curves of the glow discharge are described by Paschen's law VB=f (pd); i.e. the breakdown voltage depends on the electrode distance (d) and the gas pressure (p) [3]. Primary electronic ionization occurs prior to cascade ionization. Townsend introduced a coefficient α known as Townsend's first ionization coefficient and is defined as the number of electrons produced by an electron per unit length of path in the direction of field. Once the Townsend ionization coefficient becomes sufficiently high along with the intensification of electric field, current will transfer from non-self-maintained to self-maintained process, that is, electric breakdown occurs.

Let $n0$ be the number of electrons leaving the cathode and when these have moved through a distance x from the cathode, these become n. Now when these n electrons move through a distance dx produce additional dn electrons due to collision. Therefore, [4]

$$dn = \alpha n\, dx \quad (1)$$

$$\ln n = \alpha x + A \quad (2)$$

Now, at x=0, $n=n_0$, therefore,

$$\ln n_0 = A$$

$$\ln n = \alpha x + \ln n_0 \quad (3)$$

At x=d, $n=n_0 e^{\alpha x}$ (4)

The term ($e^{\alpha x}$) is called the electron avalanche and it represents the number of electrons produced by one electron in traveling from cathode to anode. The first Townsend's coefficient, which depends on the gas type and gas pressure, as well as on the electric field E in the inter-electrode space, can be expressed following Townsend theory as:

$$\frac{\alpha}{P} = A\exp[-\frac{BP}{E}] \quad (5)$$

where A and B are normally determined experimentally and have been found to be relatively constant for a given gas over a range of fields and pressures. It is more convenient to use the ionization coefficient η (or ionization efficiency) defined as the number of ionization events caused by an electron in passing through a potential difference of one volt [5]:

$$\eta = \alpha/E \quad (6)$$

This quantity depends only on the reduced electric field *E/P*. The experimental data are usually presented either in the form (*E/P*). Next, attention is turned to the consequences of the subsequent motion of the positive ions. Acceleration of the positive ions in the electric field leads, in principle, to secondary emission of electrons from the negative electrode, when they reach there, at a rate of γ electrons per incident ion [6] is known as the effective secondary electron emission coefficient, or second Townsend coefficient γ. Additionally to α it is an important parameter in the Townsend regime and it depends on the electrode material and on the nature of the filling gas used. The secondary ionization coefficient is related to that of Townsend's first ionization coefficient α, and by using eq.6, this dependence can be expressed in terms of the ionization coefficient η [5, 7]:

$$\gamma = \frac{1}{e^{\eta V_B}} \frac{}{-1} \quad (7)$$

Thus, γ depends on the cathode material and gas type, as well as on the ratio *E/P* [8].

Gas discharge breakdown voltage VB is the minimum voltage required for initial breakdown of discharge. Before Townsend proposed the gas discharge breakdown theory, Paschen has found through experiment the function between gas discharge breakdown voltage and the product of gas pressure（p）and cathode-anode distance (d), following is the Paschen law expression of Townsend discharge [9]:

$$V_b = \frac{Bpd}{ln\left[Apd/ln\left(1+\frac{1}{\gamma}\right)\right]} = f(pd) \quad (8)$$

The existence of a minimum breakdown voltage in Paschen's curve may be explained as follows: For values of pd > $(pd)_{min}$, electrons crossing the gap make more frequent collisions with gas molecules than at $(pd)_{min}$, but the energy gained between collisions is lower. Hence, to maintain the desired ionization more voltage has to be applied. For pd < $(pd)_{min}$, electron may cross the gap without even making a collision or making only less number of collisions. Hence, more voltage has to be applied for breakdown to occur [2, 4].

2. Experimental Setup

The experimental setup of home- made dc magnetron sputtering device is shown in Fig. (2). The discharge was operated in DC mode; the external resistance was used to limit the discharge current, to ensure that the discharge would be limited to the abnormal glow discharge region. The plasma chamber consists of stainless steel cylindrical vacuum chamber, discharge electrodes, which included two parallel high voltage electrodes the anode of stainless steel disk, while the cathode was made of four different materials (stainless steel Al, Cu and Ni). The distance between electrodes can be varied in range of (2-5cm). In this work the magnetic field generated behind the cathode. The magnetic field was provided, firstly, by using the electromagnetic coils. The magnetic field, various from 0 to 100 gauss, controlled by the amount of current passes through the coil. Secondly, the magnetic field generated by pair of permanent magnets, generated magnetic field to 200 gauss. To ensure a minimal concentration of uncontrolled contaminations during the experiments, a double-stage rotary pump (Edward 8m³/h) operating to a base pressure of about $3x10^{-2}$ mbar was used. Then, it is pumped by an oil diffusion pump (Alcatel 480 L/s) to a base pressure of about $5x10^{-5}$ mbar. The pressure was monitored with a pirani gauge with Edward controller (1105) was necessary to install in the plasma chamber in order to monitor actual pressure there and the partial pressure of discharge gases. The applied voltage was controlled by high-voltage DC power supply (0-1400 V).

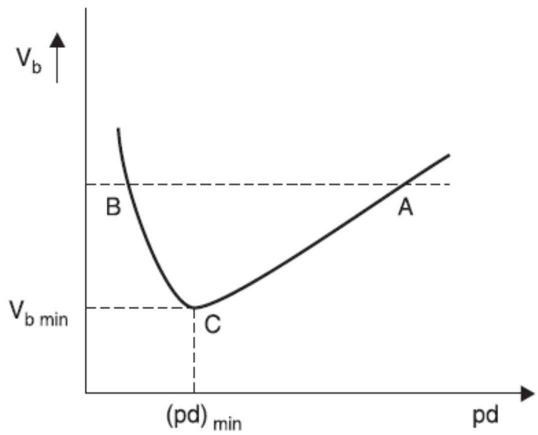

Fig. (1) Paschen's law curve

In this work, the effects of some operating parameters on breakdown voltage in low pressure of argon and argon-oxygen mixture are studied.

Fig. (2) The lab-made dc magnetron sputtering device

3. Results and Discussion

Figure (3) show the breakdown curves for argon we measured with different inter-electrode distance. It follows from this figure, that on increasing the gap d the curves is shifted not only to the region of higher breakdown voltages, but simultaneously to higher pd values. This shift of the breakdown curves to higher VB and pd values with the increase of the inter-electrode distance d is associated with the growth of the losses of charged particles on the lateral walls of the discharge tube due to the diffusion across the electric field [10].

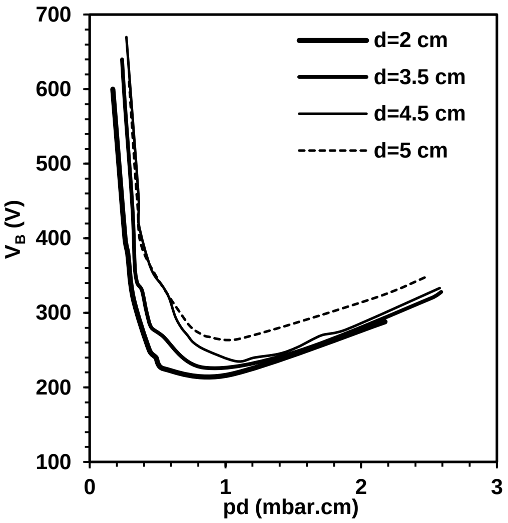

Fig. (3) Measured breakdown curves of the glow discharge in argon for the stainless-steel cathode and different inter-electrode gaps

Figure (4) shows the variation of the breakdown potential as a function of gas pressure at constant inter-electrode distance (d=4.5cm). It is clear that the breakdown voltage VB increases as oxygen gas percentage increase. This effect is due to, the additional energy loss channel oxygen gas such as vibration, rotational and molecular dissociation, V_B abruptly was increased when the small amount of oxygen was added. In addition, since plasma resistance was increased due to high electron affinity of oxygen, discharge sustains voltage was also increased. Furthermore, the oxygen is electronegative gas and the loss of electrons due to diffusion and attachment to oxygen molecules in (O_2/Ar) plasma requires the electric field strength in the plasma to be higher than in argon plasma so as to produce enough electrons to maintain the plasma discharge. As the number of additional oxygen molecules increases, a progressively higher electrical field is required. Rhee et al [11] had shown the same results.

Figure (5) shows the breakdown voltage of Ar as a function of (pd), at the distance between the electrodes (4.5cm) for various values of magnetic field (B). The results show a high influence of magnetic field, at low pressures. At 0.068 mbar the breakdown voltage reduce from 1040 to about 635 Volt when the magnetic field increases from zero to 200 gauss. The $(pd)_{min}$ of Paschen's curve shift to low pressures when magnetic field increases, and at higher pressures the effect of magnetic field decrease. It is known that the application of a magnetic field on a glow discharge has the equivalent effect of an increase of the gas pressure [12], thereby an increase of the breakdown voltage with increase of magnetic field after $(V_B)_{min}$.

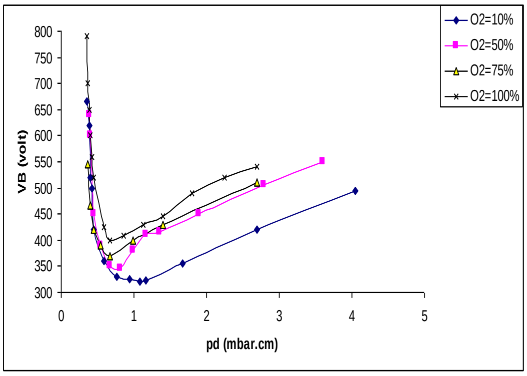

Fig. (4) Paschen curves for the stainless-steel cathode at different Ar/O_2 gas mixture

The magnetic field acts more efficiently for lower pressures, because the probability of collision decreases by decreasing the pressure; thus enhancing the effectiveness of the magnetic confinement. The consequences of the action of the magnetic field are that the electron free paths across the residual gas are lengthened and also that the lateral diffusion of the electrons can be reduced. These combined effects imply that the losses of electrons are reduced and they can now make more collisions with the gas molecules than they could do in the absence of the magnetic field. Ions produced near the cathode are more efficient in producing electrons by secondary emission. Ionization cascades are more probable and longer and ions strike the cathode more frequently. The self-sustained discharge situation is then less demanding on voltage at higher magnetic field confinement [13]

Figure (6) shows the Paschen curves for Ar/O_2 mixture using the three cathodes materials. It follows from this figure that for the cathodes with higher secondary electron emission coefficient, (Aluminum), the breakdown curve is shifted simultaneously to lower breakdown voltages. This can be explained as follows: increasing secondary electron emission coefficient (decreasing work function) increases number of emitted secondary electrons from cathode surface due to ion impact, which are responsible for the ionization of neutral gas atoms and molecules [14]. At the same time the minima of the breakdown curves we measured are on one straight line. Table 1 illustrated the measured breakdown voltage (V_B) $(pd)_{min}$ and work function for Al, Cu, and Ni cathode materials.

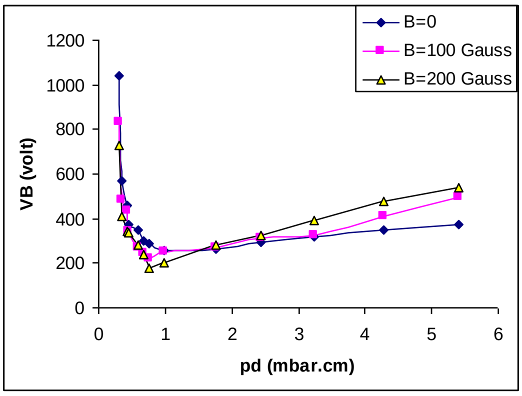

Fig. (5) Paschen curve of Ar for different values of transverse magnetic field

In this work, the glow discharge doesn't convert to filamentary arcs since the radial dimension of electrodes is much larger than the radial extent of the electron avalanche in the gas gap, and the discharge will tend to be filamentary. Since at high pressure, an electron Avalanche crossing the gap would have a radial extension (due to diffusion) much smaller than the diameter of the electrodes, avalanches are unlikely to overlap each other and the discharge usually consists of several filaments. Our experiment was conducted at low pressure; so no filamentary arcs were seen. Furthermore, the electronegativity of gas (O_2) decreases the electron density due to the electron attachment. This plays a very important role in the removal of free electrons from an ionized gas when arc interruption occurs, therefore, O_2 is considered a stable factor.

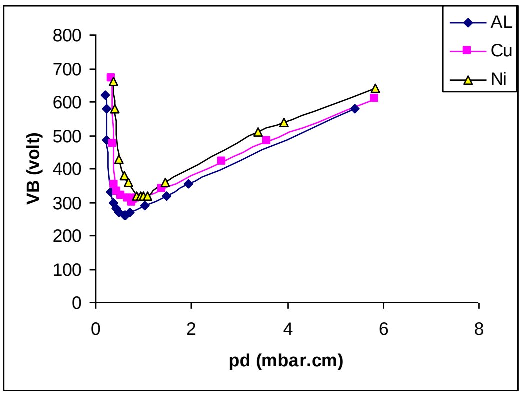

Fig. (6) Paschen's curves for Ar/O_2 (9:1) gas mixture and at applied 200 gauss, measured under different cathode materials

Table (1) The variation of breakdown voltage, $(pd)_{min}$ with work function of the electrode materials

Electrode Material	Work Function (eV) [15, 16]	VB (Volt)	(pd)min (mbar.cm)
Aluminum (Al)	4.28	260	0.585
Copper (Cu)	4.65	300	0.765
Nickel	5.15	319	0.99

4. Conclusion

The main results of this work can be summarized as follows: As the inter-electrode distance increased the breakdown voltage increases of range (2-5) cm. The addition of O_2 to Ar discharge causes an increase in the values of breakdown voltage value. At lower pressures the breakdown voltage has a strong dependence on magnetic field. At higher pressures the breakdown voltage is less sensitive to the magnetic field. The breakdown voltage increased with the increase in the work function of the cathode materials.

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