CHAPTER (1)

THEORETICAL CONSIDERATIONS .

INTRODUCTION .

Ordinarily , we hardly come into contact with plasma in our life . Matter which is normally seen exists in the solid , liquid , or gas phase . However , the conducting gas in a fluorescent tube or in a neon sign is in the plasma state . All the stars , including the sun , are masses of high temperature plasmas . The interstellar matter and nebulae are also in the plasma state , so , it has been said that the greater part of the universe is in the plasma state .

The flow of electricity through a gas is often called a discharge , because a gas consisting only of neutral atoms is a perfect insulator ; but an ionized gas will conduct electric current . In general , many useful applications of the gas discharge are due to two main properties :- the extreme rapidity of the transition from complete insulating to perfect conducting behaviour and the ability of the discharge gap itself to pass high current , and then recover its original insulating state . The transition from insulating to conducting states is called "electrical discharge" .

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Some of these applications are for example , thyratrons , high energy particle counting apparatus , flash tubes , lightning lamps , radiation sources , such as :- gas Lasers , metal vapour Lasers and X-ray Lasers . Also , another very important branch of electric discharge application is the surface and thin film technology , where it is used extensively in plasma etching , plasma deposition , surface cleaning , surface activation , sputtering and synthesis and production of new materials .

Behaviour of the ionized gases depends on the effective ionization processes . Ionization of the electrical breakdown can be classified into gas processes (involving the collisions of electrons , ions and photons with gas atoms) and electrode processes (which take place at or near the electrode surfaces) .

1-1. FUNDAMENTAL PROCESSES OF GAS DISCHARGE .

1.1.1- GAS PROCESSES .

1.1.1.1- Ionization Processes :-

a- Electron - Atom Collision :-

When the kinetic energy ($1/2\ mv_e^2$) of an electron , in collision with a neutral gas atoms , exceeds the ionization energy E_i of the atom , ionization may occur , and , in general , a positive ion and two slow electrons are resulted .

$$e + A \rightarrow A^+ + 2e$$

b- Electron - Excited Atom Collision :-

Ionization may be also produced by a relatively slow electron with energy less than the ionization energy, in collision with an atom which has been previously raised to an excited state E_e, i.e. ionization can be occurs if $(1/2\ m v_e^2) > E_i - E_e$.

$$e + A^* \rightarrow A^+ + 2e$$

c- Positive Ion-Atom Collision :-

According to the classical treatment, the ion loses half of its energy in collision with the gas atom. Thus an ion will be capable of ionizing an atom in collision if :-

$$E_{ion} > 2E_i$$

It has been shown that ionization of neutral He atoms could occur at ion energies just greater than 49.4 eV since the ionization energy of He is 24.6 eV.

However it is known that energy of the ions differs little from that of the gas atoms in Townsend and glow discharge, therefore it is unlikely that this process of secondary electron production is important in such discharges.

Another type of collision is that in which charge transfer occurs such that :-

$$A + B^+ \rightarrow A^+ + B + \text{Kinetic energy}$$

Kinetic energy ($K.E = E_i [A] - E_i [B]$) is released and is distributed between the two particles .

d- Photo-Ionization :-

An atom in the ground state may be ionized by a photon of frequency ν provided that $h\nu > E_i$;

$$A + h\nu \rightarrow A^{+} + e$$

or

$$A^{*} + h\nu \rightarrow A^{+} + e$$

The process of photo-ionization can be very effective at high pressures and high currents , where high concentrations of excited states and photons exist in the discharge .

e- Auto-Ionization :-

In metal vapour auto-ionization may occur as follows :-
If two atoms are firstly excited , one of them may be ionized if the total potential energy of the excited atom exceeds the ionization energy of one of them .

$$A^{*} + B^{*} \rightarrow A^{+} + B + e$$

e.1- Atom - Atom Collision :-

Two identical atoms in the ground state may become ionized in collision if their relative velocity exceeds the value corresponding to twice of their ionization energy , so that this process becomes significant only at very high gas temperatures and at high currents (e.g. arc discharge) .

$$A + B \rightarrow A + B^{+} + e$$

e.2- Exited Atom-Atom Collision (Penning Ionization) :-

Penning ionization is an ionization process caused by the collision between metastable particles at excited states and neutral particles which have a lower ionization energy than the excitation energy of the metastable particles . It is expressed as :-

$$A + B^{*} \rightarrow A^{+} + e + B \quad ,$$

Where :-

B^{*} is the excited atom or molecule . The difference between the excitation energy of B^{*} and the ionization energy of A is transferred to the kinetic energy of the electron .

It is concluded that during a sputter deposition , the observed target metal ions are associated with the Penning ionization process induced by excited noble gas atoms . Penning ionization is significant in the longer mean free-path pressure regime , i.e. < 10 mtorr .

1.1.1.2- De-Ionization Processes :-

De-ionization may takes place in two processes i.e. recombination or attachment .

i- Recombination :-

Positive ions and electrons may recombine together in a collision to form neutral atoms . When an electron is captured , it losses some of its kinetic energy , which can be either transferred to a third body or be emitted as a quantum of radiation . The transfer to a third body is the most probable process .

$$e + A^{+} \rightarrow A^{*} + h\nu$$

Little recombination in the volume of the gas may be occurred at low pressures in the discharge tubes ; at the walls which acts as a third body . At high gas pressures , three-body collisions is the most probable process and recombination is then more likely to occur .

$$A^{+} + B + e \rightarrow A + B$$

ii- Attachment :-

Negative ions are formed by the attachment of an electron to an atom or molecule . Gases with high attachment tendency , which form stable negative ions (e.g. halogens , O , S , ...) , have a slightly lower potential energy in the form of a negative ion than in the normal neutral state .

$$A + e \rightarrow A^{-} + h\nu$$

1.1.3- ELECTRODE PROCESSES .

Electrons may be released from solids to take part in electrical discharges either by (i) providing them with sufficient kinetic energy or (ii) by reducing the height of , or thinning , the potential barrier at the surface of solid . The electrode processes can be summarized in the following :-

1.1.3.1- Incidence of Positive Ions :-

When a positive ion approaches a metallic cathode surface it may be :- (1) reflected as an ion , (2) reflected as an unexcited atom , (3) reflected as an excited atom , (4) cause sputtering of the surface , (5) cause electrons to be emitted due to :- (i) the kinetic energy given up on impact , and (ii) a double process of metastable atom formation and radiation-less transition ; or (6) form a negative ion .

1.1.3.2- Incidence of Metastable and Normal Atoms .

1- Metastable Atoms :-

Metastable atoms incident on a surface may :- (i) be reflected ; (ii) eject electrons ; (iii) be ionized ; (iv) be repelled as a negative ion .

2- Normal Atoms :-

A normal atom incident on a surface may be :-
(i) reflected ; (ii) eject electrons ; (iii) ionized ; (iv) reflected as a negative ion .

1.2- THE DC (COLD CATHODE) GLOW DISCHARGE.

There are three main types of electrical discharges that have been studied frequently ; namely , the arc discharge , the glow discharge and the Townsend discharge . It is evident that the glow discharge plays an important role in the modern technology that we are witnessing nowadays , however it still presents a challenge for the basic reach , since ***Townsend*, *(1910)*** has started the first pioneering research on electrical discharges .

Up to now glow discharge still studied extensively , since its applications range from household appliances (e.g. the fluorescence tube) to the most advanced technologies , Laser pumping , sputtering thin film and deposition processes .

1.2.1- I-V CHARACTERISTIC CURVE OF THE GAS DISCHARGE .

The electrical characteristic of the discharge is described by its I-V curve (where I is tube current and V is the potential difference between the two electrodes of the tube) . Figure (1) shows an example of the I-V characteristic curve of the gas discharge , determined by the external parameters ; namely , the gas pressure P , the electrodes separation d , the electrode material , the gas type and the external current density . The electrical characteristic can be subdivided into three regions :-

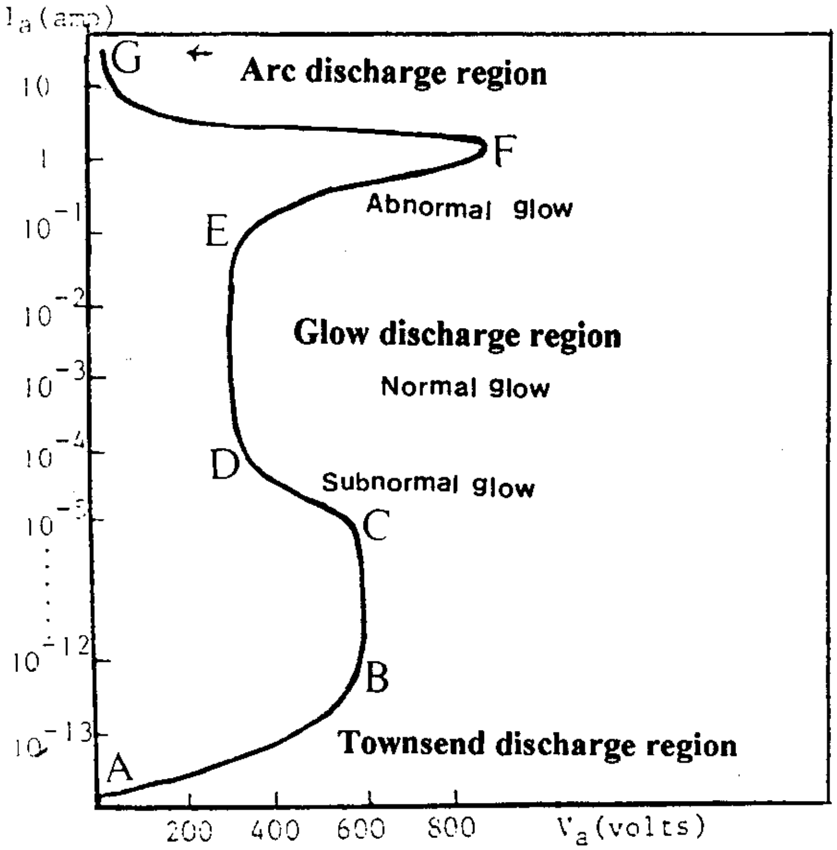

Fig. (1) The I-V characteristic curve of the electrical discharge .

1- The Low Current Region (Pre-Breakdown Region) :-

The Townsend discharge region where the tube current I is less than 10^{-6} A . In this region , the electric field is uniform and no light is emitted .

2- The Medium Current Region (Glow Discharge Region) :-

where $I \geq 10^{-5}$ A and the electric field configuration is no longer uniform due to the onset of the space charge distortions . The glow discharge region can be subdivided into three regions depending on the passing current and the potential difference between the two electrodes . These subdivided regions are sub-normal , normal and abnormal glow discharge regions ; respectively .

3- The High Current Region (Arc Discharge Region) :-

Further increases of the current leads to the arc region (where I is higher than of 1A) . The cathode region undergoes a transformation from a cold cathode discharge to a hot cathode discharge with thermoionic emission is the most dominant .

1.2.2- THE REGIONS OF THE GLOW DISCHARGE .

When a gas breaks down , it glows and most of its atoms are therefore excited or ionized by electron collision . In the glowing gas there are so many positive ions and a positive space- charge near the cathode are setting up , which distorts the potential distribution in the discharge tube {see Fig. (2)} . This distortion causes the glow to break up into several distinct regions (Fig. 3) . At the surface of the cathode , there is a thin layer of glow , which called the Aston space . Beyond this , there is a region , first observed by Crookes , called the Crookes dark space or the cathode dark space . It is generally rather narrow , but the action in it controls the behaviour of the whole discharge . Beyond the cathode dark space there is a bright region called the negative glow. The negative glow region is the brightest region of the glow discharge regions . The negative glow is followed by another dark space , called Faraday dark space . It is usually longer and darker than the cathode dark space . The rest of the discharge is a brilliant glow which is called the positive column region .

Most of the main regions of the discharge are :- cathode fall , negative glow and positive column regions which will be discussed in the following sections .

1.2.2.1- The Cathode-Fall Region :-

This region includes Aston , cathode layer and cathode dark space . The most interesting fact about this region is that most of the potential difference maintained between the two electrodes is dropped across this region as shown in Fig.(3) . This implies that the electrons and ions are accelerated mainly across the cathode fall region which usually has a thickness of a few mm. for a discharge at gas pressure of 1 torr . This thickness d_c has been found to vary inversely with the gas pressure P for a particular type of the gas used in the discharge .

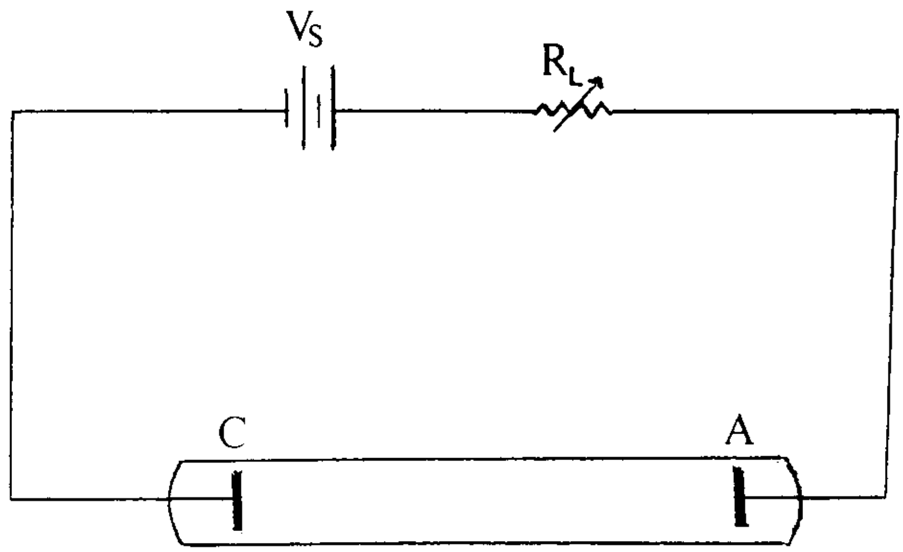

Fig.(2) Circuit used to Establish Glow discharge .-

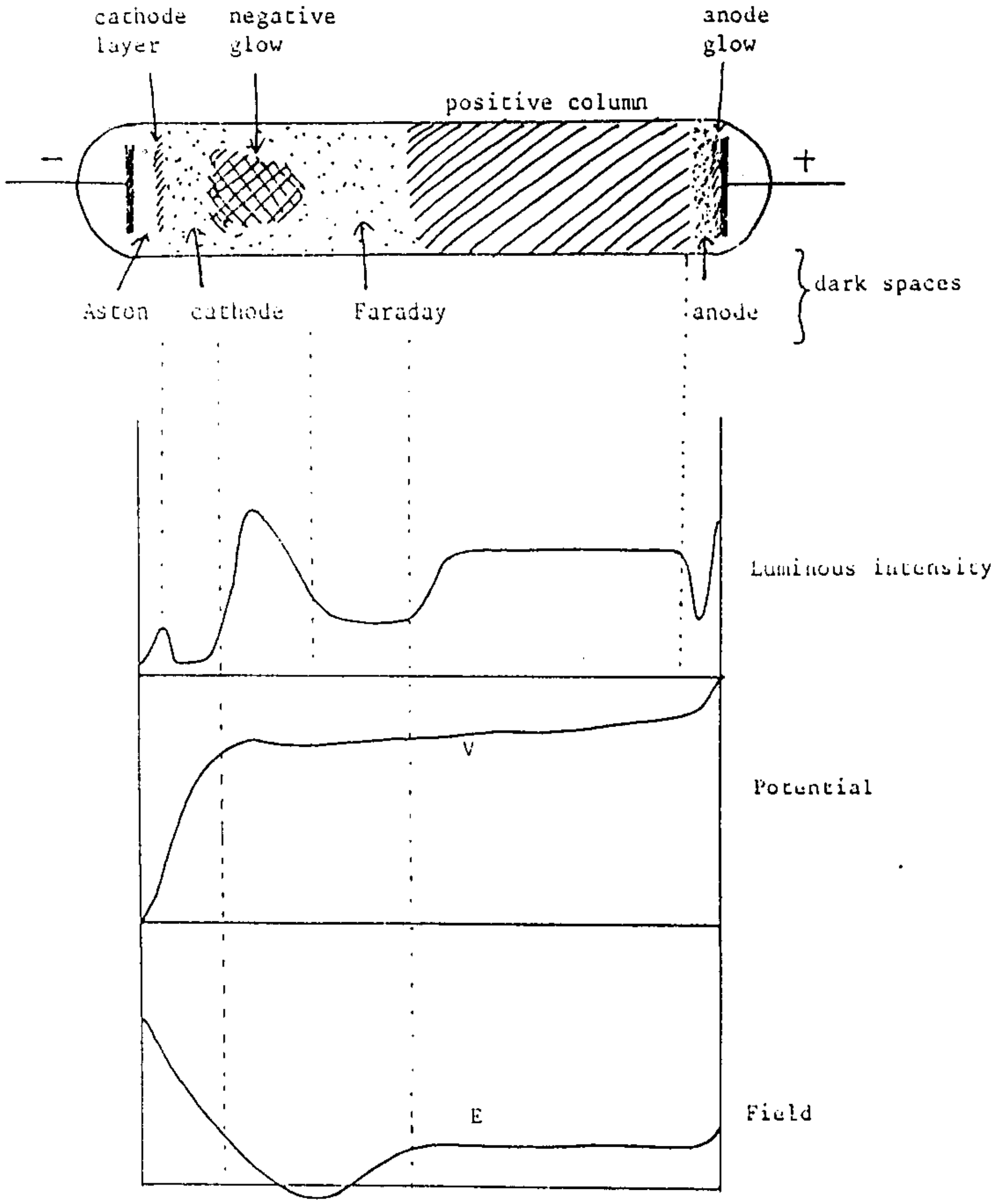

Fig. (3) The regions , luminous intensity , potential and electric field distributions of the glow discharge .

The value of $P.d_c$ will remain constant for a fixed experimental setup for each gas (in the normal glow discharge) . The cathode fall voltage V_c is a constant as the current varies within the normal glow discharge region .

The physical processes occurring in the cathode fall region can be described as follows :-

The electrons may be emitted from the surface of the cathode by positive ion bombardment , as well as by incident radiation . The initial energy of these electrons is low such that a thin sheath of electron space-charge is formed adjacent to the surface of the cathode . In this thin sheath of electron space charge , the current is carried mainly by the ions and there is little chance of radiation processes and this is called the cathode layer . Beyond the cathode layer , the electrons are accelerated. Due to the drop of recombination cross-section for energetic electrons , the region immediately after the cathode layer becomes less luminous compared to the cathode layer . This is the cathode dark space and it extends to the end of the cathode fall region . In the cathode dark space , the electrons continue to accelerate under the effect of the electric field until a threshold energy for excitation and ionization of atoms is achieved at the boundary between the cathode dark space and the negative glow . The acceleration of electrons depends on the magnitude and direction of the field , which is axial because a plane cathode has always been assumed . It is the purpose of the present work to investigate the electron energy distribution function in this region and determining the electron temperature & density and define the plasma model .

positive column until it disappears, without interrupting the discharge cathode regions and the current flow.

The longitudinal field along the positive column is small and uniform (Fig. 3). Poisson's equation can be applied as follows :-

$$\frac{dE}{dX} = \frac{e(n^{+} - n^{-})}{\varepsilon_{o}}$$

and E is found experimentally to be independent of X, thus :-

$$n^{+} - n^{-} = 0$$

which is a proof for the macroscopic neutrality of the positive column. So, $n^{+} = n^{-} = n$, and hence, E_X = constant. Therefore at steady state, the rate of loss of charged particles to the wall of the container through diffusion is balanced by the rate of ionization.

1.2.3- THE EFFECTIVE PARAMETERS ON THE GLOW DISCHARGE.

The physical appearance of the glow discharge has been found to be affected by a set of parameters such as the gas pressure, the electrode separation, the type of gas used, the current flows in the system and the cathode material. Their effects are described in the following sections.

1.2.3.1- Effect of the Gas Pressure :-

The pressure of the gas in the discharge tube has a significant effect on the relative length of the various regions of the glow discharge. Generally , the glow discharge is operated at a pressure less than 100 torr . The negative glow and cathode fall regions are compressed at high pressure values while the positive column extends to fill the space between the electrodes .

1.2.3.2- Effect of Electrode Separation :-

Once a glow discharge has been initiated , the voltage required to maintain it will only increases slightly if the distance between the two electrodes is increased . The length of the positive column increases to fill the extra space created by increasing the separation while the other regions remain practically undisturbed .

1.2.3.3- Effect of the Discharge Current :-

Figure (1) shows that the voltage across the tube will hardly vary, whereas the current varies by two , and in some cases three , orders of magnitude .

At a low current the cathode layer occupies only a part of the cathode surface and the voltage must be increased to maintain the glow of low light intensity . Here the discharge is known as the subnormal glow region . As the current increases , the area which is occupied by the cathode layer increases in proportional to the current . This continues to happen until the whole cathode surface is covered by the cathode layer . Hence the current density , as well as the voltage across the tube , is more or less constant . This is known as the normal glow region . Excessive increase in the discharge current may lead to an abnormal glow region .

The brightness of the luminous parts increases with the current in all three glow modes . Their boundaries also become better defined.

1.2.3.4- Effect of the Gas Used :-

The general characteristics of the glow discharge do not change very much with the gas type . However , the colours of the luminous regions may vary for different types of the used gases . The characteristic colours for some commonly used gases are listed in Table (1) .

1.2.3.5- Effect of Cathode Material :-

The cathode has a marked effect upon the voltage necessary to maintain the discharge . When the cathode has a low work function , a lower voltage is required to maintain the same discharge . Otherwise , the cathode material does not effect the glow discharge .

Table [1] :- Characteristic Colours of the Glow Discharge Regions .

Gas	Cathode Fall Region	Negative Glow Region	Positive Column Region
Air	Pink	Blue	Red
Ar	Pink	Dark blue	Dark red
H_2	Brownish-red	Pale blue	Pink
He	Red	Green	Red to violet
N_2	Pink	Blue	Red
Ne	Yellow	Pink	Brick red

1.3.2. The DC Glow Discharge Technique (Cathodic Sputtering or Diode Sputtering) .

In a DC glow discharge at low pressure ($1-5 \times 10^{-3}$ torr) , applied voltage of 0.5 to 15 KV and current density of 0.1 to 20 mA cm^{-2} , two distinct regions are established ; namely , the positive column and the cathode dark space . In the positive column a plasma is found whereas $T_e >> T_i$ and $T_i \geq T_{gas}$, where T_e , T_i and T_{gas} are the temperatures of the electron , the ion and the gas ; respectively .

However , once the ions enter the cathode dark space , they will be accelerated and gaining higher energies before impacting on the cathode . Due to the atomic scattering and charge exchange , a few ions will reach the full cathode potential . Consequently , the neutral atoms will be ejected along with the secondary electrons which assist in sustaining the discharge .

In order to prevent excessive heating of the cathode and unwanted sputtering , a plasma shield is placed behind the target . The shielding will also assist in establishing uniform electric fields around the edge of the target , this arrangement assures uniform sputtering .

Gaseous impurities disrobed from the chamber walls (such as water vapour , CO_2 ,...) will contaminate the plasma and affect the thin film parameters . Therefore , cares must be taken to generate clean plasmas which serve as source of high flux and high energy ions .

One of the purposes of the present work is to construct and investigate a DC-magnetron sputtering unit whereas Ar ions are used to eject the sputtered atoms .