CHAPTER 41

ELECTRIC CURRENT THROUGH GASES

Gases are, in general, poor conductors of electricity. This is because they do not have free charged particles in large numbers which may respond to an applied electric field. There may be some ionization due to cosmic rays and other factors, but regular recombination of ions of opposite polarity also takes place and the number of charged particles does not increase much. Electric current may be passed through a gas if we ensure that by some mechanism charged particles are continuously produced in the gas. This can be done in many ways. One such method is to apply a large potential difference across a gas column at very low pressure. Another method is to heat a metal kept in an evacuated chamber to high temperatures at which electrons are ejected from the metal. Yet another method is to pass X-rays through the gas. There are several other methods.

41.1 DISCHARGE THROUGH GASES AT LOW PRESSURE

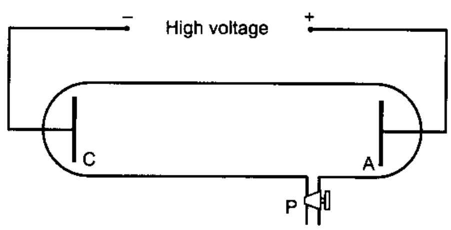


Figure 41.1

To study electric currents through gases at low pressures, one uses a glass tube known as *discharge tube*. Normally, it is a closed tube of length of about 30 cm and diameter of about 4 cm. It is fitted with two metal electrodes C and A (figure 41.1). A side tube P is used to pump out the enclosed gas so as to obtain the desired low pressure. The electrodes are connected to the secondary of an induction coil so that a high potential difference may be applied across the gas. The electrode C connected to the negative terminal is called the cathode and the electrode A connected to the positive terminal is called the anode.

Sparking Potential

If the potential difference between the electrodes is gradually increased, sparking occurs in the gas at a certain stage. The minimum potential difference which can cause sparks in a gas is called the *sparking potential.* Sparking potential depends on the pressure of the gas as well as on the separation between the electrodes. After careful studies, Paschen found that the sparking potential of a gas in a discharge tube is a function of the product of the pressure of the gas and the separation between the electrodes:

$$V = f(pd). \qquad \dots (41.1)$$

This is called the *Paschen's law.*

Low-Pressure Phenomena

In general, when a high potential difference is applied across a gas, sparking occurs in the form of irregular streaks of light. Suppose, in a typical case, the pressure of the gas is about 10 cm of mercury and sparking occurs. The sparking is accompanied by crackling noise. If the pressure of the gas is gradually decreased by pumping out the gas, a series of phenomena take place. At a pressure of about 10 mm of mercury, the irregular streaks broaden out in a luminous column extending from the anode almost up to the cathode (figure 41.2a). The crackling sound is replaced by a continuous buzzing sound. This column is known as *positive column.* The colour of the positive column depends on the nature of the enclosed gas. It

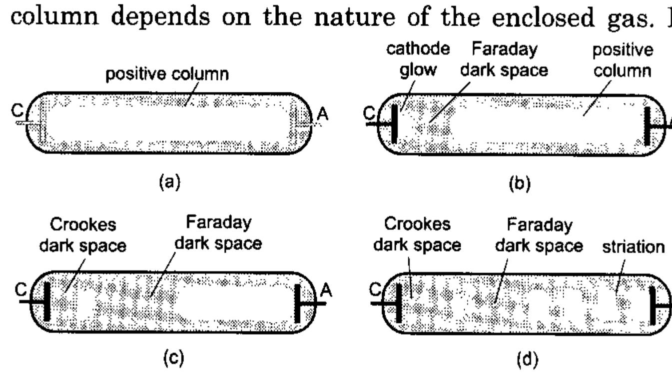


Figure 41.2

is reddish for air, bright red for neon, bluish for CO_2, etc.

As the pressure is further decreased to about 3–4 mm of mercury, the positive column decreases in length. It starts from the anode but ends well before the cathode. A bluish glow is seen around the cathode and there is a dark space between this glow and the positive column (figure 41.2b). The glow around the cathode is called *cathode glow* or *negative glow*. The dark space between the cathode glow and the positive column is called *Faraday dark space*.

When the pressure is reduced to about 1 mm of mercury, the positive column is further shortened and the length of the Faraday dark space increases. The cathode glow is detached from the cathode and a new dark space, called *Crookes dark space* (figure 41.2c), appears between the cathode and the cathode glow.

As the pressure is decreased further, the Crookes dark space and the cathode glow expand. At about 0·1 mm of mercury, the positive column is split into alternate bright and dark bands called *striations* (figure 41.2d).

With further reduction in pressure, the striations move towards the anode and finally vanish. The cathode glow also vanishes at around 0·01 mm of mercury and the Crookes dark space fills the entire tube. A new phenomenon starts at this stage. The walls of the tube begin to glow. This is called *fluorescence*. The colour of the glow depends on the nature of the glass. It is yellowish green for soda glass.

If the pressure is still decreased, the current through the gas gradually decreases and finally the tube stops conducting.

The values of pressure mentioned in the above discussion represent only typical values. The actual pressures at which these phenomena start, depend on the geometry of the discharge tube, the potential difference applied, the gas contained in the tube, etc.

Explanation of Discharge Phenomena

Due to cosmic rays and other factor, some ions are always present in a gas. When a potential difference is applied across a discharge tube, the ions are accelerated due to the electric field. They soon collide with other molecules of the gas and share the excess energy acquired. If the potential difference is sufficiently high, the ions get enough energy to ionize the molecules on collision. This way, ions are produced in large number and conductions starts. Generally, an electron is detached from a molecule to make the molecule a positive ion. At low pressures, this electron can move through a considerably large distance before attaching to another molecule forming a negative ion. These free electrons and the positive ions play important roles in discharge-tube phenomena.

Let us consider the case when the discharge tube looks the most beautiful—there is Crookes dark space, cathode glow, Faraday dark space and then alternate dark and bright bands.

The positive ions produced near the surface of the cathode are attracted towards it. Hence, the ions are accelerated as they move towards the cathode. In the process they gain kinetic energy. The ions strike the cathode with sufficient kinetic energy to liberate more electrons from its surface. These electrons are accelerated away from the cathode and they ionize the gas further by collision. Thus, ionization takes place much more rapidly near the cathode.

When a molecule gets ionized, the electron moves towards the anode and the positive ion towards the cathode. The electron being light, is swept away very fast by the electric field as compared to the slow-moving, heavy, positive ions. Thus, a positive charge density builds up near the cathode and an intense electric field is produced between the cathode and this region. The electrons emitted by the cathode acquire sufficient kinetic energy while passing through this intense electric field to ionize the neutral molecules with which they collide. These ionized molecules emit light which appears as the cathode glow. The electrons emitted from the cathode travel on the average a distance equal to the mean free path before they collide and cause cathode glow. Thus cathode glow appears some distance away from the cathode and this explains the Crookes dark space.

The slow-moving, positive ions create a positive charge density in the region of cathode glow. As the fast-moving electrons, coming from the cathode, pass through this region they are slowed down and hence lose their ionizing capacity. Thus, there is no emission of light for some distance beyond the cathode glow and this makes the Faraday dark space. After coming out of the cathode glow, the electrons again accelerate due to the electric field and acquire sufficient energy to ionize the molecules. This starts the positive column. The Faraday dark space is several times longer than the Crookes dark space because the electric field here is not as intense as it is near the cathode.

The successive process of ionizing, losing ionizing power, accelerating for some distance and again ionizing, is repeated till the electrons reach the anode. Thus, we have alternate dark and bright bands, i.e., the striations.

As the pressure is still lowered, the mean free path increases and hence the length of the Crookes dark space increases. At very low pressure, when the mean free path becomes larger than the length of the tube, the Crookes dark space fills the entire tube and no cathode glow or positive column is observed. The electrons coming out of the cathode strike the walls of the tube and this impact causes fluorescence.

41.2 CATHODE RAYS

When the pressure of the gas in a discharge tube is lowered, at a certain stage the Crookes dark space fills the whole length of the tube. The fact that the walls of the tube glows (fluorescence) shows that something is coming out from the cathode, travelling through the length of the tube and falling on the walls. As we have discussed above, this something is a stream of fast-moving electrons. This fact was recognised after a series of experiments carried out by Crookes, Thomson and others. They named these invisible streams coming from the cathode *cathode rays* and established the following main properties.

(a) *Cathode rays are emitted normally from the cathode surface. Their direction is independent of the position of the anode.*

Figure 41.3

This can be shown by taking the cathode in the shape of a concave surface. If a fluorescent material is placed at the centre of curvature of the cathode surface, the material glows with maximum intensity. Any lateral shift reduces the glow.

(b) *Cathode rays travel in straight lines.*

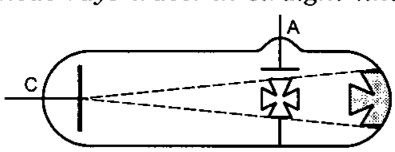


Figure 41.4

This can be shown by placing a metal cross in the path of the cathode rays. A shadow appears on the wall on the opposite side as the cathode rays do not reach there (there is no fluorescence in the shadow region). If the cross is lowered, the shadow disappears.

(c) *Cathode rays exert mechanical force on the object they strike.*

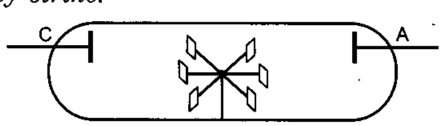


Figure 41.5

To show this, one can put a light wheel of mica in the path of the cathode rays. With proper arrangement, the wheel starts rotating as the cathode rays fall on it.

(d) *Cathode rays produce heat when they strike a material surface.*

If a blackened platinum strip is placed at the centre of curvature of a concave-shaped cathode, the strip becomes red-hot after some time.

(e) *Cathode rays produce fluorescence when they strike a number of crystals, minerals and salts.*

(f) *When cathode rays strike a solid object, specially a metal,* X*-rays are emitted from the object.*

(g) *Cathode rays can be deflected by an electric field and also by a magnetic field. The direction of deflection is the same as that of a stream of negatively charged particles. The deflection in such a condition is independent of the gas present, the material of the cathode, the position of the anode, etc.*

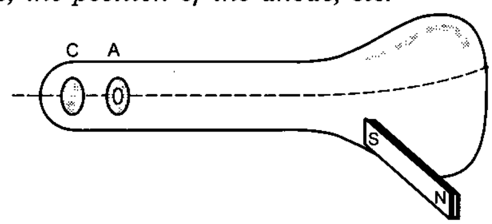


Figure 41.6

Such a deflection was studied by Thomson using an apparatus of the design similar to that shown in figure (41.6). Cathode rays start from the cathode C and pass undeflected into the larger bulb where it causes fluorescence on the opposite surface. The particular design ensures that the glow is in the shape of a small dot. If a magnet is now brought closer to the larger bulb, the dot moves on the wall showing that the rays have been deflected. The direction of the deflection confirms that cathode rays contain negatively charged particles. Similar deflection can be studied in electric field by bringing a charged rod near the larger bulb.

(h) *Cathode rays ionize the gas through which they are passed.*

(i) *Cathode rays can penetrate thin foils of metal.*

(j) *Cathode rays affect photographic plates.*

All the above properties can be easily understood once we recognise that cathode rays are nothing but a stream of fast-moving electrons.

41.3 CANAL RAYS OR POSITIVE RAYS

If the cathode of a discharge tube has holes in it and the pressure of the gas is around 1 mm of mercury, streams of faint luminous glow come out from each hole on the back side of the cathode. This shows that something is coming out of the holes. These are called *canal rays* or *positive rays.* The origin of the canal rays can be easily understood. When the molecules near the cathode are ionized, the positive ions move slowly towards the cathode. The positive ions passing through the holes constitute the positive or canal rays. The positive rays are deflected by electric and magnetic field. The direction of the deflection is the same as that of a stream of positively charged particles. They also cause fluorescence when incident on certain materials.

41.4 DISCOVERY AND PROPERTIES OF ELECTRON

The experiments on discharge tube towards the end of the nineteenth century played an important role in the discovery of electron. The fact that cathode rays are deflected in electric and magnetic field led scientists to believe that they are made of tiny negatively charged particles. These particles are the electrons as we know them today. J J Thomson (1856–1940) is often credited with the discovery of electron. This is not because he was the first to perform the discharge-tube experiment or was the first to explain cathode rays in terms of negatively charged particles. The credit goes to him for studying the properties of electrons and suggesting that electrons are necessary constituents of all atoms. The basic physics behind his famous experiment to measure the "charge by mass" (*e*/*m*) ratio of electrons is described below. This ratio is also called the *specific charge* of the electron.

Determination of *e*/*m*

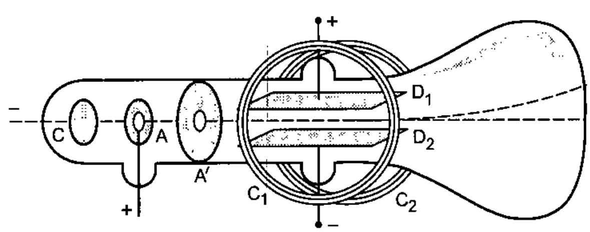


Figure 41.7

Figure (41.7) shows the basic design of Thomson's experiment to measure *e*/*m*. A large potential difference V is applied between the cathode C and the anode A sealed in a highly evacuated tube. A narrow beam of electrons, ejected from the cathode, passes through the holes in the anode A and in a parallel metal electrode A'. The beam passes through the region between the two metal plates D_1, D_2 and then strikes the end of the tube. A fluorescent material is coated on the inner surface of the tube at this end so that a visible glow is produced when electrons strike the end. The plate D_1 is connected to the positive terminal of a power supply and D_2 to the negative. Thus, a constant potential difference is maintained between them. Knowing the separation between the plates, the electric field E in the region between the plates can be computed. This field E is in the downward direction in figure (41.7) and exerts a force in the upward direction on the electrons. When the potential difference is applied, the glow at the end of the tube shifts in the upward direction.

A magnetic field B can also be applied in the region between the plates by passing electric currents in circular coils C_1, C_2. This field is perpendicular to the electric field as well as to the undeviated path of the cathode rays. If this field alone is present, the electrons move in a circular arc in the field region and hence are deflected from their straight path. The direction of the current in C_1, C_2 is so chosen that the magnetic force on the electrons is in the downward direction in the figure. Thus, the electron beam is deflected downwards due to the magnetic force.

If both the electric and the magnetic field are switched on and the values are so chosen that

$$v = E/B, \qquad \text{... (i)}$$

the magnetic force evB will exactly cancel the electric force eE and the beam will pass undeflected. If the potential difference between the anode A and the cathode C is V, the speed of the electrons coming out of A is given by

$$\frac{1}{2} m v^2 = eV. \qquad \text{... (ii)}$$

Putting the value of v from (i) into (ii),

$$\frac{1}{2} m \left(\frac{E}{B}\right)^2 = eV$$

or,
$$\frac{e}{m} = \frac{E^2}{2 B^2 V}. \qquad \text{... (41.2)}$$

In an experiment, the position of the glow at the end of the tube is noted without applying any electric or magnetic field. The fields are now applied and the potential difference between D_1 and D_2 is adjusted till the glow returns to its original position. The value of *e*/*m* is calculated by equation (41.2) in this situation.

Millikan Oil-drop Experiment : Determination of *e*

Thomson's experiment described above, could determine the value of *e*/*m*. The value of electronic charge e was measured by Robert Andrews Millikan about fifteen years after Thomson's experiment. Millikan was awarded the Nobel Prize in physics for 1923 for this

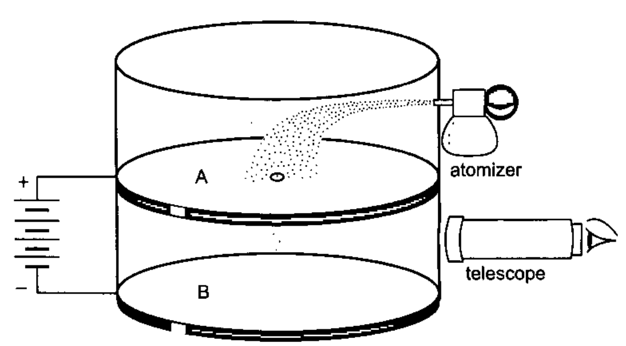


Figure 41.8

classic experiment. The basic design of the Millikan oil-drop experiment is shown in figure (41.8).

Two accurately-aligned, parallel metal plates A and B are separated by a small distance of the order of few millimetres. The plates are enclosed in a chamber with glass walls. An electric potential difference is applied between the plates to produce an electric field E in the vertically downward direction. Small droplets of oil are sprayed in the region between the plates through a hole in the upper plate A. Some of the droplets acquire electric charge due to friction with air (this process may be aided by passing X-rays through the air or by putting some radioactive material in the chamber). The chamber is illuminated by sending light horizontally through it. The drops can be seen by using a telescope placed perpendicular to the light beam. A drop looks like a bright star moving either downwards or upwards. If a droplet has a mass m and charge q, the forces on it are (a) its weight mg, (b) electric force qE, (c) buoyancy B and (d) viscous force F.

Most of the drops acquire a negative charge so that the electric force is upwards. A particular drop is chosen in the field of view of the telescope and the magnitude of the field E is adjusted to make the drop stationary. In this case, there is no force of viscosity and the other three forces add to zero. Thus,

$$qE + B = mg$$

or, $$qE = mg - B$$

$$= \frac{4}{3}\pi r^3(\rho - \sigma)g$$

or, $$q = \frac{4\pi r^3(\rho - \sigma)g}{3E} \qquad \text{... (i)}$$

Here r is the radius of the drop, and ρ and σ are the densities of the oil and the air respectively.

To determine the radius of the drop, the electric field is switched off. The drop accelerates downwards. After a while, the speed of the drop becomes constant. This speed v is measured by noting the time taken by the drop to fall through a predetermined distance. In this case, the viscous force $6\pi\eta rv$ and the buoyancy B taken together balance the weight mg.

$$6\pi\eta rv + \frac{4}{3}\pi r^3\sigma g = \frac{4}{3}\pi r^3\rho g$$

or, $$6\pi\eta v = \frac{4}{3}\pi r^2(\rho - \sigma)g$$

or, $$r = \left[\frac{9\eta v}{2(\rho - \sigma)g}\right]^{1/2}.$$

Putting this value of r in (i)

$$q = \frac{18\pi}{E}\sqrt{\frac{\eta^3 v^3}{2(\rho - \sigma)g}}.$$

Millikan and his coworkers repeated the experiement thousands of times and measured the charges on so many drops. It was found that each drop had a charge that was a small integral multiple of a basic value $e = 1{\cdot}6 \times 10^{-19}$ C within the accuracy of the experiment. From this observation, Millikan concluded that $e = 1{\cdot}6 \times 10^{-19}$ C is the charge on an electron. If one electron is attached to a drop, the charge on the drop is e. If two electrons are attached to a drop, the charge on the drop is $2e$ and so on.

41.5 THERMIONIC EMISSION

When a metal is heated to a high temperature, electrons escape from its surface. This phenomenon is called *thermionic emission* and the electrons coming out are called *thermions*. When an electron attempts to come out, the remaining metal, which becomes positively charged, pulls it back. The electron is thus slowed down and is able to come out only if it has got some extra kinetic energy to overcome the pull. The minimum energy that must be given to an electron to take it out of the metal is called the *work function* of the metal. Work function is denoted by the symbol φ and is different for different metals.

At ordinary temperatures, the free electrons of a metal do not have sufficient energy to come out. As the temperature is increased, the average kinetic energy of the electrons increases. Some of the electrons having sufficient kinetic energy are able to come out from the metal.

If n thermions are ejected per unit time by a metal surface, the thermionic current is $i = ne$. This current is given by the *Richardson–Dushman equation*

$$i = ne = AST^2 e^{-\varphi/kT}. \qquad \text{... (41.3)}$$

Here S is the surface area, T is the absolute temperature of the surface, φ is the work function of the metal, k is the Boltzmann constant and A is a constant which depends only on the nature of the metal.

Example 41.1

The work function of a thermionic emitter is 4·5 eV. *By what factor does the thermionic current increase if its temperature is raised from* 1500 K *to* 2000 K?

Solution :

If i_1 and i_2 represent the thermionic currents at temperatures $T_1 = 1500$ K and $T_2 = 2000$ K respectively,

$$i_1 = AST_1^2 e^{-\varphi/kT_1}$$

and $$i_2 = AST_2^2 e^{-\varphi/kT_2}.$$

Thus, $$\frac{i_2}{i_1} = \left(\frac{T_2}{T_1}\right)^2 e^{-\frac{\varphi}{k}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}.$$

Putting the values of T_1, T_2, φ and k

$$\frac{i_2}{i_1} = 10625.$$

41.6 DIODE VALVE

A diode valve consists of a cathode which can be heated to a high temperature to emit electrons and an anode which can collect these electrons. The cathode and the anode are sealed in an evacuated glass bulb. The cathode is also called *filament* and the anode is also called *plate*. In one design, a pure tungsten wire or a thorium-coated tungsten wire is used as the cathode. This wire can be directly connected to an external circuit driving current through it and hence increasing its temperature. In another design, a hollow nickel tube coated with barium oxide is used as the cathode. The tube surrounds a heater coil. When the external circuit drives a current through the heater coil, the nickel tube gets heated by radiation. The anode is in the form of a hollow nickel cylinder which surrounds the cathode. Potential difference may be applied between the cathode and the anode by connecting a battery through the leads coming out of the sealed valve. The positive terminal of the battery is connected to the anode and the negative terminal to the cathode.

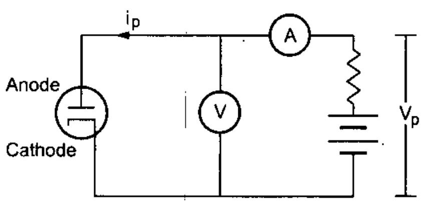


Figure 41.9

Figure (41.9) shows the symbolic representation of a diode valve and the circuit to study the current through the valve. When the cathode is heated, it emits electrons. These electrons are attracted towards the anode when a positive potential V_p (with respect to the cathode) is applied to it. This potential V_p is called the *plate voltage*. The electrons pass through the battery and then return to the cathode. Thus, an electric current i_p is established in the circuit which can be measured by the ammeter connected in the circuit. This current is called the *plate current*. If the plate voltage V_p is changed, the plate current i_p is also changed. A set of plots between the plate current and the plate voltage is called *diode characteristics*.

Diode Charactersitics

Figure (41.10) shows the nature of diode characteristics at different temperatures of the cathode. The space between the cathode and the anode contains electrons and hence, is negatively charged.

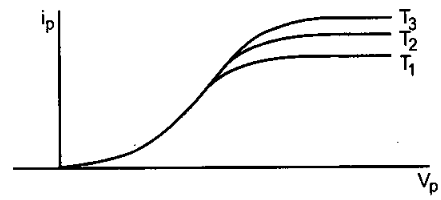


Figure 41.10

This negative charge is called the *space charge* and it repels the newly ejected electrons back to the cathode. The plate current i_p is thus reduced due to the space charge. As the plate voltage is increased, the electrons are pulled with a greater force and the effect of space charge decreases. Thus, the plate current i_p increases as the plate voltage V_p increases. When V_p is sufficiently large, all the electrons emitted by the cathode are collected by the anode and the current becomes saturated. Further increase in V_p does not increase i_p.

If the anode is given a negative potential with respect to the cathode, the electrons are pushed back towards the cathode and no current flows in the external circuit. We say that the diode *does not conduct* in this case. Thus, the diode allows current only in one direction. The electrons can leave the diode at the anode and enter into it at the cathode. Correspondingly, positive current can enter the diode at the anode and may come out at the cathode.

If the temperature of the filament is increased, greater number of electrons are ejected from the cathode and the saturation current increases.

Far from the saturation, the current is roughly proportional to $V_p^{3/2}$. Thus,

$$i_p = k\,V_p^{3/2}$$

where k is a constant for a given diode. This law is called *Langmuir–Child law*.

Dynamic Plate Resistance

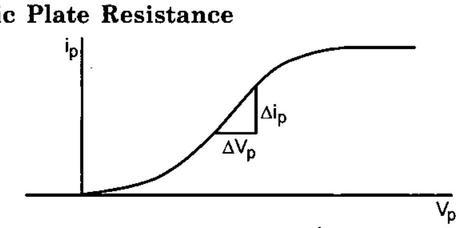


Figure 41.11

The resistance of a metallic conductor is defined as $R = V/i$. One can define the resistance of a diode using this equation. However, a more useful quantity, called the *dynamic plate resistance* of the diode, is defined as follows. Suppose the diode is operated at a plate voltage V_p and the plate current is i_p (figure 41.11). Now the plate voltage V_p is changed by a small amount to $V_p + \Delta V_p$. Consequently, the current will change by a small amount from i_p to $i_p + \Delta i_p$. The dynamic plate resistance of the diode is defined as

$$r_p = \frac{\Delta V_p}{\Delta i_p} . \qquad \dots (41.4)$$

It is clear that r_p depends on the operating conditions (V_p, i_p). Referring to figure (41.11), the dynamic plate resistance is the inverse of the slope of the i_p–V_p characteristic at the operating point.

Example 41.2

When the plate voltage applied to a diode valve is changed from 40 V *to* 42 V, *the plate current increases from* 50 mA *to* 60 mA. *Calculate the dynamic plate resistance at the operating condition.*

Solution : Here $\Delta V_p = 42\text{ V} - 40\text{ V} = 2\text{ V}$

and $\Delta i_p = 60\text{ mA} - 50\text{ mA} = 10\text{ mA}$.

Thus, the dynamic plate resistance is

$$r_p = \frac{\Delta V_p}{\Delta i_p} = \frac{2\text{ V}}{10\text{ mA}} = 200\ \Omega.$$

Rectification

If a source of alternating current is conneted to a resistor, the direction of the current in the resistor changes alternately. By using a diode in the circuit, one can have current in the resistor in a fixed direction. *Obtaining a unidirectional current from an AC source is called rectification.*

Half-Wave Rectification

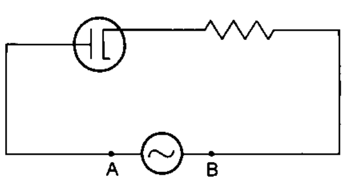


Figure 41.12

Figure (41.12) shows a circuit containing an AC source, a diode and a resistor. When the point A is at a potential higher than that of B, the anode is also at a potential higher than that of the cathode. The diode allows current to pass through. Thus, the AC source sends a current which goes through the diode, through the resistor and then back to the source. The current in the resistor is from left to right.

When the potential at A becomes less than that at B, the diode does not allow a current. There is no current in the resistance in this case.

Figure (41.13) shows the variations in the applied AC voltage (potential of A with respect to B) and the current in the resistor as time passes. The current is allowed only in the positive half-cycles and is stopped in the negative half-cycles.

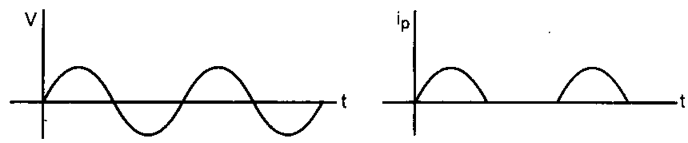
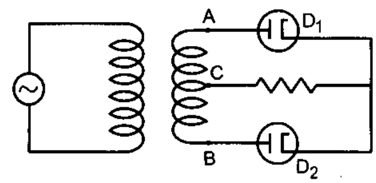


Figure 41.13

We see that the current in the resistor is always from left to right. The diode has *rectified* the AC voltage. As the current is allowed only for half the time, the rectification is called *half-wave rectificition.*

Full-Wave Rectification



Figurre 41.14

Figure (41.14) shows the circuit for full-wave rectification. The AC source is connected to the primary of a transformer. The terminals of the secondary are connected to the anodes of two diodes D_1 and D_2. The two cathodes are connected to one end of a resistor. The other end of the resistor is connected to the centre C of the secondary of the transformer.

Let us take the potential at C to be zero. Consider a half-cycle in which the potential of A is positive and that of B is negative. The diode D_1 conducts but D_2 does not. So a current passes through D_1 and then through the resistor back to the secondary. The current in the resistor is from right to left. In the next half-cycle, the potential at B is positive and that at A is negative. The diode D_2 conducts, but D_1 does not. The current passes through D_2 and then through the resistor back to the secondary. Again, the current in the resistor is from right to left. So, the current in the resistor is from right to left in both the half-cycles. Figure (41.15) shows the variations in the applied AC voltage and the current in the resistor as time passes.

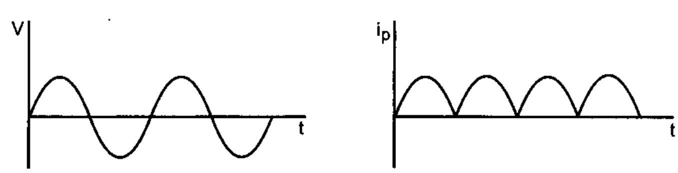


Figure 41.15

41.7 TRIODE VALVE

A triode valve is similar in construction to a diode valve except that a wire grid is inserted between the cathode and the anode. Thus, there are three external terminals in a triode which are connected to the cathode, the grid and the anode. Figure (41.16) shows the symbol of a triode valve.

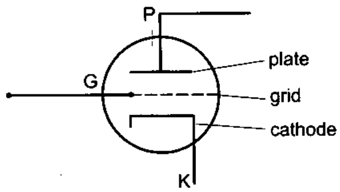


Figure 41.16

When the cathode is heated, it emits thermions. These thermions pass through the holes in the grid and reach the anode. If the anode is given a positive potential and the grid is kept at zero potential (both with respect to the cathode), the anode attracts the electrons and the triode works like a diode. The current through the anode is called the *plate current* or *anode current* and is denoted by i_p. This current is affected by the space charge near the cathode. The space charge is controlled both by the *grid voltage* V_g (with respect to the cathode) and the plate voltage V_p. If the *grid voltage* V_g is made negative, the grid repels the electrons coming from the cathode and the current decreases. If the grid voltage is made positive, it will help the electrons to go towards the anode, increasing the current. As the grid is closer to the cathode, changing grid voltage is more effective than changing plate voltage in bringing about a change in the plate current. In absence of the grid, the current is roughly given by $i_p = k\, V_p^{3/2}$. When the grid is added, the current is given by

$$i_p = k(V_p + \mu\, V_g)^{3/2}. \quad \dots (41.4)$$

Thus, a grid voltage V_g has the same effect as a plate voltage μV_g. The constant μ, which may be typically of the order of 10, is called *amplification factor.*

Triode Characteristics

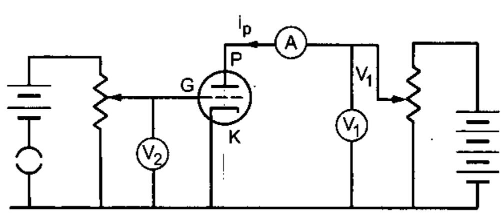


Figure 41.17

Figure (41.17) shows the circuit used to study the current in a triode. The plate current is measured by the ammeter A, the plate voltage V_p by the voltmeter V_1 and the grid voltage V_g by the voltmeter V_2. These voltages may be changed by changing the rheostat settings. The grid potential may be made positive or negative.

In a triode, there are several currents and voltages and one can draw a number of characterstic curves. More important are i_p–V_p curves at constant V_g and i_p–V_g curves at constant V_p. The curves in the first set are called the *anode characteristics* and those in the second set are called the *mutual characteristics.* Figure (41.18a) and (41.18b) show the two characteristics qualitatively.

The operating point of a triode is determined by specifying V_p, V_g and i_p. Generally, the triode is operated in the linear portions of its characteristics (figure 41.18).

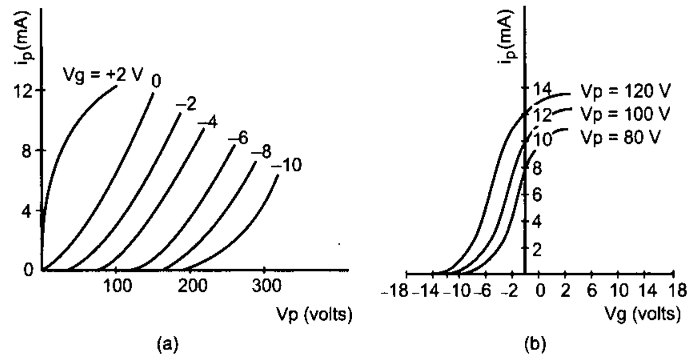


Figure 41.18

Dynamic plate resistance

If the grid voltage is kept constant and the plate voltage is changed, the plate current changes. We define the *dynamic plate resistance* r_p as

$$r_p = \left(\frac{\Delta V_p}{\Delta i_p}\right)_{\Delta V_g = 0}. \quad \dots (41.5)$$

Mutual conductance

If the plate voltage V_p is kept constant and the grid voltage V_g is changed, the plate current changes. The *mutual conductance* g_m is defined as

$$g_m = \left(\frac{\Delta i_p}{\Delta V_g}\right)_{\Delta V_p = 0}. \quad \dots (41.6)$$

Mutual conductance is also called *transconductance.*

If both V_g and V_p change, the plate current changes by

$$\Delta i_p = \left(\frac{\Delta i_p}{\Delta V_p}\right)_{\Delta V_g = 0} \Delta V_p + \left(\frac{\Delta i_p}{\Delta V_g}\right)_{\Delta V_p = 0} \Delta V_g$$

$$= \frac{1}{r_p}\Delta V_p + g_m\, \Delta V_g. \quad \dots (41.7)$$

Amplification factor

If the grid voltage is increased, the plate current i_p also increases. One can bring the current back to i_p by decreasing the plate voltage V_p. The *amplification factor* μ is defined as

$$\mu = -\left(\frac{\Delta V_p}{\Delta V_g}\right)_{\Delta i_p = 0}. \quad \dots (41.8)$$

The negative sign is put in the definition because if the grid voltage is increased, one should decrease the plate voltage so as to maintain the same current. Thus, ΔV_p and ΔV_g are of opposite signs so that the definition makes μ positive. This same μ is used in equation (41.4).

From equation (41.7), if $\Delta i_p = 0$,

$$-\frac{\Delta V_p}{\Delta V_g} = \frac{g_m}{1/r_p}$$

or, $$\mu = r_p \times g_m. \qquad \dots (41.9)$$

41.8 TRIODE AS AN AMPLIFIER

We have seen that a small change in the grid voltage leads to a large change in the plate current. This fact is used for amplification of small signals. Figure (41.19) shows the basic circuit for amplification. A small fluctuating voltage v_s (from a microphone for example) is included in the grid circuit. This voltage is called the *signal*. The value v_s also gives the amount by which the grid voltage changes. Thus,

$$v_s = \Delta V_g.$$

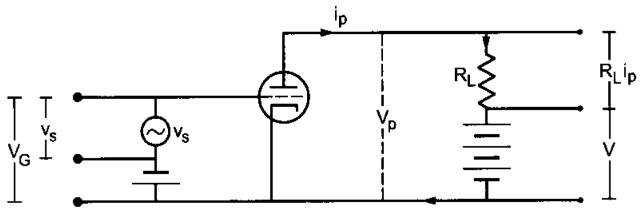


Figure 41.19

A load resistance R_L is included in the plate circuit. The value of V_g (with zero signal), and V_p are so adjusted that the operating point lies on the linear portion of the mutual characteristics (figure 41.18). As the signal v_s changes, the grid potential changes and consequently the plate current i_p changes. The voltage appearing across the load resistance also changes accordingly. Suppose that the signal is small enough so that the operating point always remains on the linear portion. The change in the voltage across the load resistance, then, follows the pattern of the signal but the amplitudes are much larger. The change in the voltage across the load resistance is called the *output voltage* v_0.

Thus,

$$v_0 = R_L \Delta i_p. \qquad \dots \text{(i)}$$

The ratio $A = \frac{v_0}{v_s}$ is called the *voltage-gain* or *gain factor*.

If V is the potential difference across the battery in the plate circuit, that across the triode is

$$V_p = V - R_L\, i_p$$

or, $$\Delta V_p = -R_L\, \Delta i_p = -v_0.$$

From equation (41.7),

$$\Delta i_p = \frac{\Delta V_p}{r_p} + g_m\, \Delta V_g$$

$$= -\frac{v_0}{r_p} + g_m\, v_s.$$

From (i), the output voltage is,

$$v_0 = R_L\, \Delta i_p$$

$$= -\frac{R_L v_0}{r_p} + R_L\, g_m\, v_s$$

or, $$v_0 \left[1 + \frac{R_L}{r_p} \right] = R_L\, g_m v_s$$

or, $$\frac{v_0}{v_s} = \frac{R_L\, g_m}{1 + \frac{R_L}{r_p}} = \frac{R_L\, g_m r_p}{r_p + R_L}$$

or, $$A = \frac{R_L\, \mu}{r_p + R_L} = \frac{\mu}{1 + \frac{r_p}{R_L}} \qquad \dots (41.10)$$

where $\mu = g_m r_p$ is the amplification factor.

Worked Out Examples

1. *The mean free path of the electrons in a discharge tube is* 20 cm. *The tube itself is* 10 cm *long. What is the length of the Crookes dark space ?*

Solution : The mean free path of the electrons is much longer than the length of the tube. Thus, the electrons, in general, do not collide in between, no ionization takes place and hence no light is emitted. The Crookes dark space fills the entire tube and hence is 10 cm long.

2. *Consider a cylindrical tube closed at one end and fitted with a conducting, movable piston at the other end. A cathode is fixed in the tube near the closed end and an anode is fixed with the piston. A gas is filled in the tube at pressure p. Using Paschen equation V = f(pd), show that the sparking potential does not change as the piston is slowly moved in or out. Assume that the temperature does not change in the process.*

Solution : As the piston is moved, the volume of the gas and hence its pressure changes. As the tube is cylindrical, the volume is proportional to the length of the tube. From Boyle's law, pd = constant and hence the sparking potential does not change as the piston is moved.

3. *The number of thermions emitted in a given time increases* 100 *times as the temperature of the emitting surface is increased from* 600 K *to* 800 K. *Find the work function of the emitter. Boltzmann constant* $k = 8{\cdot}62 \times 10^{-5}$ eV K^{-1}.

Solution : The number of thermions n, emitted by a surface, in a given time is given by (Richardson–Dushman equation)

$$n = A'ST^2 e^{-\varphi/kT}$$

where A' is a constant and other symbols have their usual meanings. Let n_1 and n_2 be the number of electrons emitted at temperatures T_1 and T_2. Then

$$\frac{n_1}{n_2} = \frac{T_1^2 \, e^{-\varphi/kT_1}}{T_2^2 \, e^{-\varphi/kT_2}}$$

or, $$\frac{n_1 T_2^2}{n_2 T_1^2} = e^{-\frac{\varphi}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)}$$

or, $$-\frac{\varphi}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) = \ln \frac{n_1 T_2^2}{n_2 T_1^2}$$

or, $$\frac{\varphi(T_2 - T_1)}{kT_1T_2} = \ln \frac{n_2 T_1^2}{n_1 T_2^2}$$

or, $$\varphi = \frac{kT_1 T_2}{T_2 - T_1} \ln \frac{n_2 T_1^2}{n_1 T_2^2}$$

$$= \frac{(8{\cdot}62 \times 10^{-5}\ \text{eV K}^{-1})(600\ \text{K})(800\ \text{K})}{200\ \text{K}} \ln\left(100 \times \frac{36}{64}\right)$$

$$= 0{\cdot}83\ \text{eV}.$$

4. *The constant A in the Richardson–Dushman equation is* 60×10^4 A m^{-2}K^{-2} *for tungsten. A tungsten cathode has a total surface area of* $2{\cdot}0 \times 10^{-5}$ m^2 *and operates at* 2000 K. *The work function of tungsten is* 4·55 eV. *Calculate the electric current due to thermionic emission.*

Solution :

The Richardson–Dushman equation is

$$i = AST^2 e^{-\varphi/kT}.$$

We have, $$\frac{\varphi}{kT} = \frac{4{\cdot}55\ \text{eV}}{(8{\cdot}62 \times 10^{-5}\ \text{eV K}^{-1})\ (2000\ \text{K})}$$

$$= 26{\cdot}4.$$

Thus, the thermionic current i is

$$= 60 \times 10^4\ \text{A m}^{-2}\text{K}^{-2} \times (2{\cdot}0 \times 10^{-5}\ \text{m}^2) \times (2000\ \text{K})^2 \times e^{-26{\cdot}4}$$

$$= (4{\cdot}8 \times 10^5\ \text{A})\ e^{-26{\cdot}4} = 0{\cdot}16\ \text{mA}.$$

5. *Calculate the saturation thermionic current if* 120 W *is applied to a thoriated-tungsten filament of surface area* 1·0 cm^2. *Assume that the surface radiates like a blackbody. The required constants are*

$A = 3 \times 10^4$ A m^{-2}–K^2, $\varphi = 2{\cdot}6$ eV, $k = 8{\cdot}62 \times 10^{-5}$ eV K^{-1} *and* $\sigma = 6 \times 10^{-8}$ W m^{-2}K^{-4}.

Solution : The thermionic current is given by the Richardson–Dushman equation

$$i = AST^2 e^{-\varphi/kT}. \qquad \text{... (i)}$$

When the power input to the filament equals the power radiated, the temperature becomes constant. The thermionic current then becomes saturated. The power radiated is given by the Stefan's law

$$P = S\sigma T^4$$

or, $120\ \text{W} = (1{\cdot}0 \times 10^{-4}\ \text{m}^2) \times (6 \times 10^{-8}\ \text{W m}^{-2}\text{K}^{-4}) \times T^4$

or, $T = 2114$ K.

Now $$\frac{\varphi}{kT} = \frac{2{\cdot}6\ \text{eV}}{(8{\cdot}62 \times 10^{-5}\ \text{eV K}^{-1})\ (2114\ \text{K})} = 14{\cdot}26.$$

Putting in (i),

$$i = 3 \times 10^4\ \text{A m}^{-2}\text{K}^{-2} \times (1{\cdot}0 \times 10^{-4}\ \text{m}^2)\ (2114\ \text{K})^2\ e^{-14{\cdot}26}$$

$$= (1{\cdot}34 \times 10^7\ \text{A})\ e^{-14{\cdot}26} = 8{\cdot}6\ \text{A}.$$

6. *In a Millikan-type oil-drop experiment, the plates are* 8 mm *apart. An oil drop is found to remain at rest when the upper plate is at a potential* 136 V *higher than that of the lower one. When the electric field is switched off, the drop is found to fall a distance of* 2·0 mm *in* 36 seconds *with a uniform speed. Find (a) the charge on the drop and (b) the number of electrons attached to this drop. Density of oil* = 880 kg m^{-3} *and coefficient of viscosity of air* = 180 µpoise.

Solution : (a) The charge on the drop is

$$q = \frac{18\pi}{E}\sqrt{\frac{\eta^3 v^3}{2(\rho - \sigma)g}}. \qquad \text{... (i)}$$

Here $$E = \frac{136\ \text{V}}{8 \times 10^{-3}\ \text{m}} = 1{\cdot}7 \times 10^4\ \text{V m}^{-1}$$

$$\eta = 180\ \mu\text{poise} = 1{\cdot}8 \times 10^{-5}\ \text{N sm}^{-2}$$

$$v = \frac{2{\cdot}0\ \text{mm}}{36\ \text{s}} = \frac{1}{18} \times 10^{-3}\ \text{m s}^{-1}$$

and $\rho = 880$ kg m^{-3}.

The density of air σ (1·29 kg m^{-3}) may be neglected in comparison to that of the oil. Putting values in (i),

$$q = 7{\cdot}93 \times 10^{-19}\ \text{C}.$$

(b) The number of electrons attached to the drop is,

$$n = \frac{7.93 \times 10^{-19}\ \text{C}}{1.6 \times 10^{-19}\ \text{C}} = 4.96.$$

It is clear that 5 electrons are attached to the drop.

7. *Show that the dynamic plate resistance of a diode is* $\frac{2V}{3i}$ *where V and i are the plate voltage and the plate current respectively. Assume Langmuir–Child equation to hold.*

Solution :

The dynamic plate resistance of the diode is $R = \frac{dV}{di}$.

The Langmuir–Child equation is

$$i = cV^{3/2} \quad \text{... (i)}$$

where c is a constant for a given diode. This gives

$$\frac{di}{dV} = \frac{3}{2} cV^{1/2}. \quad \text{... (ii)}$$

Dividing (ii) by (i), $\frac{1}{i}\frac{di}{dV} = \frac{3}{2V}$

or, $$\frac{dV}{di} = \frac{2V}{3i}.$$

8. *The mutual conductance of a triode valve is* 2·5 millimho. *Find the change in the plate current if the grid voltage is changed from* –2·0 V *to* –4·5 V.

Solution :

The mutual conductance of a triode valve is

$$g_m = \left[\frac{\Delta i_p}{\Delta V_g}\right]_{\Delta V_p = 0}$$

or, $$\Delta i_p = g_m \Delta V_g$$

$$= (2.5 \times 10^{-3}\ \Omega^{-1}) \times (-4.5\ \text{V} + 2.0\ \text{V})$$

$$= -6.25 \times 10^{-3}\ \text{A}.$$

9. *A triode valve has amplification factor* 21 *and dynamic plate resistance* 10 kΩ. *This is used as an amplifier with a load of* 20 kΩ. *Find the gain factor of the amplifier.*

Solution :

The gain factor of a triode valve amplifier is

$$A = \frac{\mu}{1 + \frac{r_p}{R_L}}$$

where μ is the amplification factor, r_p is the plate resistance and R_L is the load resistance. Thus,

$$A = \frac{21}{1 + \frac{10\ \text{k}\Omega}{20\ \text{k}\Omega}} = 14.$$

□

QUESTIONS FOR SHORT ANSWER

1. Why is conduction easier in gases if the pressure is low ? Will the conduction continue to improve if the pressure is made as low as nearly zero ?
2. An AC source is connected to a diode and a resistor in series. Is the current through the resistor AC or DC ?
3. How will the thermionic current vary if the filament current is increased ?
4. Would you prefer a material having a high melting point or a low melting point to be used as a cathode in a diode ?
5. Would you prefer a material having a high work function or a low work function to be used as a cathode in a diode ?
6. An isolated metal sphere is heated to a high temperature. Will it become positively charged due to thermionic emission ?
7. A diode valve is connected to a battery and a load resistance. The filament is heated so that a constant current is obtained in the circuit. As the cathode continuously emits electrons, does it get more and more positively charged ?
8. Why does thermionic emission not take place in nonconductors ?
9. The cathode of a diode valve is replaced by another cathode of double the surface area. Keeping the voltage and temperature conditions the same, will the plate current decrease, increase or remain the same ?
10. Why is the linear portion of the triode characteristic chosen to operate the triode as an amplifier ?

OBJECTIVE I

1. Cathode rays constitute a stream of
(a) electrons (b) protons
(c) positive ions (d) negative ions.

2. Cathode rays are passing through a discharge tube. In the tube, there is
(a) an electric field but no magnetic field

(b) a magnetic field but no electric field
(c) an electric as well as a magnetic field
(d) neither an electric nor a magnetic field.

3. Let i_0 be the thermionic current from a metal surface when the absolute temperature of the surface is T_0. The temperature is slowly increased and the thermionic current is measured as a function of temperature. Which of the following plots may represent the variation in (i/i_0) against (T/T_0)?

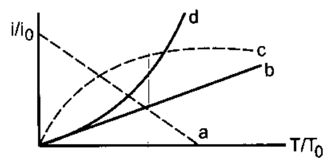


Figure 41-Q1

4. When the diode shows saturated current, dynamic plate resistance is
(a) zero (b) infinity
(c) indeterminate (d) different for different diodes.

5. The anode of a thermionic diode is connected to the negative terminal of a battery and the cathode to its positive terminal.
(a) No appreciable current will pass through the diode.
(b) A large current will pass through the diode from the anode to the cathode.
(c) A large current will pass through the diode from the cathode to the anode.
(d) The diode will be damaged.

6. A diode, a resistor and a 50 Hz AC source are connected in series. The number of current pulses per second through the resistor is
(a) 25 (b) 50 (c) 100 (d) 200.

7. A triode is operated in the linear region of its characteristics. If the plate voltage is slightly increased, the dynamic plate resistance will
(a) increase (b) decrease
(c) remain almost the same
(d) become zero.

8. The plate current in a triode valve is maximum when the potential of the grid is
(a) positive (b) zero (c) negative (d) nonpositive.

9. The amplification factor of a triode operating in the linear region depends strongly on
(a) the temperature of the cathode
(b) the plate potential (c) the grid potential
(d) the separations of the grid from the cathode and the anode.

OBJECTIVE II

1. Electric conduction takes place in a discharge tube due to the movement of
(a) positive ions (b) negative ions
(c) electrons (d) protons.

2. Which of the following are true for cathode ray?
(a) It travels along straight lines.
(b) It emits X-ray when strikes a metal.
(c) It is an electromagnetic wave.
(d) It is not deflected by magnetic field.

3. Because of the space charge in a diode valve,
(a) the plate current decreases
(b) the plate voltage increases
(c) the rate of emission of thermions increases
(d) the saturation current increases.

4. The saturation current in a triode valve can be changed by changing
(a) the grid voltage (b) the plate voltage
(c) the separation between the grid and the cathode
(d) the temperature of the cathode.

5. Mark the correct options.
(a) A diode valve can be used as a rectifier.
(b) A triode valve can be used as a rectifier.
(c) A diode valve can be used as an amplifier.
(d) A triode valve can be used as an amplifier.

6. The plate current in a diode is zero. It is possible that
(a) the plate voltage is zero
(b) the plate voltage is slightly negative
(c) the plate voltage is slightly positive
(d) the temperature of the filament is low.

7. The plate current in a triode valve is zero. The temperature of the filament is high. It is possible that
(a) $V_g > 0,\ V_p > 0$ (b) $V_g > 0,\ V_p < 0$
(c) $V_g < 0,\ V_p > 0$ (d) $V_g < 0,\ V_p < 0$.

EXERCISES

1. A discharge tube contains helium at a low pressure. A large potential difference is applied across the tube. Consider a helium atom that has just been ionized due to the detachment of an atomic electron. Find the ratio of the distance travelled by the free electron to that by the positive ion in a short time dt after the ionization.

2. A molecule of a gas, filled in a discharge tube, gets ionized when an electron is detached from it. An electric field of $5{\cdot}0\ \mathrm{kV\ m^{-1}}$ exists in the vicinity of the event. (a) Find the distance travelled by the free electron in $1\ \mu s$ assuming no collision. (b) If the mean free path of the electron is $1{\cdot}0$ mm, estimate the time of transit of the free electron between successive collisions.

3. The mean free path of electrons in the gas in a discharge tube is inversely proportional to the pressure inside it. The Crookes dark space occupies half the length of the discharge tube when the pressure is 0·02 mm of mercury. Estimate the pressure at which the dark space will fill the whole tube.
4. Two discharge tubes have identical material structure and the same gas is filled in them. The length of one tube is 10 cm and that of the other tube is 20 cm. Sparking starts in both the tubes when the potential difference between the cathode and the anode is 100 V. If the pressure in the shorter tube is 1·0 mm of mercury, what is the pressure in the longer tube?
5. Calculate $n(T)/n(1000\text{ K})$ for tungsten emitter at T = 300 K, 2000 K and 3000 K where $n(T)$ represents the number of thermions emitted per second by the surface at temperature T. Work function of tungsten is 4·52 eV.
6. The saturation current from a thoriated-tungsten cathode at 2000 K is 100 mA. What will be the saturation current for a pure-tungsten cathode of the same surface area operating at the same temperature? The constant A in the Richardson–Dushman equation is $60 \times 10^4 \text{ A m}^{-2}\text{K}^{-2}$ for pure tungsten and $3·0 \times 10^4 \text{ A m}^{-2}\text{K}^{-2}$ for thoriated tungsten. The work function of pure tungsten is 4·5 eV and that of thoriated tungsten is 2·6 eV.
7. A tungsten cathode and a thoriated-tungsten cathode have the same geometrical dimensions and are operated at the same temperature. The thoriated-tungsten cathode gives 5000 times more current than the other one. Find the operating temperature. Take relevant data from the previous problem.
8. If the temperature of a tungsten filament is raised from 2000 K to 2010 K, by what factor does the emission current change? Work function of tungsten is 4·5 eV.
9. The constant A in the Richardson–Dushman equation for tungsten is $60 \times 10^4 \text{ A m}^{-2} \text{ K}^{-2}$. The work function of tungsten is 4·5 eV. A tungsten cathode having a surface area $2·0 \times 10^{-5} \text{ m}^2$ is heated by a 24 W electric heater. In steady state, the heat radiated by the cathode equals the energy input by the heater and the temperature becomes constant. Assuming that the cathode radiates like a blackbody, calculate the saturation current due to thermions. Take Stefan constant $= 6 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$. Assume that the thermions take only a small fraction of the heat supplied.
10. A plate current of 10 mA is obtained when 60 volts are applied across a diode tube. Assuming the Langmuir–Child equation $i_p \propto V_p^{3/2}$ to hold, find the dynamic resistance r_p in this operating condition.
11. The plate current in a diode is 20 mA when the plate voltage is 50 V or 60 V. What will be the current if the plate voltage is 70 V?
12. The power delivered in the plate circuit of a diode is 1·0 W when the plate voltage is 36 V. Find the power delivered if the plate voltage is increased to 49 V. Assume Langmuir–Child equation to hold.
13. A triode valve operates at $V_p = 225$ V and $V_g = -0·5$ V. The plate current remains unchanged if the plate voltage is increased to 250 V and the grid voltage is decreased to $-2·5$ V. Calculate the amplification factor.
14. Calculate the amplification factor of a triode valve which has plate resistance of 2 kΩ and transconductance of 2 millimho.
15. The dynamic plate resistance of a triode valve is 10 kΩ. Find the change in the plate current if the plate voltage is changed from 200 V to 220 V.
16. Find the values of r_p, μ and g_m of a triode operating at plate voltage 200 V and grid voltage −6 V. The plate characteristics are shown in figure (41-E1).

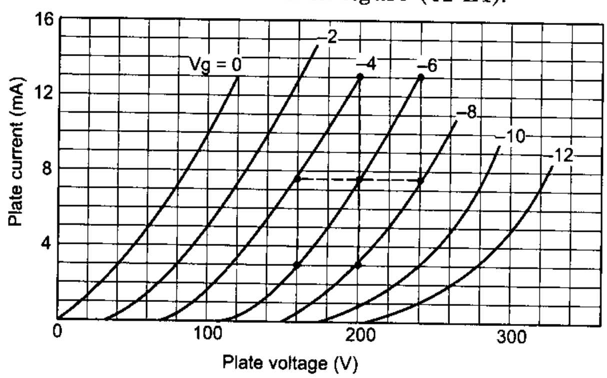


Figure 41-E1

17. The plate resistance of a triode is 8 kΩ and the transconductance is 2·5 millimho. (a) If the plate voltage is increased by 48 V, and the grid voltage is kept constant, what will be the increase in the plate current? (b) With plate voltage kept constant at this increased value, how much should the grid voltage be decreased in order to bring the plate current back to its initial value?
18. The plate resistance and the amplification factor of a triode are 10 kΩ and 20. The tube is operated at plate voltage 250 V and grid voltage −7·5 V. The plate current is 10 mA. (a) To what value should the grid voltage be changed so as to increase the plate current to 15 mA? (b) To what value should the plate voltage be changed to take the plate current back to 10 mA?
19. The plate current, plate voltage and grid voltage of a 6F6 triode tube are related as

$$i_p = 41(V_p + 7\,V_g)^{1·41}$$

where V_p and V_g are in volts and i_p in microamperes. The tube is operated at $V_p = 250$ V, $V_g = -20$ V. Calculate (a) the tube current, (b) the plate resistance, (c) the mutual conductance and (d) the amplification factor.
20. The plate current in a triode can be written as

$$i_p = k\left(V_g + \frac{V_p}{\mu}\right)^{3/2}.$$

Show that the mutual conductance is proportional to the cube root of the plate current.
21. A triode has mutual conductance = 2·0 millimho and plate resistance = 20 kΩ. It is desired to amplify a signal by a factor of 30. What load resistance should be added in the circuit?

22. The gain factor of an amplifier is increased from 10 to 12 as the load resistance is changed from 4 kΩ to 8 kΩ. Calculate (a) the amplification factor and (b) the plate resistance.

23. Figure (41-E2) shows two identical triode tubes connected in parallel. The anodes are connected together, the grids are connected together and the cathodes are connected together. Show that the equivalent plate resistance is half of the individual plate resistance, the equivalent mutual conductance is double the individual mutual conductance and the equivalent amplification factor is the same as the individual amplification factor.

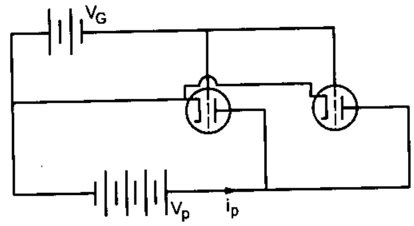


Figure 41-E2

ANSWERS

OBJECTIVE I

1. (a)	2. (c)	3. (d)	4. (b)	5. (a)	6. (b)
7. (c)	8. (a)	9. (d)			

OBJECTIVE II

1. (a), (b), (c)	2. (a), (b)	3. (a)
4. (d)	5. (a), (b), (d)	6. all
7. (b), (c), (d)		

EXERCISES

1. 7340
2. (a) 440 m (b) 1·5 ns
3. 0·01 mm of mercury
4. 0·5 mm of mercury
5. $6{\cdot}57 \times 10^{-55}$, $9{\cdot}73 \times 10^{11}$, $1{\cdot}37 \times 10^{16}$
6. 33 μA
7. 1914 K
8. 1·14
9. 1·0 mA
10. 4 kΩ
11. 20 mA
12. 2·2 W
13. 12·5
14. 4
15. 2 mA
16. 8·0 kΩ, 20 and 2·5 millimho
17. (a) 6 mA (b) 2·4 V
18. (a) –5·0 V (b) 200 V
19. (a) 30 mA (b) 2·53 kΩ (c) 2·77 millimho (d) 7
21. 60 kΩ
22. (a) 15 (b) 2 kΩ