Contents

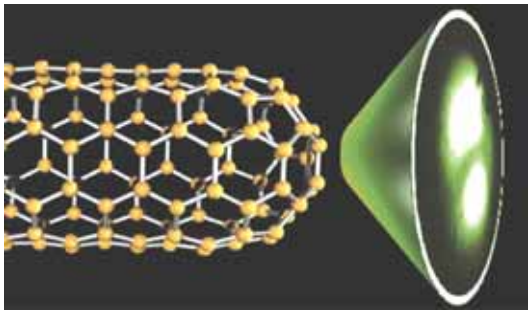
2

Electron Emission

2.1 Electron Emission
2.2 Types of Electron Emission
2.3 Thermionic Emission
2.4 Thermionic Emitter
2.5 Commonly Used Thermionic Emitters
2.6 Cathode Construction
2.7 Field Emission
2.8 Secondary Emission
2.9 Photo Electric Emission

INTRODUCTION

The reader is familiar with the current conduction (*i.e.* flow of electrons) through a conductor. The valence electrons of the conductor atoms are loosely bound to the atomic nuclei. At room temperature, the thermal energy in the conductor is adequate to break the bonds of the valence electrons and leave them unattached to any one nucleus. These unbound electrons move at random within the conductor and are known as *free electrons*. If an electric field is applied across the conductor, these free electrons move through the conductor in an orderly manner, thus constituting electric current. This is how these free electrons move through the conductor or electric current flows through a wire.



Electron Emission

Many electronic devices depend for their operation on the movement of electrons in an evacuated space. For this purpose, the free electrons must be ejected from the surface of metallic con-

ductor by supplying sufficient energy from some external source. This is known as *electron emission*. The emitted electrons can be made to move in vacuum under the influence of an electric field, thus constituting electric current in vacuum. In this chapter, we shall confine our attention to the various aspects of electron emission.

2.1 Electron Emission

The liberation of electrons from the surface of a substance is known as **electron emission.**

For electron emission, metals are used because they have many free electrons. If a piece of metal is investigated at room temperature, the random motion of free electrons is as shown in Fig. 2.1. However, these electrons are free only to the extent that they may transfer from one atom to another within the metal but they cannot leave the metal surface to provide electron emission. It is because the free electrons that start at the surface of metal find behind them positive nuclei pulling them back and none pulling forward. Thus at the surface of a metal, a free electron encounters forces that prevent it to leave the metal. In other words, the metallic surface offers a barrier to free electrons and is known as *surface barrier*.

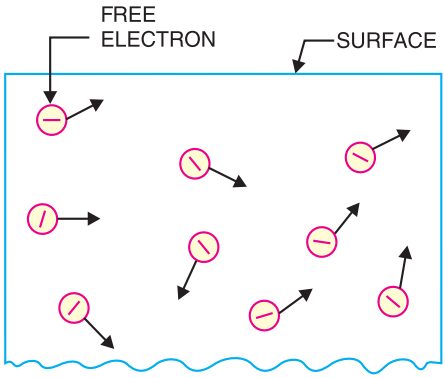


Fig. 2.1

However, if sufficient external energy is given to the free electron, its kinetic energy is increased and thus electron will cross over the surface barrier to leave the metal. This additional energy required by an electron to overcome the surface barrier of the metal is called *work function* of the metal.

The amount of additional energy required to emit an electron from a metallic surface is known as **work function** *of that metal*.

Thus, if the total energy required to liberate an electron from a metal is 4 eV* and the energy already possessed by the electron is 0.5 eV, then additional energy required (*i.e.*, work function) is 4.0– 0.5 = 3.5 eV. The work function of pure metals varies roughly from 2 to 6 eV. It depends upon the nature of metal, its purity and the conditions of its surface. It may be noted that it is desirable that metal used for electron emission should have low work function so that a small amount of energy is required to cause emission of electrons.

2.2 Types of Electron Emission

The electron emission from the surface of a metal is possible only if sufficient additional energy (*equal to the work function of the metal*) is supplied from some external source. This external energy may come from a variety of sources such as heat energy, energy stored in electric field, light energy or kinetic energy of the electric charges bombarding the metal surface. Accordingly, there are following four principal methods of obtaining electron emission from the surface of a metal :

* Work function is the additional energy required for the liberation of electrons. Therefore, it should have the conventional unit of energy *i.e.* joules. But this unit is very large for computing electronics work. Therefore, in practice, a smaller unit called *electron volt* (abbreviated as eV) is used.

One electron-volt is the amount of energy acquired by an electron when it is accelerated through a potential difference of 1 V.

Thus, if an electron moves from a point of 0 potential to a point of +10V, then amount of energy acquired by the electron is 10 eV.

Since charge on an electron $= 1.602 \times 10^{-19}$ C and voltage = 1 V,

$\therefore$ 1 electron-volt $= Q\,V = (1.602 \times 10^{-19}) \times 1$ J

or 1 eV $= 1.602 \times 10^{-19}$ J

(*i*) Thermionic emission. In this method, the metal is heated to sufficient temperature (about 2500°C) to enable the free electrons to leave the metal surface. The number of electrons emitted depends upon the temperature. The higher the temperature, the greater is the emission of electrons. This type of emission is employed in vacuum tubes.

(*ii*) Field emission. In this method, a strong electric field (*i.e.* a high positive voltage) is applied at the metal surface which pulls the free electrons out of metal because of the attraction of positive field. The stronger the electric field, the greater is the electron emission.

(*iii*) Photo-electric emission. In this method, the energy of light falling upon the metal surface is transferred to the free electrons within the metal to enable them to leave the surface. The greater the intensity (*i.e.* brightness) of light beam falling on the metal surface, the greater is the photo-electric emission.

(*iv*) Secondary emission. In this method, a high velocity beam of electrons strikes the metal surface and causes the free electrons of the metal to be knocked out from the surface.

2.3 Thermionic Emission

The process of electron emission from a metal surface by supplying thermal energy to it is known as **thermionic emission**.

At ordinary temperatures, the energy possessed by free electrons in the metal is inadequate to cause them to escape from the surface. When heat is applied to the metal, some of heat energy is converted into kinetic energy, causing accelerated motion of free electrons. When the temperature rises sufficiently, these electrons acquire additional energy equal to the work function of the metal. Consequently, they overcome the restraining surface barrier and leave the metal surface.

Metals *with lower work function* will require less additional energy and, therefore, will emit electrons at lower temperatures. The commonly used materials for electron emission are *tungsten, thoriated tungsten* and *metallic oxides of barium and strontium*. It may be added here that high temperatures are necessary to cause thermionic emission. For example, pure tungsten must be heated to about 2300°C to get electron emission. However, oxide coated emitters need only 750°C to cause thermionic emission.

Richardson-Dushman equation. The amount of thermionic emission increases rapidly as the emitter temperature is raised. The emission current density is given by Richardson-Dushman equation given below :

$$J_s = A T^2 e^{-\frac{b}{T}} \text{ amp/m}^2 \qquad ...(i)$$

where J_s = emission current density *i.e.* current per square metre of the emitting surface

T = absolute temperature of emitter in K

A = constant, depending upon the type of emitter and is measured in amp/m^2/K^2

b = a constant for the emitter

e = natural logarithmic base

The value of b is constant for a metal and is given by :

$$b = \frac{\phi e}{k}$$

where ϕ = work function of emitter

e = electron charge = 1.602×10^{-19} coulomb

k = Boltzmann's constant = 1.38×10^{-23} J/K

$$\therefore \quad b = \frac{\phi \times 1.602 \times 10^{-19}}{1.38 \times 10^{-23}} = 11600\, \phi \text{ K}$$

Putting the value of b in exp. (i), we get,

$$J_s = AT^2 e^{-\frac{11600\,\phi}{T}} \qquad ...(ii)$$

The following points may be noted from eqn. (ii) :

(*i*) The emission is markedly affected by temperature changes. Doubling the temperature of an emitter may increase electron emission by more than 10^7 times. For instance, emission from pure tungsten metal is about 10^{-6} ampere per sq. cm. at 1300°C but rises to enormous value of about 100 amperes when temperature is raised to 2900°C.

(*ii*) Small changes in the work function of the emitter can produce enormous effects on emission. Halving the work function has exactly the same effect as doubling the temperature.

Example 2.1. *A tungsten filament consists of a cylindrical cathode 5 cm long and 0.01 cm in diameter. If the operating temperature is 2500 K, find the emission current. Given that* $A = 60.2 \times 10^4$ *A/m*^{2} */ K*^{2}, $\phi = 4.517$ *eV.*

Solution. $A = 60.2 \times 10^4$ amp/m^2/K^2, $T = 2500$ K, $\phi = 4.517$ eV

$\therefore$ $b = 11600\,\phi\,\text{K} = 11600 \times 4.517\ \text{K} = 52400\ \text{K}$

Using Richardson-Dushman equation, emission current density is given by :

$$J_s = AT^2 e^{-\frac{b}{T}}\ \text{amp/m}^2 = 60.2 \times 10^4 \times (2500)^2 \times (2.718)^{-\frac{52400}{2500}}$$

$$= 0.3 \times 10^4\ \text{amp/m}^2$$

Surface area of cathode, $a = \pi\, d\, l = 3.146 \times 0.01 \times 5 = 0.157\ \text{cm}^2 = 0.157 \times 10^{-4}\ \text{m}^2$

$\therefore$ Emission current $= J_s \times a = (0.3 \times 10^4) \times (0.157 \times 10^{-4}) =$ **0.047 A**

Example 2.2. *A tungsten wire of unknown composition emits 0.1 amp/cm*^{2} *at a temperature of 1900 K. Find the work function of tungsten filament. Determine whether the tungsten is pure or contaminated with substance of lower work function. Given that A = 60.2 amp/cm*^{2}*/K*^{2}.

Solution. $J_s = 0.1$ amp/cm^2 ; $A = 60.2$ amp/cm^2/K^2 ; $T = 1900$ K

Let ϕ electron-volt be the work function of the filament.

$\therefore$ $b = 11600\,\phi$ K

Using Richardson-Dushman equation, emission current density is given by :

$$J_s = AT^2 e^{-\frac{b}{T}}\ \text{amp/cm}^2$$

or $$0.1 = 60.2 \times (1900)^2 \times e^{-\frac{11600\,\phi}{1900}}$$

or $$e^{-\frac{11600\,\phi}{1900}} = \frac{0.1}{60.2 \times (1900)^2} = 4.6 \times 10^{-10}$$

or $$e^{-6.1\,\phi} = 4.6 \times 10^{-10}$$

or $$-6.1\,\phi \log_e e = \log_e 4.6 - 10 \log_e 10$$

or $$-6.1\,\phi = 1.526 - 23.02$$

$\therefore$ $$\phi = \frac{1.526 - 23.02}{-6.1} =$$ **3.56 eV**

Since the work function of pure tungsten is 4.52 eV, the sample must be contaminated. Thoriated tungsten has a work function ranging from 2.63 eV to 4.52 eV, depending upon the percentage of metallic thorium. Therefore, the sample is most likely to be thoriated tungsten.

2.4 Thermionic Emitter

Thermionic Emitter

The substance used for electron emission is known as an *emitter* or *cathode*. The cathode is heated in an evacuated space to emit electrons. If the cathode were heated to the required temperature in open air, it would burn up because of the presence of oxygen in the air. A cathode should have the following properties:

(*i*) Low work function. The substance selected as cathode should have low work function so that electron emission takes place by applying small amount of heat energy *i.e.* at low temperatures.

(*ii*) High melting point. As electron emission takes place at very high temperatures (>1500ºC), therefore, the substance used as a cathode should have high melting point. For a material such as copper, which has the advantage of a low work function, it is seen that it cannot be used as a cathode because it melts at 810ºC. Consequently, it will vaporise before it begins to emit electrons.

(*iii*) High mechanical strength. The emitter should have high mechanical strength to withstand the bombardment of positive ions. In any vacuum tube, no matter how careful the evacuation, there are always present some gas molecules which may form ions by impact with electrons when current flows. Under the influence of electric field, the positive ions strike the cathode. If high voltages are used, the cathode is subjected to considerable bombardment and may be damaged.

2.5 Commonly Used Thermionic Emitters

The high temperatures needed for satisfactory thermionic emission in vacuum tubes limit the number of suitable emitters to such substances as *tungsten, thoriated tungsten* and certain *oxide coated metals*.

Thoriated Tungsten

(*i*) Tungsten. It was the earliest material used as a cathode and has a slightly higher work function (4.52 eV). The important factors in its favour are : high melting point (3650 K), greater mechanical strength and longer life. The disadvantages are : high operating temperature (2500 K), high work function and low emission efficiency. Therefore, it is used in applications involving voltages exceeding 5 kV *e.g.* in X-ray tubes.

(*ii*) Thoriated tungsten. A mixture of two metals may have a lower work function than either of the pure metals alone. Thus, a tungsten emitter with a small quantity of thorium has a work function of 2.63 eV, compared with 3.4 eV for thorium and 4.52 eV for tungsten. At the same time, thoriated tungsten provides thermionic emission at lower temperature (1700ºC) with consequent reduction in the heating power required.

In the manufacture of this type of cathode, tungsten filament is impregnated with thorium oxide and heated to a very high temperature (1850ºC to 2500ºC). The thorium oxide is reduced to metallic thorium and coats the filament surface with a thin layer of thorium. Thoriated tungsten cathodes are used for intermediate power tubes at voltages between 500 to 5000 volts.

(*iii*) Oxide-coated cathode. The cathode of this *type consists of a nickel ribbon coated with

* Oxides of any alkaline-earth metal (*e.g.* calcium, strontium, barium etc.) have very good emission characteristics. In the manufacture of this type of emitter, the base metal (*e.g.* nickel) is first coated with a mixture of strontium and barium carbonates. It is then heated to a high temperature in vacuum glass tube until the carbonates decompose into oxides. By proper heating, a layer of oxides of barium and strontium is coated over the cathode surface to give oxide-coated emitter.

barium and strontium oxides. The oxide-coated cathode has low work function (1.1 eV), operates at comparatively low temperature (750ºC) and has high emission efficiency. However, the principal limitation of oxide-coated cathode is that it cannot withstand high voltages. Therefore, it is mostly used in receiving tubes or where voltages involved do not exceed 1000 volts.

S.No.	Emitter	Work Function	Operating temperature	Emission efficiency
1	*Tungsten*	4.52 eV	2327ºC	4 mA/watt
2	*Thoriated tungsten*	2.63 eV	1700ºC	60 mA/watt
3	*Oxide-coated*	1.1 eV	750ºC	200 mA/watt

2.6 Cathode Construction

As cathode is sealed in vacuum, therefore, the most convenient way to heat it is electrically. On this basis, the thermionic cathodes are divided into two types viz directly heated cathode and indirectly heated cathode.

(*i*) Directly heated cathode. In this type, the cathode consists of oxide-coated nickel ribbon, called the *filament. The heating current is directly passed through this ribbon which emits the electrons. Fig. 2.2 (*i*) shows the structure of directly heated cathode whereas Fig. 2.2 (*ii*) shows its symbol.

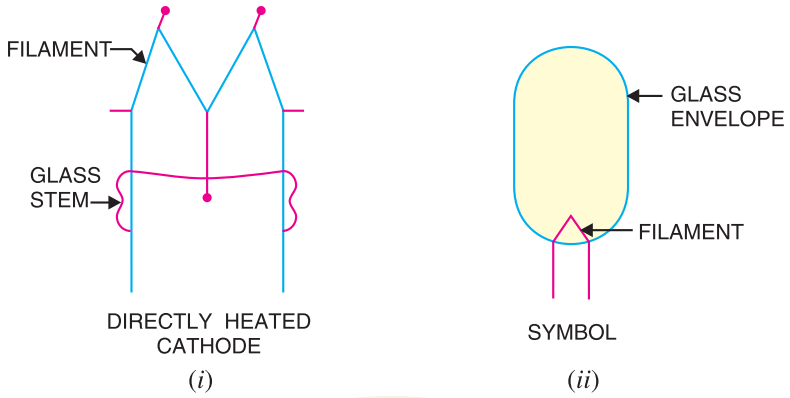


Fig. 2.2

The directly heated cathode is more efficient in converting heating power into thermionic emission. Therefore, it is generally used in power tubes that need large amounts of emission and in small tubes operated from batteries where efficiency and quick heating are important. The principal limitation of this type of cathode is that any variation in heater voltage affects the electron emission and thus produces *hum* in the circuit.

(*ii*) Indirectly heated cathode. In this type, the cathode consists of a thin metal sleeve coated with barium and strontium oxides. A filament or heater is enclosed within the sleeve and insulated from it. There is no electrical connection between the heater and the cathode. The heating current is passed through the heater and the cathode is heated indirectly through heat transfer from the heater element. Fig. 2.3 (*i*) shows the structure of indirectly heated cathode whereas Fig. 2.3 (*ii*) shows its symbol.

* ***Filament.*** The term filament (literally means a thin wire) denotes the element through which the cathode heating current flows. In case of directly heated, cathode is itself the filament. If indirectly heated, heater is the filament.

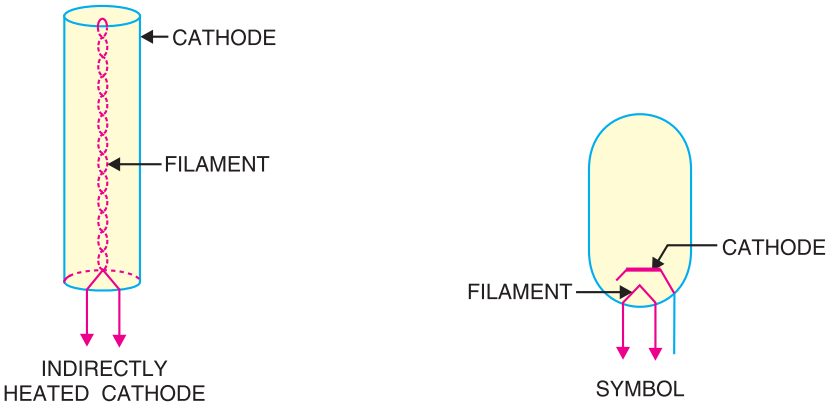


Fig. 2.3

Indirectly heated cathode has many advantages. As cathode is completely separated from the heating circuit, therefore, it can be readily connected to any desired potential as needed, independent of the heater potential. Furthermore, because of relatively large mass of cylindrical cathode, it takes time to heat or cool and as such does not introduce hum due to heater voltage fluctuations. Finally, a.c. can be used in the heater circuit to simplify the power requirements. Almost all modern receiving tubes use this type of cathode.

2.7 Field Emission

The process of electron emission by the application of strong electric field at the surface of a metal is known as **field emission.**

When a metal surface is placed close to a high voltage conductor which is positive *w.r.t.* the metal surface, the electric field exerts attractive force on the free electrons in the metal. If the positive potential is great enough, it succeeds in overcoming the restraining forces of the metal surface and the free electrons will be emitted from the metal surface as shown in Fig. 2.4.

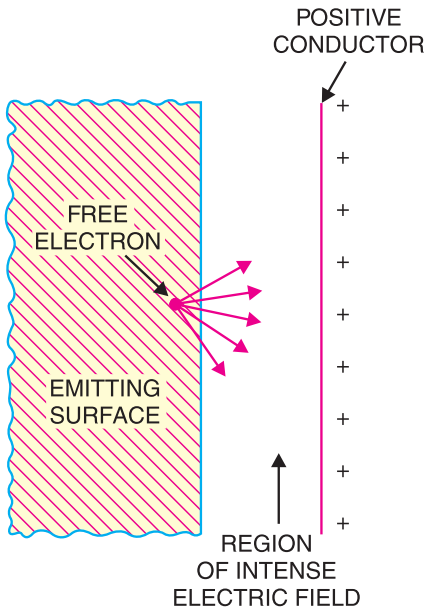


Fig. 2.4

Very intense electric field is required to produce field emission. Usually, a voltage of the order of a million volts per centimetre distance between the emitting surface and the positive conductor is necessary to cause field emission. Field emission can be obtained at temperatures much lower (*e.g.* room temperature) than required for thermionic emission and, therefore, it is also sometimes called *cold cathode emission* or *auto- electronic emission.*

2.8 Secondary Emission

Electron emission from a metallic surface by the bombardment of high-speed electrons or other particles is known as **secondary emission.**

When high-speed electrons suddenly strike a metallic surface, they may give some or all of their kinetic energy to the free electrons in the metal. If the energy of the striking electrons is sufficient, it may cause free electrons to escape from the metal surface. This phenomenon is called *secondary emission*. The electrons that strike the metal are called *primary electrons* while the emitted electrons are known as *secondary electrons*. The intensity of secondary emission depends upon the emitter material, mass and energy of the bombarding particles.

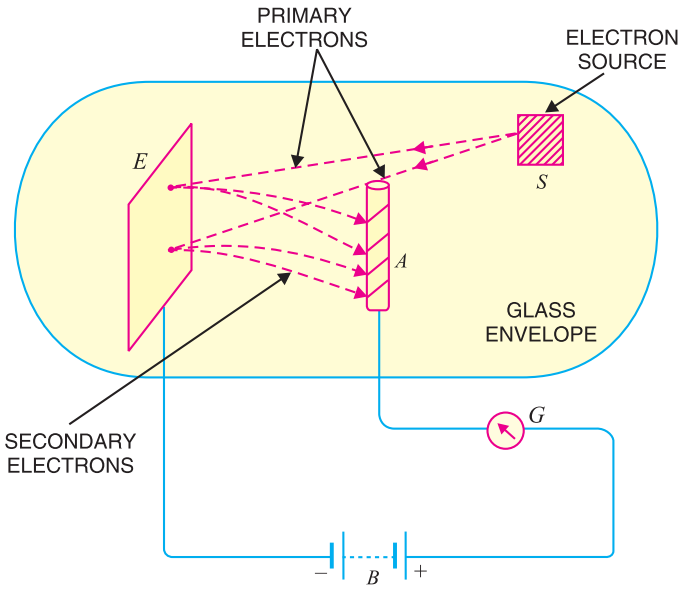


Fig. 2.5

The principle of secondary emission is illustrated in Fig. 2.5. An evacuated glass envelope contains an emitting surface *E*, the collecting anode *A* and a source of primary electrons *S*. The anode is maintained at positive potential *w.r.t.* the emitting surface by battery *B*. When the primary electrons strike the emitting surface *E*, they knock out secondary electrons which are attracted to the anode and constitute a flow of current. This current may be measured by connecting a sensitive galvanometer *G* in the anode circuit.

The effects of secondary emission are very undesirable in many electronic devices. For example, in a tetrode valve, secondary emission is responsible for the negative resistance. In some electronic devices, however, secondary emission effects are utilised *e.g.* *electron multiplier, cathode ray tube etc.

2.9 Photo Electric Emission

Electron emission from a metallic surface by the application of light is known as **photo electric emission.**

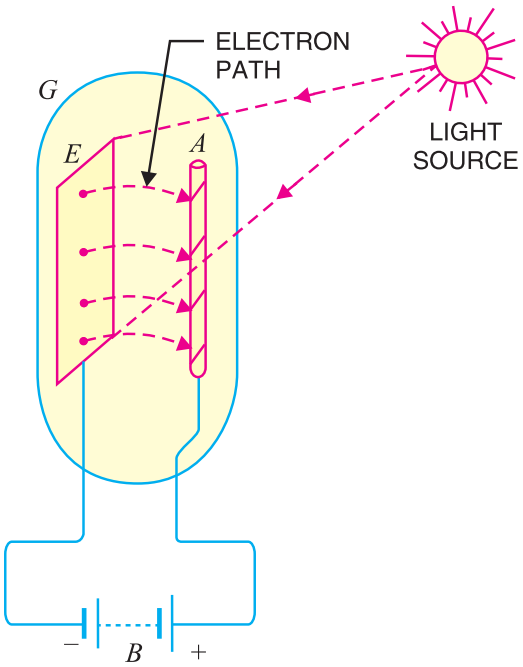


Fig. 2.6

When a beam of light strikes the surface of certain metals (*e.g.* potassium, sodium, cesium), the energy of photons of light is transferred to the free electrons within the metal. If the energy of the

* An interesting aspect of secondary emission is that a high-speed bombarding electron may liberate as many as 10 "secondary electrons". This amounts to a multiplication of electron flow by a ratio as great as 10 and is utilised in current multiplier devices.

striking photons is greater than the work function of the metal, then free electrons will be knocked out from the surface of the metal. The emitted electrons are known as *photo electrons* and the phenomenon is known as *photoelectric emission*. The amount of photoelectric emission depends upon the intensity of light falling upon the emitter and frequency of radiations. The greater the intensity and frequency of radiations, the greater is the photo electric emission. Photo-electric emission is utilised in photo tubes which form the basis of television and sound films.

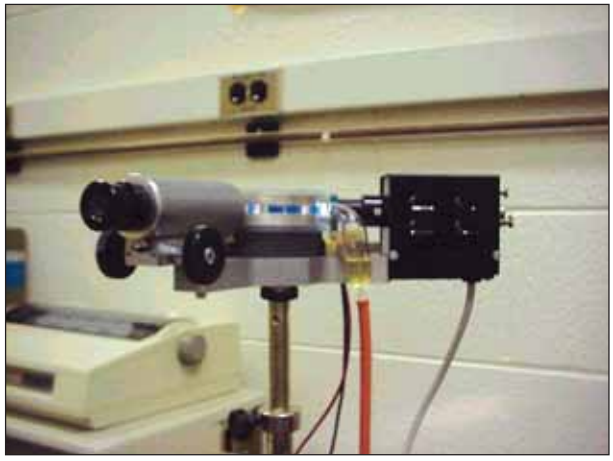


Photo Tube

Fig. 2.6 illustrates the phenomenon of photoelectric emission. The emitter *E* and anode *A* are enclosed in an evacuated glass envelope *G*. A battery *B* maintains the anode at positive potential w.r.t. emitter. When light of suitable intensity and frequency falls on the emitter, electrons are ejected from its surface. These electrons are attracted by the positive anode to constitute current in the circuit. It may be noted that current will exist in the circuit so long as illumination is maintained.

MULTIPLE-CHOICE QUESTIONS

1. Work function of metals is generally measured in .....
(*i*) joules (*ii*) electron-volt
(*iii*) watt-hour (*iv*) watt

2. The operating temperature of an oxide-coated emitter is about .....
(*i*) 750°C (*ii*) 1200°C
(*iii*) 2300°C (*iv*) 3650°C

3. ..... is used in high voltage (> 10 kV) applications.
(*i*) tungsten emitter
(*ii*) oxide-coated emitter
(*iii*) thoriated-tungsten emitter
(*iv*) none of the above

4. A desirable characteristic of an emitter is that it should have ..... work function.
(*i*) large (*ii*) very large
(*iii*) small (*iv*) none of the above

5. The thermionic emitter that has the highest operating temperature is .....
(*i*) oxide-coated (*ii*) thoriated-tungsten
(*iii*) tungsten (*iv*) none of the above

6. If the temperature of an emitter is increased two times, the electron emission is .....
(*i*) increased two times
(*ii*) increased four times
(*iii*) increased several million times
(*iv*) none of the above

7. In X-ray tubes, ... emitter is used.
(*i*) thoriated tungsten
(*ii*) tungsten
(*iii*) oxide-coated
(*iv*) none of the above

8. The life of an oxide-coated emitter is about .....
(*i*) 500 hours (*ii*) 1000 hours
(*iii*) 200 hours (*iv*) 10,000 hours

9. The electrons emitted by a thermionic emitter are called .....
(*i*) free electrons
(*ii*) loose electrons
(*iii*) thermionic electrons
(*iv*) bound electrons

10. The work function of an oxide-coated emitter is about .....

(*i*) 1.1 eV (*ii*) 4 eV

(*iii*) 2.63 eV (*iv*) 4.52 eV

11. The warm-up time of a directly heated cathode is ..... that of indirectly heated cathode.

(*i*) more than (*ii*) less than

(*iii*) same as (*iv*) data incomplete

12. The most commonly used emitter in the tubes of a radio receiver is .....

(*i*) tungsten (*ii*) thoriated-tungsten

(*iii*) oxide-coated (*iv*) none of the above

13. Field emission is utilised in .....

(*i*) vacuum tubes

(*ii*) TV picture tubes

(*iii*) gas-filled tubes

(*iv*) mercury pool devices

14. Oxide-coated emitters have electron emission of ..... per watt of heating power.

(*i*) 5-10 mA (*ii*) 40-90 mA

(*iii*) 50-100 mA (*iv*) 150-1000 mA

15. The oxide-coated cathodes can be used for voltages upto .....

(*i*) 1000 V (*ii*) 3000 V

(*iii*) 4000 V (*iv*) 10,000 V

Answers to Multiple-Choice Questions

1. (*ii*)	**2.** (*i*)	**3.** (*i*)	**4.** (*iii*)	**5.** (*iii*)
6. (*iii*)	**7.** (*ii*)	**8.** (*iv*)	**9.** (*iii*)	**10.** (*i*)
11. (*ii*)	**12.** (*iii*)	**13.** (*iv*)	**14.** (*iv*)	**15.** (*i*)

Chapter Review Topics

1. What is electron emission ? Explain the terms : surface barrier and work function.

2. What general conditions must be satisfied before an electron can escape from the surface of a material ?

3. Name and explain briefly four practical ways by which electron emission can occur.

4. What are the materials used for thermionic emitters ? Compare the relative merits of each.

5. Discuss briefly construction and relative advantages of directly and indirectly heated cathodes.

Problems

1. An oxide-coated emitter has a surface area of 0.157 cm^2. If the operating temperature is 110 K, find the emission current. Given A = 100 $A/m^2/K^2$, work function = 1.04 eV. **[0.0352 A]**

2. A tungsten filament of unknown composition emits 1000 A/m^2 at an operating temperature of 1900 K. Find the work function of tungsten filament. Given $A = 60.2 \times 10^4$ $A/m^2/K^2$. **[3.44 eV]**

3. Calculate the total emission available from barium-strontium oxide emitter, 10 cm long and 0.01 cm in diameter, operated at 1900 K. Given that $A = 10^{-12}$ $Amp/cm^2/K^2$ and b = 12,000. **[0.345 A]**

Discussion Questions

1. Why does electron emission not occur at room temperature ?

2. Why are high temperatures necessary for thermionic emission ?

3. Why are electron emitters heated electrically ?

4. Why are thermionic emitters heated in vacuum ?

5. Why are tungsten and thoriated tungsten cathodes always of directly heated type ?

6. Why cannot oxide-coated cathodes be used for voltages exceeding 1000 volts?

7. Why do directly heated cathodes introduce hum in the circuit ?

8. Why are directly heated cathodes used in high power applications ?

Top