CHAPTER 2

2. Electrical breakdown and DC discharges

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Introduction

There are a variety of methods for sustaining a plasma. For most technological applications the most commonly used method for creating and sustaining a plasma is by applying electric fields to a neutral gas.

In this cpapter we restrict ourselves to discussing plasma generation and breakdown for the low pressure case (< 100 Torr), high pressure breakdown will be discussed later in chapter 6.

2.1 Discharge Structure

If we consider a very simple plasma as shown in figure 2.1. Two parallel plate electrodes are placed in an evacuated tube filled with gas and a dc voltage is applied. The ignition of a plasma is initially generated through a free electron (e.g. created through cosmic radiation). These free electrons are accelerated by the electric field and gain energy from it.

Various discharge modes can exist between parallel plate electrodes in a low-pressure gas environment. The different modes can be identified through the voltage-current characteristic as illustrated in figure 2.1. This curve can be experimentally reproduced by carefully changing the resistance in the circuit.

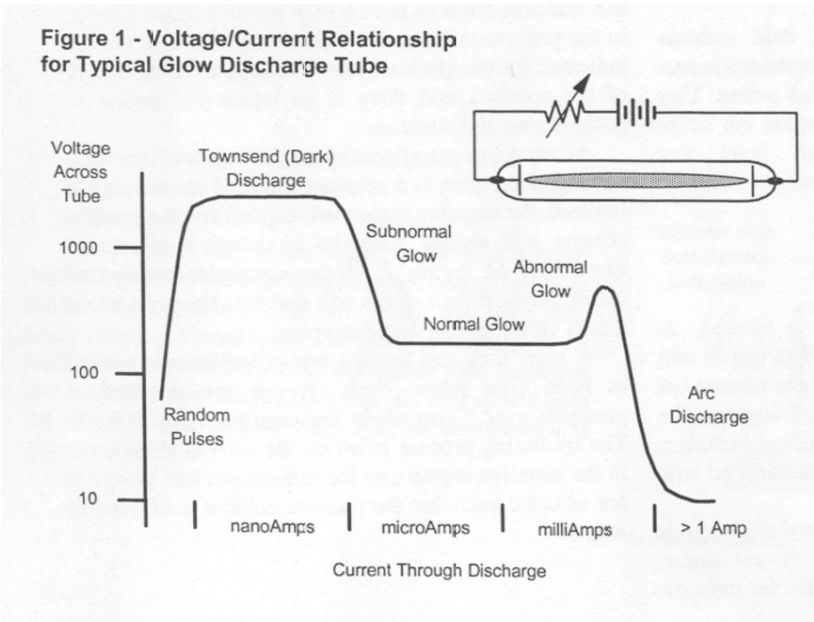

Figure 2.1: *(a) Schematic diagram of a discharge with dc voltage applied across two parallel plates in an evacuated tube (b) a typical current-voltage characteristic for this type of discharge.*

1. Ionization region: non-self-sustaining discharge:

When a low voltage is applied to an electrode gap containing neutral gas, an extremely small current can be observed. This is caused by electrons in the gap created by external sources, for instance cosmic rays or a nearby UV lamp. These few electrons are accelerated towards the anode, and their drift will produce a very small electric current.

However, the applied voltage is not high enough to cause ionization of atoms by electron impact, which is observed for higher voltages as will be shown later. Since the discharge needs external sources for the creation of electrons it is *non-self-sustaining*; it will die out when the electron source is removed.

2. Townsend discharge:

The Townsend discharge is also known as *dark discharge* since there is no appreciable light emission from such a discharge. Starting from the non-self-sustaining discharge, increasing of the applied voltage causes a transition to a *self-sustaining discharge*. The electrons have gained sufficient energy from the applied electric field to cause ionization of neutral atoms or molecules through electron impact producing new ion-electron pairs.

This results in a multiplication, and an avalanche of electrons and ions in the discharge gap. At the cathode surface, new electrons can be emitted into the gas by secondary emission caused by ion impact and also excited neutrals (see section 2.2). This provides a feedback mechanism which sustains a current through the discharge gap. The voltage marking the transition between a non-self-sustaining and a self-sustaining discharge is known as the *breakdown voltage* (section 2.4). In the case of a Townsend discharge, the applied voltage is just above the breakdown voltage and the current is limited to low values by a large external resistance R. The number of charged particles in the discharge gap is limited which gives no significant space charge effects and the applied potential in the gap is not disturbed. The $V - I$ characteristic for the Townsend discharge is almost flat. This originates from the fact that a small increase in voltage leads to a higher electron multiplication in the gap, producing more electrons and ions, giving more secondary emission at the cathode, leading to even more electrons in the gap and a further multiplication of charges. This means that for a small increase in voltage, the current rises considerably.

3. subnormal glow discharge:

A further increase of voltage leads to significant space charge effects in the discharge gap. Since there is a large difference between the mobilities of the ions and electrons, there will be mainly positive space charge. This will concentrate in front of the cathode, creating a *cathode fall* region. The potential drop across the cathode fall is almost equal to the potential difference across the electrodes. In other words, the electric field in this region is higher than when the potential was uniformly distributed over the gap. Since the electron multiplication increases for increasing electric field, there will be an enhancement of electron multiplication across the cathode fall. The result is that the total voltage needed to sustain the discharge can be reduced. Therefore, the $V - I$ curve shows a drop of voltage for increasing current. This discharge mode is often unstable and goes easily into a glow discharge.

4. glow discharge:

In this discharge mode, the formation of the cathode fall region has completed; the voltage needed to sustain the discharge is at its minimum. A further increase in current does not lead to a decrease of voltage, but to spreading of the discharge over the electrode surfaces, keeping the current density constant. The electrons in this region have sufficient energy to now produce light emission and thus called glow region. The glow discharge region ends when the whole surface of the electrodes is covered by the discharge and the current is further increased.

5. abnormal glow discharge:

The electrodes are fully covered by the discharge and a further current increase leads to an increase of the cathode fall. The voltage across the electrodes rises sharply.

6. arc discharge:

When the current is further increased a change into an arc discharge is observed. Different processes such as gas heating and thermionic electron emission from the electrodes become important. The result is that the voltage needed to sustain the discharge can be lowered substantially.

Which of these steady-state discharge modes will be formed depends on the external circuit; the voltage that is applied and the current that can be sustained.

2.2 Secondary electron emission and electron avalanches

Secondary electrons can be produced at the electrode surface and can hugely influence the discharge. Several mechanisms can result in the release of an electron from a surface e.g. thermionic emission, field emission. For low pressure plasmas, secondary electron emission is the most common. In this process a particle, e.g. typically an ion, impacts on the electrode with sufficient energy that an electron is released from the surface. The emission of an electron is through the Auger process, where the electric field of the ion can release electrons from the material. Secondary electron emission is typically characterised by the secondary electron emission coefficient γ and is naturally very material dependent (work function of material). Metastable particles and photons can also contribute to secondary electron emission.

These secondary electrons can collide with the background gas and cause ionization of the neutral atoms and molecules in the plasma. The mean free path for ionizing collisions in a plasma can be defined as:

$$\lambda_i = \frac{1}{\sqrt{2}\sigma n} \qquad (2.1)$$

Assuming that for each ionization event a free electron produces an average of one new free electron – ion pairs, the increase in the number of electrons in a distance *dx* is:

$$dn = \frac{n}{\lambda_i} dx \qquad (2.2)$$

where *n* is the number of electrons. If we integrate equation 2.2 we can see that the number of electrons and ions grows exponentially with distance:

$$n = n_0 \exp\left(\frac{x}{\lambda_i}\right) \qquad (2.3)$$

or:

$$\frac{n}{n_0} = \exp\left(\frac{x}{\lambda_i}\right) \qquad (2.4)$$

This is often called the "*avalanche effect*".

Task: Find data on secondary electron emission coefficients for different material surfaces and incident ion energies and share and discuss this data online.

2.3 Paschen's Law

In 1889, Paschen, studied the breakdown voltage of parallel plates in a gas as a function of pressure and gap distance. The voltage necessary to induce breakdown across the gap decreased up to a point as the pressure was reduced. It then increased gradually exceeding its original value (figure 2.2). Decreasing the gap with constant pressure caused the same behaviour in the voltage required to cause breakdown. The breakdown voltages could be experimentally measured, however, the underlying breakdown processes were not fully understood. 20 years later, in 1909, Townsend developed a theory that could explain breakdown and also provide an accurate description of the breakdown voltages measured in the Paschen curves.

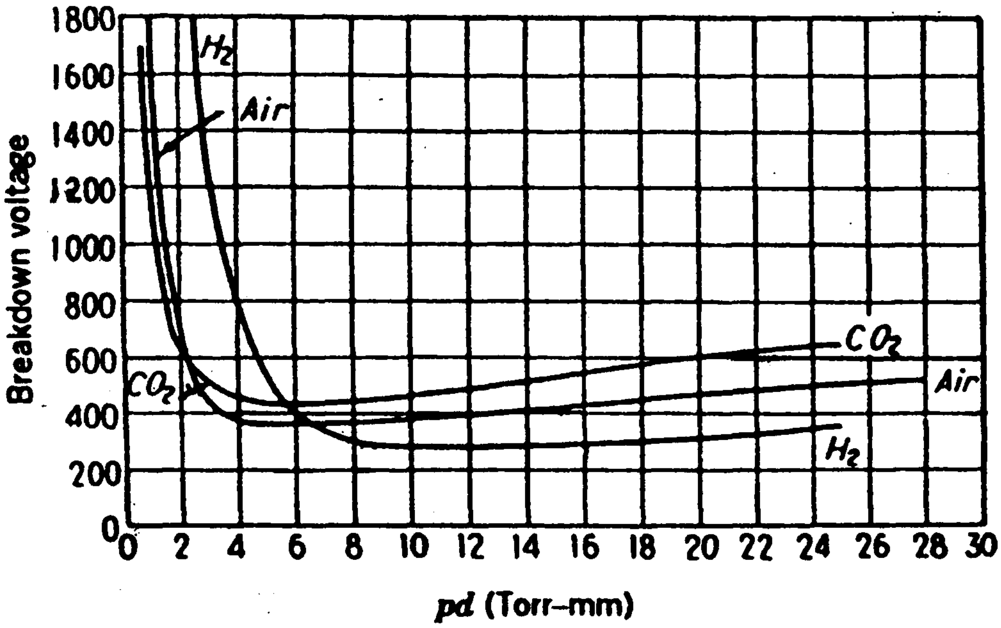

Figure 2.2: *Paschen curves for various gases*

2.4 Townsend's theory

- One electron leaving the cathode gives rise to an avalanche that will arrive at the anode with $e^{\alpha d}$ electrons.
- Where α is the *first Townsend ionisation coefficient* and *d* the distance from the cathode.
- The number of positive ions that head back towards the cathode is $\left(e^{\alpha d}-1\right)$
- One ion produces γ electrons

- Therefore, one electron gives rise to $\gamma\left(e^{\alpha d}-1\right)$ electrons
- For breakdown to occur this must be ≥1. This is known as the ***breakdown criterion***.

$$\gamma\left(e^{\alpha d}-1\right) \geq 1 \qquad (2.5)$$

The ionization coefficient can be described as

$$\alpha = Ap\exp\left(-\frac{Bp}{E}\right) \qquad (2.6)$$

As the number of free electrons increases so does the number of positive ions. The motion of these positively charges ions is obviously also influenced by the external electric field.

Considering uniform electric fields in a plane parallel plate discharge, the electric field is simply the voltage divided by gap distance:

$$E = \frac{V}{d} \qquad (2.7)$$

The breakdown criteria in equation 2.5 can be rewritten as

$$\begin{aligned} e^{\alpha d} &= \frac{1}{\gamma}+1 \\ \alpha d &= \ln\left(\frac{1}{\gamma}+1\right) \end{aligned} \qquad (2.8)$$

$$\begin{aligned} d &= \frac{\exp\left(Bpd/V_{Br}\right)}{Ap}\ln\left(\frac{1}{\gamma}+1\right) \\ V_{Br} &= \frac{Bpd}{\ln\left(Apd/\ln(1/\gamma+1)\right)} \end{aligned} \qquad (2.9)$$

This shows that the breakdown voltage is only dependent on the product of pressure and inter-electrode distance *pd* and is called *Paschen's Law.* At large *pd*, V_{Br} increases – this is termed high pressure insulation. At some critical value of *pd,* V_{Br} tends to infinity – this is termed vacuum insulation.

2.5 Minimum Breakdown Voltage

In order to determine the minimum breakdown voltage we need to differentiate with respect to *pd* and set the result to zero.

$$V_{Br(\min)} = 2.718\frac{B}{A}\ln\left(1+\frac{1}{\gamma}\right) \qquad (2.10)$$

This gives the value of *pd* at which the minimum breakdown voltage occurs.

2.6 Self-sustaining glow discharge

For many discharges in the range *pd* = 0.1 – 100 Pa m, the breakdown process transforms the neutral gas into a glow discharge. In the glow discharge mode, the potential drop across the plasma is mainly concentrated to the boundary layers adjacent to the electrodes, while the potential drop across the central plasma is very small. This region in front of the electrodes is referred to as the plasma boundary sheath. The electric field in this region serves to repel electrons and accelerate ions. The discharge is referred to as a glow discharge due to its characteristic luminosity. The electrons gain enough energy to cause excitation of the background gas and this can result in light emission when the spontaneously decay.

2.7 Sheath Formation in a DC Plasma

Task: Revise article 2.1 in relation to the different glow regions of a dc discharge

If an electrically insulated object (such as a wafer) is placed within a plasma, it will begin to build up a negative charge. This is due to the higher velocity of electrons vs. ions (~1000x). The negative charge will act as a repelling force to any additional incoming electrons. This will create a positively charged space around the object known as a dark space sheath.

The impact energy of ions on the electrode is dependent on the sheath characteristics such as sheath potential, sheath thickness, ion-neutral mean free path and the ion transit time through the sheath. To obtain deeper understanding a 1-D model can be used to describe the behavior of ions and electrons in the sheath. The following conditions and basic assumptions are considered.

The potential $\Phi = 0$ at the sheath edge.

Energy conservation for ions (collisionless sheath) gives

$$\frac{1}{2}Mu^2(x) = \frac{1}{2}Mu_S{}^2 - e\Phi(x) \qquad (2.11)$$

where *M* is the mass of ions, *u* is the drift velocity, u_S is the drift velocity of ions at the plasma sheath boundary, *e* is the elementary charge, and $\Phi(x)$ is the variation of potential across the sheath.

Assuming low pressure and a thin sheath, ionization in the sheath can be ignored, and conservation of ion flux gives

$$n_i(x)u(x) = n_{iS}u_S \qquad (2.12)$$

where n_i is the ion density and n_{iS} is the ion density at the sheath edge. Solving for u we obtain

$$n_i = n_{iS}\left(1 - \frac{2e\Phi}{Mu_S{}^2}\right)^{-1/2} \qquad (2.13)$$

Assuming the electrons are in Boltzmann equilibrium at a temperature, T_e, the electron density is given by the Boltzmann relation

$$n_e(x) = n_{eS}e^{e\Phi(s)/kT_e} \qquad (2.14)$$

where n_{eS} is the electron density at the sheath edge, $n_{eS} = n_{iS} = n_S$.

The variation of potential across the sheath is described by Poisson's equation

$$\frac{d^2\Phi}{dx^2} = \frac{e}{\varepsilon_0}(n_e - n_i) \qquad (2.15)$$

where ε_0 is the permittivity of free space.

This gives us a non linear equation governing the sheath potential and ion and electron densities. The complete solution of Poisson's equation for the sheath can only be found numerically. However, analytically it is apparent that the equation can only be satisfied for

$$u_S \geq u_B = \sqrt{\frac{kT_e}{M}} \qquad (2.16)$$

This is known as the *Bohm criterion* for the formation of the sheath. The velocities of ions at the sheath edge must exceed the critical value of the *Bohm velocity, u_B*. Therefore, a small electric field must be present between the main plasma bulk and the sheath to accelerate the ions to the Bohm velocity. This region is called the presheath. A small potential can have a significant influence on ions whereas not such a big effect on the already *hot* electrons. Quasi-neutrality still holds in the presheath.

2.8 Sheath potential at a floating wall

The potential drop between a plasma and an electrically floating wall is determined by equation the ion flux Γ_i to the electron flux Γ_e at the wall. That is, the electron current through the sheath should balance the ion current

$$\Gamma_I = \Gamma_e \qquad (2.17)$$

Due to conservation of flux in the sheath, the flux of ions at the wall is assumed to be the same as the flux of ions at the sheath edge. Therefore, the ion flux at the wall can be given by

$$\Gamma_i = n_S u_B \qquad (2.18)$$

where n_S is the plasma density at the sheath edge.

The electron flux at the wall is given by

$$\Gamma_e = \frac{1}{4} n_S \exp\left(\frac{e\Phi}{kT_e}\right)\bar{v}_e \qquad (2.19)$$

where $\bar{v}_e$ is the mean electron speed for an assumed Maxwellian distribution and T_e the electron temperature.

From this the sheath potential can be calculated to be

$$\Phi = -\frac{kT_e}{\mathrm{e}} \ln\left(\frac{M}{2\pi m}\right) \qquad (2.20)$$

which is dependent on, the ratio of ion mass M to electron mass m and on the electron temperature T_e.

Task: In a low pressure hydrogen plasma H^+ ions are usually the dominant ion species, what is the energy the ions will gain in the presheath and sheath?

2.9 DC Magnetron

These sources are used primarily for plasma-assisted sputtering and deposition and, lighting aside, are probably the most used dc technology today. High deposition rates are possible. They generally consist of a cathode, an anode and either permanent magnets or electromagnets to produce a magnetic field. The reason for the magnetic field is again to increase the efficiency of the source. This is due to the Lorentz force causing the electrons (and ions) to move in a circular motion with the cyclotron frequency:

$$\omega_{ce} = \frac{eB}{m_e} \qquad (2.21)$$

Since, $v = r\omega$, then the radius of this motion is:

$$r_c = \frac{m_e v}{eB} \qquad (2.22)$$

Task: Show that the cyclotron frequency can be expressed as $\omega_{ce} = \frac{eB}{m_e}$ and the Larmor radius as $r_c = \frac{m_e v}{eB}$

Thus having the sheath electric field and applied magnetic field at right angles to each other increases the distance travelled by the electrons (illustrated in figure 2.3) and substantially increases the probability of an ionising collision occurring. Magnetic field strengths between 10 to 50 mTesla are typically used, this is sufficient to significantly affect the motion of the electrons, but has little affect on the motion of the ions. Magnetron sources typically have input powers of a few hundred watts to kilowatts for large sources used to deposit coatings over considerable surface areas. In sources used for sputtering the sputter coating produced depends on the cathode material used.

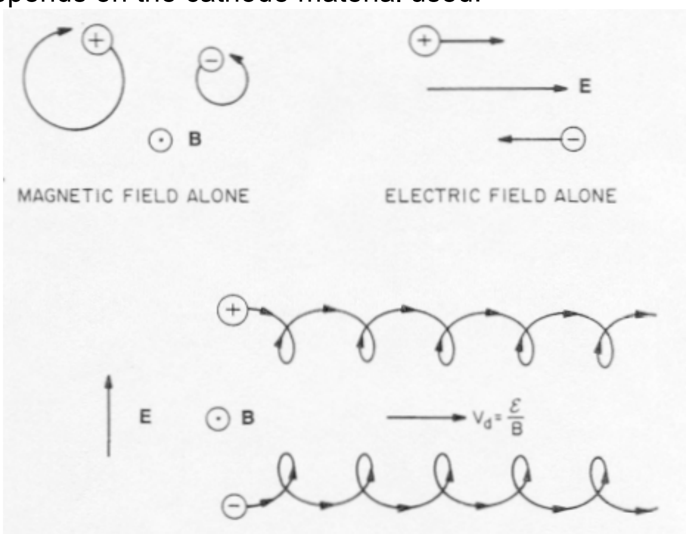

Figure2.3: *Diagram illustrating the motion of positively and negatively charged particles in magnetic and electric fields.*

Magnetron Configurations

One of the earliest and most widely used configurations is the *parallel plate magnetron*. A typical parallel plate configuration is shown figure 2.4. Applying a few hundred volts to the parallel plates produces a glow discharge. The secondary electrons (negative glow region) are confined by the magnetic field to a region close to the cathode producing a relatively high plasma density, ~10^9 cm^{-3}, and an increase in the discharge current for relatively modest applied voltages. Strong electric fields exist between the cathode and the negative glow and these accelerate the positive ions into the cathode producing sputtering of the cathode material. If this is done at sufficiently low background gas pressures, typically 5-50 mTorr, then the sputtered particles may traverse the inter-electrode gap and be deposited on the anode. For parallel plate systems the discharge can have a linear, axis symmetric or racetrack configuration.

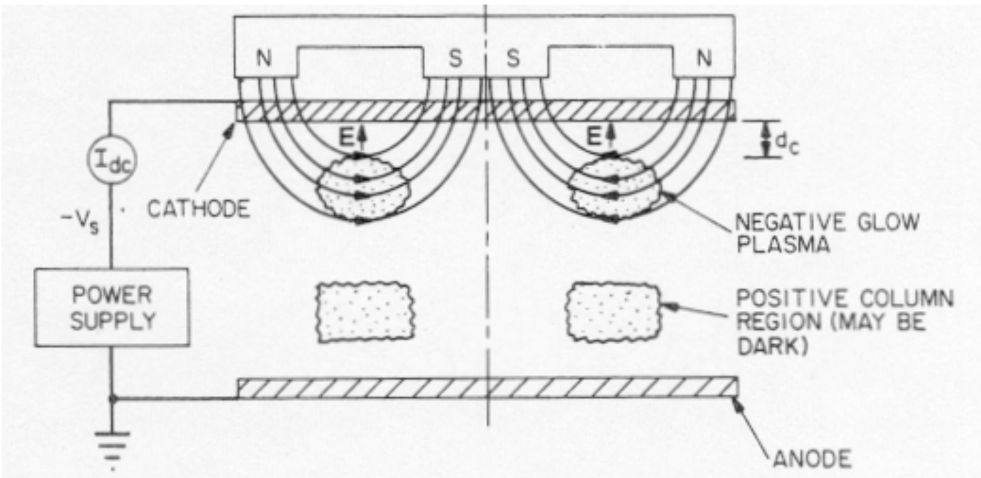

***Figure 2.4**: Schematic diagram of a parallel plate magnetron source*

Often having the anode opposite the cathode is inconvenient and this has led to the development of the co-planar magnetron, shown schematically in figure 2.5.

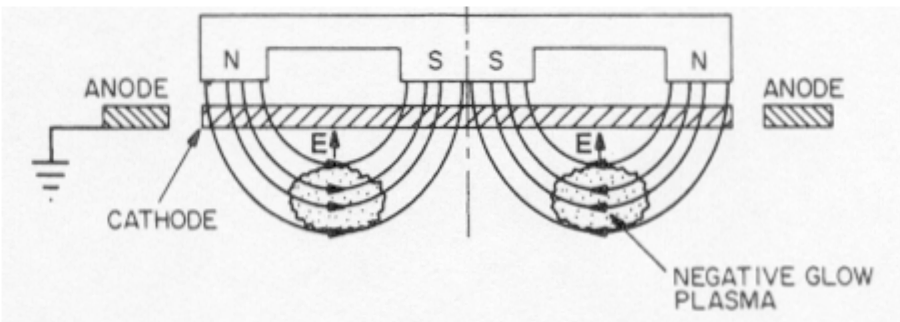

***Figure 2.5:** Schematic diagram of a co-planar magnetron source.*

Again the electrons are trapped by the magnetic field, but in this case the sputtered particles are free to deposit onto a substrate placed below the negative glow. This configuration produces curved electric field lines and has the major advantage that the discharge current between the cathode and the anode does not have to pass through the work-piece or substrate. This greatly reduces contamination and radiation damage and allows the use of insulating substrates.

Other forms of magnetron sources have also been developed, such as the normal and inverted cylindrical post magnetrons, (figure 2.6), the unbalanced magnetron and the closed field unbalanced magnetron. The latter of these are described in detail in an excellent review article by Kelly and Arnell [10].

Task: Read article [10] in detail, gain a good understanding of these type of magnetron sources and discuss at least one aspect you find interesting.

You should be able to sketch each configuration and give a reasonably detailed explanation of the operation, including advantages and any disadvantages, of each source type.

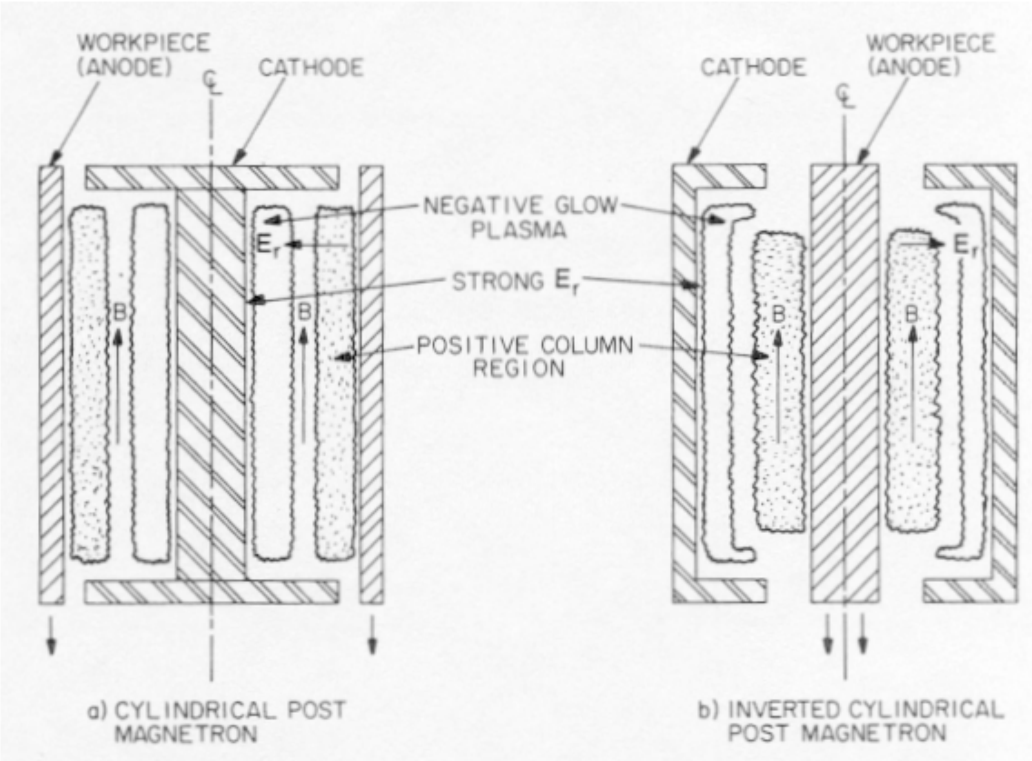

Figure 2.6: *Schematic diagram of a cylindrical post magnetron source.*

Some disadvantages of magnetrons are localised erosion of the cathode material causing the deposition rate to vary with time and due to this erosion the replacement of the cathode. The localised erosion problem can be somewhat overcome by the use of a cylindrical configuration. The other common problem with magnetron sources is arcing; this is mainly due to the high currents being used. Some methods of overcoming this problem are discussed in an article by Safi [11]. You should read this article in some detail and able to explain possible causes of arcing and methods of avoiding it. Besides arcing, the generation of high currents also means that it is necessary to cool the cathode or target.

2.10 Pulsed DC discharges

As well as traditional continuous DC glow discharges, pulsed dc glow discharges are also often used in plasma technology applications. They have a number of advantages.

- Can operate at higher instantaneous powers in the pulsed regime.
- Variation of the on/off duty cycle produces a plasma / afterglow regime which allows more detailed control of the particle energies and chemistry.
- Allow gas flushing of species between pulses. This can be useful for removing surface contaminants from the discharge and introducing fresh background gas or different gas mixtures.

Task: From article [10] discuss the advantages of pulsed magnetron sputtering for deposition of insulating coatings. You should become aware of typical operational parameters (pulse repetition rates, configurations, etc.) and be able to give examples of physical improvements in deposited coatings, etc.

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