UNIT 4 BASIC ELECTRONICS

Structure

4.1 INTRODUCTION

We begin this block with the study of electron emission and types of electron emission. Then we will discuss P-type semiconductor, N-type semiconductor, formation of PN junction and how biasing affects conduction in PN junction. After that we will proceed to characteristics of semiconductor diode and its applications in rectifiers.

In this unit, need of filter circuits in D.C. power supply system and different types of filters are also introduced.

Finally, Zener diode, Zener break-down mechanism, characteristics of Zener diode and Zener diode as voltage stabilizer are covered.

Objectives

After studying this unit, you should be able to

- explain electron emission, and define and calculate work function of metal,
- explain thermionic, field, secondary and photoelectric emission,
- distinguish among P-type, N-type semiconductors and PN junction,
- describe V-I characteristics of semiconductor diode and its uses in rectifiers,
- discuss the role of capacitor and choke coil in filter circuit, and
- describe V-I characteristics of Zener diode and Zener diode as voltage stabilizer.

4.2 ELECTRON EMISSION

4.2.1 Concept of Electron Emission and its Types

The phenomenon of emission of electrons from the surface of a substance is called as electron emission.

The amount of additional external energy required to emit an electron from a metallic surface is known as work function of that metal. It is usually denoted by "ϕ".

In SI system, unit of work function is joule. Since it is a very big unit to express electronic work function, practical unit of work function is taken as electron volt (eV)

Note

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

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

Types of Electron Emission

(a) Thermionic emission
(b) Field emission
(c) Secondary emission
(d) Photoelectric emission

4.2.2 Thermionic Emission

The phenomenon of electron emission from the surface of a metal by supplying external thermal energy to it is known as thermionic emission.

Explanation

At room temperature the energy possessed by free electrons in the metal is not enough to cause them to escape from the surface. When heat is applied to the metal, increase in kinetic energy causes accelerated motion of free electrons. When the temperature is increased sufficiently, electrons acquire additional energy equal to the work function of the metal. Consequently, they come out from the surface of the metal, producing thermionic emission.

The device used for thermionic emission is known as thermionic emitter or cathode. A thermionic emitter or cathode should have the following characterstics:

A cathode should have

(a) Low work function
(b) High melting point
(c) High mechanical strength

Commonly used thermionic emitters are

(a) Tungsten

(b) Thoriated tungsten

(c) Oxide-coated cathode

4.2.3 Richardson-Dushman Equation

The thermionic emission current density depends upon the absolute temperature of the emitter and it is given by

$$J_s = AT^2 e^{\frac{-11600\phi}{T}}$$

where

Js - emission current density (measured in Amp/m^2 of the emitting area)

T - absolute temperature of emitter (^{o}K),

A - emitter constant (measured in amp/m^2/^{o}K^2),

e - natural logarithmic base, and

ϕ - work function of emitter (measured in electron volt)

Example 4.1

A tungsten filament consists of a cylindrical cathode 6 cm long and 0.03 cm in diameter. If the operating temperature is 2447^{o}C, find the emission current.

(Given: $A = 60.3 \times 10^4$ amp/m^2/^{o}K^2 and $\phi = 3.26$ eV.)

Solution

Given $A = 60.3\times10^4$ amp/m^2/^{o}K^2

$\phi = 3.26$ eV

$t = 2447$ C i. e. $T = 2720^o$ K

$r = 0.015$ cm

$h = 6$ cm

Current density, $J_s = AT^2 e^{\frac{-11600\,\phi}{T}}$

$$= 60.3\times10^4\times(2720)^2\times e^{\frac{-11600\times3.26}{2720}}$$

$$= 4.088\times10^6 \text{ amp/m}^2$$

Emission current $=$ Current density$\times$area

$$= 4.088\times10^4\times2\pi\times0.015\times10^{-2}\times6\times10^{-2}$$

$$= 2.31 \text{ amp}$$

Example 4.2

A tungsten wire of unknown composition emits 0.2 amp/cm^2 at a temperature of 2020^{o}K. Find the work function of tungsten filament.

Given $J_s = 0.2$ amp/cm^2

$= 0.2 \times 10^4$ amp/m^2

$A = 60.3\times10^4$ amp/m^2/^{o}K^2

$T = 2020^o$ K

Solution

$$J_s = AT^2 e \frac{-11600\phi}{T}$$

i.e. $0.2 \times 10^2 = 60.3 \times 10^4 \times 2020^2 \times e^{\frac{-11600\times\phi}{2020}}$

i.e. $e^{\frac{11600\times\phi}{2020}} = \dfrac{60.3\times10^4\times2020^2}{0.2\times10^4}$

i.e. $e^{5.743\phi} = 1.228\times10^9$

Taking natural logarithm on both sides,

$$\text{In}\left(e^{5.743\phi}\right) = \text{In}\left(1.228\times10^9\right)$$

i.e. $5.743\phi = 20.929$

i.e. $\phi = 3.644$ eV

SAQ 1

(a) A tungsten filament consists of a cylindrical cathode. If the operating temperature is 2200°C, find the emission current density.
(Given: A = 60×10^4 A/m^2/^{o}K^2 and $\phi = 4.25$ eV.)

(b) An oxide-coated emitter has a surface area of 0.157 cm^2. If the operating temperature is 1100^o K, find the emission current.
(Given A = 65×10^4 A/m^2/^{o}K^2, work function = 3.25 eV.)

(c) A tungsten filament consists of a cylindrical cathode 7 cm long and 0.02 cm in diameter. If the operating temperature is 2600^o K, find the emission current. (Given: A = 60.2×10^4 A/m^2/^{o}K^2 and $\phi = 4.456$ eV.)

(d) A tungsten wire of unknown composition emits 0.325 A/cm^2 at a temperature of 2150^{o}K. Find the work function of tungsten filament.
(Given: A = 60A/cm^2/^{o}K^2.)

4.2.4 Field Emission

The process of emission of electrons due to the application of strong electric field at the surface of a metal is known as field emission.

Explanation

When a metal surface is subjected to very high positive electric field, free electrons (that are negatively charged particles) in the metal experience attractive force. Due to this strong attractive force by the electric field, electrons come out from the surface of the metal. This produces field emission.

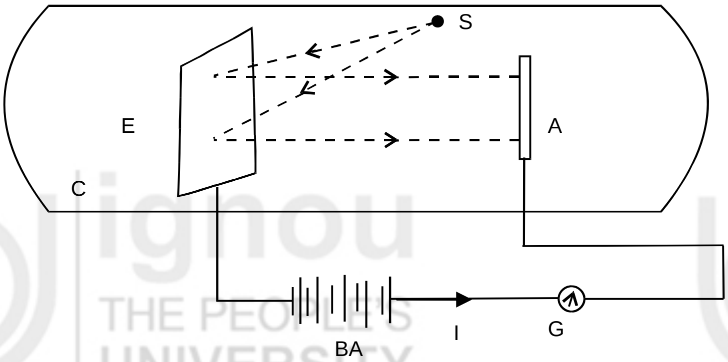
Field emission can be obtained even at room temperature. Therefore, it is also called as cold cathode emission.

4.2.5 Secondary Emission

The process of emission of electrons due to bombardment of high-speed elementary particles is called as secondary emission.

Explanation

When high-speed electrons or any elementary particles strike a metal surface, the kinetic energy carried by them is completely or partially transferred to free electrons in the metal. If energy transferred is greater than or equal to work function of the metal, electrons will come out from the surface of the metal producing secondary emission. A positive voltage applied to the anode A by the battery BA would cause an electron current to flow in the circuit. This current would of course be in opposite direction to the circuit current I which can be read from the galvanometer or an ammeter *G*.



S : Source of Electron
BA : Battery
A : Anode
G : Galvanometer or Ammeter
I : Circuit Current
C : Evacuated Glass Chamber
E : Emitting Surface

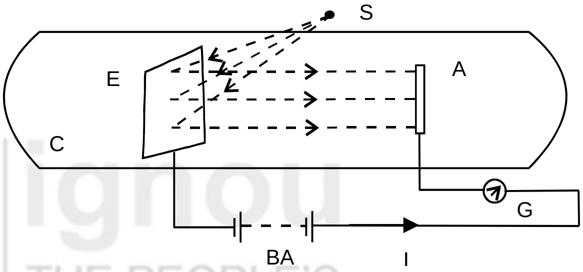
Figure 4.1

4.2.6 Photoelectric Emission

The phenomenon of emission of electrons from a metal surface due to light energy is called photoelectric emission.

Explanation

When a beam of light hits the surface of a metal, the energy carried by the photons of light is transferred to the free electrons in the metal. If the energy of photons is greater than the work function of the metal, then free electrons will come out from the surface of the metal, which would be attracted by the anode A and would cause a flow of current *I* in the circuit.



S : Source of Light
BA : Battery
A : Anode
G : Galvanometer or Ammeter
C : Evacuated Glass Chamber
E : Emitting Surface
I : Circuit Current

Figure 4.2

4.3 SEMICONDUCTORS

A semiconductor is a substance, whose resistivity lies between conductors and non-conductors or insulators of electric current.

4.3.1 Intrinsic Semiconductor

A semiconductor in pure form is called an intrinsic semiconductor, e.g. (Ge) Germanium, (Si) Silicon, etc.

4.3.2 Extrinsic Semiconductor

The conductivity of an intrinsic semiconductor can be altered by adding a suitable amount of impurities to it. The resulting substance is called extrinsic semiconductor.

The process of adding impurity to an intrinsic semiconductor is known as doping and the impurity added is known as doping agent. The common doping agents are pentavalent elements such as arsenic, antimony, phosphorous, etc. and trivalent elements such as indium, aluminum, gallium, etc. Depending on the type of doping agent, extrinsic semiconductors are classified into two types, viz, P-type and N-type semiconductors.

P-Type Semiconductor

When a small amount of trivalent impurity such as aluminium, indium, etc is added to a pure semiconductor, then resulting extrinsic semiconductor is known as P-type semiconductor. Figure 4.3 shows the structure of Ge crystal when trivalent impurity aluminium atom is added to it. Aluminium atom has three valence electrons and it forms three covalent bonds with three germanium atoms as shown in Figure 4.3.

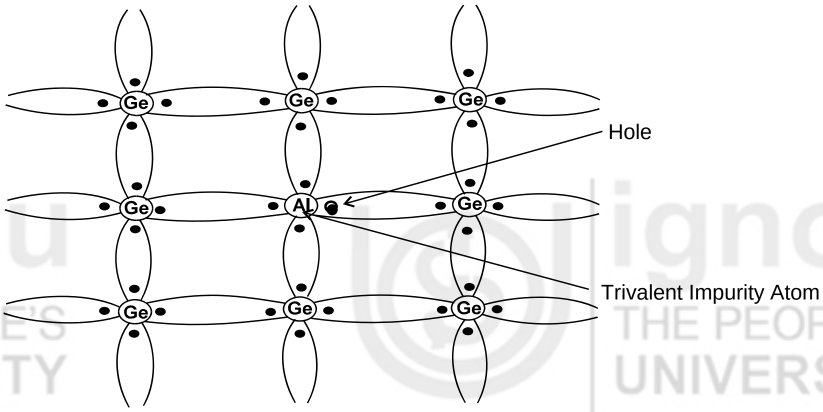


Figure 4.3: Structure of Ge crystal with a trivalent impurity atom (Al) doping, the three Al atom valence electrons forming three covalent bonds with the Ge atoms and the fourth bond having a deficiency of an electron or a hole.

In the fourth covalent bond, only germanium atom contributes one valence electron while aluminium has no valence electron to contribute. Being short of one electron, fourth bond is incomplete. The deficiency of electron is called a hole and treated as a positive charge. For each atom added, one hole is created. A small quantity of aluminum provides millions of holes.

However, there are a few free electrons due to **thermal energy**. But the number of holes far exceeds compared to number of free electrons. Thus, in P-type semiconductors, **holes are majority charge carriers** and electrons are **minority charge carriers**.

N-Type Semiconductor

When a small amount of pentavalent impurity such as arsenic, antimony, etc. is added to a pure semiconductor, then resulting extrinsic semiconductor is known as N-type semiconductor.

Figure 4.4 shows the structure of germanium crystal when pentavalent impurity arsenic is added to it. Arsenic atom has five valence electrons and it forms four covalent bonds with four germanium atoms.

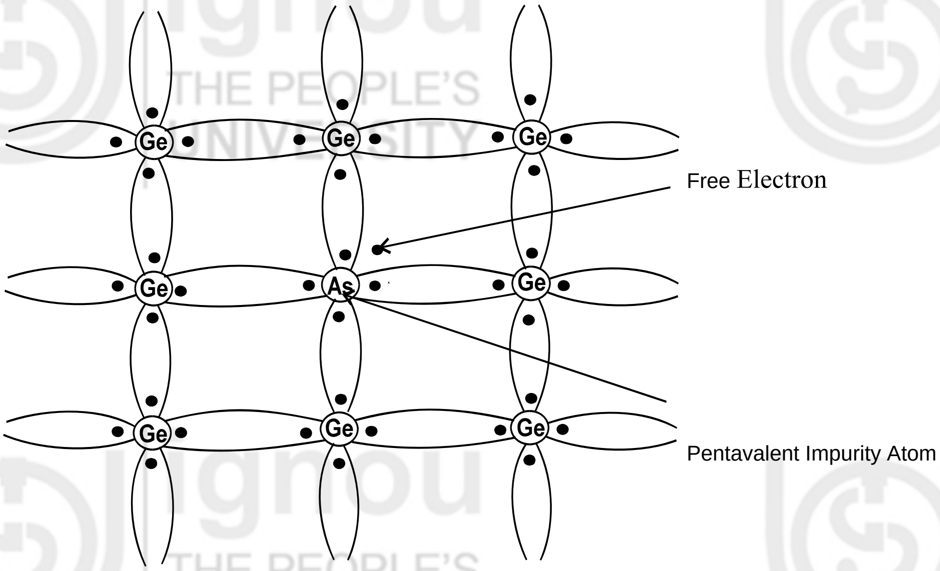


Figure 4.4: Structure of Ge crystal with a pentavalent impurity atom (As) doping, with the four As atom valence electrons forming four covalent bonds with the Ge atoms and the fifth electron of As atom seen as free electron.

The fifth valence electron of arsenic atom finds no place in covalent bonds and is thus free. Each arsenic atom added, provides one free electron. A small quantity of arsenic impurity provides millions of free electrons. However, there are a few holes due to **thermal energy**. But number of free electrons far exceeds the number of holes. Thus in N-type semiconductor, **electrons are majority carriers** and **holes are minority carriers**.

4.4 PN JUNCTION OR SEMICONDUCTOR DIODE

4.4.1 PN Junction

When a P-type semiconductor is suitably joined to an N-type semiconductor, the contact surface is called as PN junction.

Figure 4.5 shows schematic diagram of a PN junction. N-type material has a high concentration of free electrons (majority carriers) while P-type material has a high concentration of holes (majority carriers). Because of mutual repulsion electrons in the N-type region move in all directions. Some of them also cross the junction. When a free electron leaves the N-region, it produces a positively charged atom or a positive ion in the N-region depicted in the figure as ⊕. As it enters the P-region, the free electron becomes a minority carrier. Soon this minority carrier falls into a hole. The associated atom becomes negatively charged (negative ion) depicted in the figure as ⊖

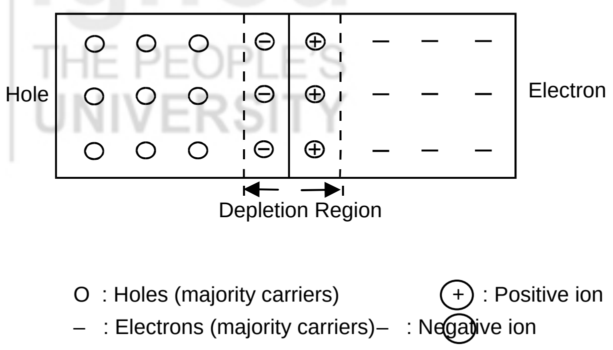


Figure 4.5

This way each free electron creates a pair of ions. As the number of ions builds up, the region near the junction is depleted of free electrons and holes. This region is called the depletion region. A net negative charge is established on P-side and a net positive charge is set up on N-side. Now, +ve charges on N-side repels holes to cross from P-type to N-type and negative charges on P-side repel free electrons to enter from N-type to P-type. Thus, a barrier is set up against further movement of holes and electrons. This is called potential barrier. The order of this potential barrier in a germanium *P-N* junction or diodes is around 0.2 - 0.3 volt, and in silicon *P-N* junction or diodes is around 0.6 - 0.7 volt.

4.4.2 Forward and Reverse Biasing of a PN Junction

Forward Biasing

When P-region of a PN junction is connected to positive terminal of a battery and N-region is connected to negative terminal, PN junction is said to be forward biased. This is shown in Figure 4.6

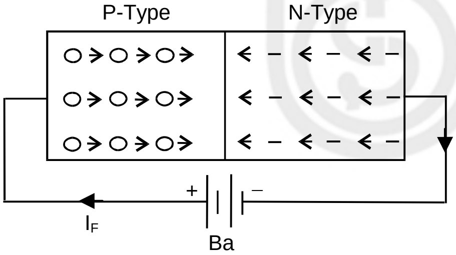


Figure 4.6: Forward biasing a p-n junction diode with holes being repelled by the battery positive potential and electrons repelled by its negative potential, establishing a flow of large forward biased current in the direction shown.

As soon as forward biasing potential is applied, holes are repelled by positive terminal of the battery and electrons are repelled by the – ve terminal. As a result, electrons and holes are driven towards the junction. The width of depletion region and therefore the barrier potential decreases and hence electrons and holes diffuse across the junction easily, resulting in a large current through the device. This current is called the forward bias current denoted by the symbol I_F.

Reverse Biasing

When P-region of a PN junction is connected to negative terminal of a battery and N region to +ve terminal, the *PN* junction is said to be reverse biased. Figure 4.7 shows a reverse biased PN junction. As soon as the potential difference is applied, positive terminal of the battery attracts electrons in *N* region and negative terminal of the battery attracts holes in *P* region. This results in widening of the depletion region. Therefore electrons and holes cannot diffuse across the junction. Thus current does not flow through the junction. Though there is no current due to majority charge carries, still there is a small current due to minority charge carriers. This current is called the reverse bias current denoted by the symbol I_R.

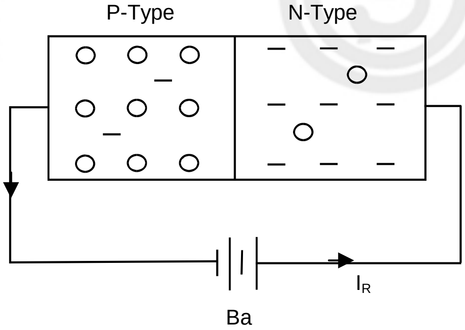


Figure 4.7

4.4.3 V-I Characteristics of a PN Junction

Case (1) : Forward Biasing a p–n Junction Diode

Figure 4.8 depicts the circuit diagram of a *p–n* junction diode operated in the forward bias mode. With forward bias to the *PN* junction, the potential barrier is reduced. At some forward voltage, the potential barrier is completely eliminated and forward current starts flowing from now onwards. The current increases with increase in forward voltage. Thus, a rising curve *OBC* is obtained with forward bias as shown in Figure 4.9.

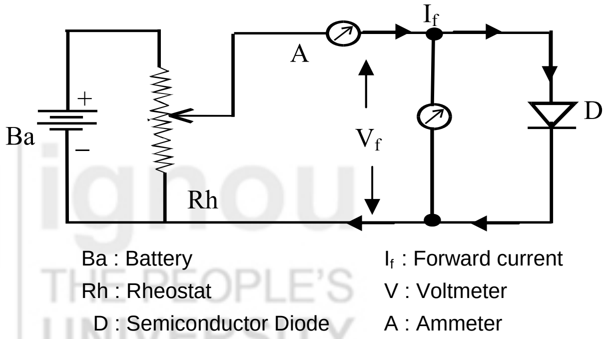


Figure 4.8: Circuit Schematic of a p–n Junction Diode Operated in the Forward Bias Mode

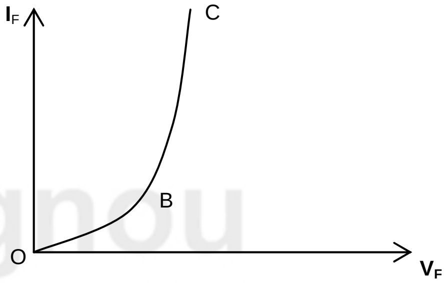


Figure 4.9: Forward Voltage – Forward Current (V_F–I_F) Characteristics of a p– n Junction Diode

In the region *OB*, the current I_F increases very slowly with the increase in forward voltage V_F and the curve is non-linear. In region *BC* the current increase is very rapid with the forward voltage and the curve is almost vertical. This current may range from a few milliamperes to many amperes.

Case (2): Reverse Biasing a p–n Junction Diode

Figure 4.10 depicts the circuit diagram of a *p–n* junction diode operated in the reverse bias mode. With reverse bias to the *PN* junction, potential barrier at the junction is increased. Therefore, the junction resistance becomes very high and hence no current flows through circuit due to majority carriers.

However, a very small current flows in the circuit with reverse bias as shown in Figure 4.10. This is called reverse current I_R and is due to the minority carriers.

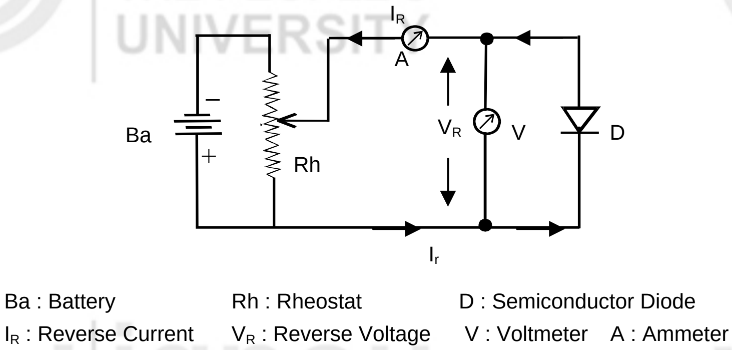


Figure 4.10: Circuit Diagram of a p–n Junction Diode Operated in the Reverse Bias Mode

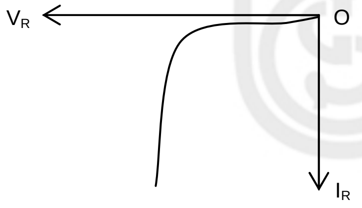


Figure 4.11: Reverse Voltage – Reverse Current (V_R – I_R) Characteristics of a p– n Junction Diode.

If reverse voltage is increased continuously, the kinetic energy of electrons may become high enough to knock them out from the semiconductor atoms. At this stage breakdown of the junction occurs, characterized by a sudden rise of reverse current. This may destroy the junction permanently.

4.5 RECTIFIERS

The production and transmission of a.c. power is more convenient and economical compared to d.c. power. So usually electrical power is generated in the form of a.c., which can be used for lighting, heating, etc. But almost all electronic equipments need d.c. power to function. Therefore it is necessary to convert a.c. power into d.c power. Rectifiers are the circuits that convert a.c. power into d.c. power.

4.5.1 Half Wave Rectifier

Circuit Diagram

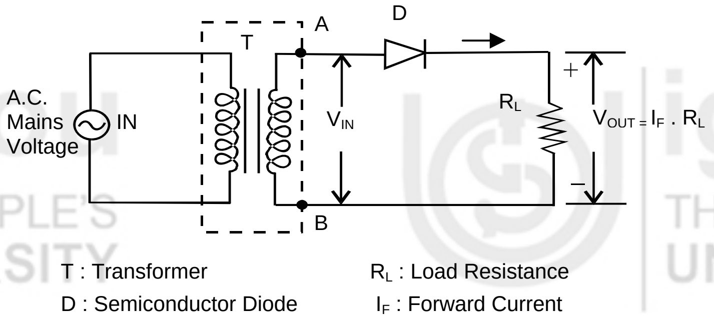


Figure 4.12: Circuit Schematic of a Half Wave Rectifier using p–n Junction Diode.

Circuit Detail

The half wave rectifier circuit consists of a transformer *T* (step up or step down), a diode *D* and a load resistance R_L. The diode and load resistance are connected to secondary terminals of the transformer as shown in Figure 4.12. The a.c. input voltage is applied across primary terminals of the transformer, the transformer steps down or steps up the voltage, as the case may be, and produces a voltage V_{IN} across the terminals *A* and *B*. The sinusoidal voltage variation (V_{IN}) vs time across the terminal *AB*, is depicted in Figure 4.13 (a).

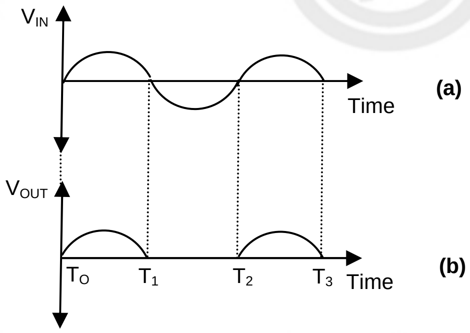


Figure 4.13: (a) Input Waveform, V_{IN};; (b) Output Waveform, V_{OUT}

Circuit Operation

During the *+ve* half cycle of the simusoidally varying voltage V_{IN} i.e. during the time T_O to T_I, as shown in Figure 4.13 (a), the end *A* in Figure 4.12 is positive w.r.t. the end *B*. This makes the diode *D* forward biased and hence a large current I_F flows through the load resistance R_L, producing a voltage $Vout = I_F.\ R_L$ across the load resistance R_L. This is shown in Figure 4.13 (b) as a positive swing from time T_O to $T_{I.}$

However, during the negative half cycle of the sinusoidal input voltage V_{IN}, i.e. during the time T_I to T_2, the end *A* is negative w.r.t. *B* and therefore, the diode *D* is reverse biased. There is a very small reverse current through the load resistance R_L, during this period, producing almost zero voltage V_{OUT} during the time T_I to T_2 as is shown in Figure 4.13 (b). During time period T_2 to T_3, the diode is again forward biased and a positive V_{OUT} swing is seen in Figure 4.13 (b). The load current, therefore, is unidirectional and the voltage V_{OUT} across R_L is rectified.

Efficiency of Half Wave Rectifier

Efficiency of a rectifier is defined as the ratio of output d.c. power to the applied input a.c. power.

$$\text{Rectifier efficiency, } \eta = \frac{\text{Output d.c. power}}{\text{Input a.c. power}}$$

$$\text{Output d.c. power} = I_{dc}^2\ R_L$$

$$\text{For half wave rectifier, } I_{dc} = \frac{I_0}{\pi}$$

$$\text{where } I_0 = \text{peak current}$$

$$\therefore \text{ Output d.c. power} = \left(\frac{I_0}{\pi}\right)^2 R_L$$

$$\text{Input a.c. power} = \left(I_{rms}\right)^2 \left(r_f + R_L\right)$$

where I_{rms} is root mean square value of input a.c. and r_f is forward diode resistance for half wave rectifier,

$$I_{rms} = \frac{I_o}{2}$$

$$\therefore \text{ Input a.c. power} = \left(\frac{I_0}{2}\right)^2 \left(r_f + R_L\right)$$

$$\therefore \eta = \frac{\left(\frac{I_0}{\pi}\right)^2 R_L}{\left(\frac{I_0}{2}\right)^2 \left(r_f + R_L\right)} = \frac{(0.406) R_L}{r_f + R_L}$$

Efficiency will be maximum if r_f is negligible compared to R_L. Therefore, Maximum efficiency of half wave rectifier is **40.6%.**

Example 4.3

A half wave rectifier in a life board battery charger circuit supplies 30V d.c. to a load of 1000Ω. The forward resistance of the diode is 15Ω. Calculate the peak value of a.c. voltage required.

Solution

Given $V_{dc} = 30$ V

$R_L = 1000\Omega$

$$r_f = 15\Omega$$

We know that $V_{dc} = I_{dc} R_L$

i.e. $$V_{dc} = \frac{I_0}{\pi} . R_L \qquad \left(\because I_{dc} = \frac{I_0}{\pi} \right)$$

or $$V_{dc} = \frac{V_o}{\pi \left(r_f + R_L \right)} \times R_L \qquad \left(\because I_0 = \frac{V_0}{\left(r_f + R_L \right)} \right)$$

Substituting the given values, we have

$$30 = \frac{V_o}{\pi \left(15 + 1000 \right)} \times 1000$$

or $$V_o = 95.66\ V$$

Hence peak value of alternating voltage required is 95.66 Volts.

SAQ 2

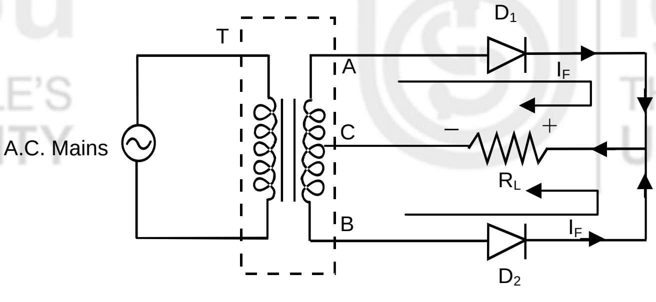
(a) A diode having internal resistance $r_f = 20\Omega$ is used for half wave rectification. If peak voltage of applied a.c. is 50V and load resistance $R_L = 800\Omega$, find

- (i) D.C. and RMS value of load current
- (ii) Input a.c power and output d.c. power
- (iii) Output d.c. voltage
- (iv) Efficiency of rectification

(b) A half wave rectifier in a life board battery charger circuit supplies 40V d.c. to a load of 1200Ω. The forward resistance of the diode is 25Ω. Calculate the peak value of a.c. voltage required.

4.5.2 Full Wave Centre Tap Rectifier

Circuit Diagram



T : Centre-tap Transformer

D_1 and D_2 : Semiconductor Diodes

R_L : Load Resistance

Figure 4.14: Circuit Schematic of a Full Wave Rectifier using two p–n Junction Diodes and a Centre Tapped Transformer

Circuit Detail

It consists of a centre tap transformer *T*, two diodes D_1 and D_2 and a load resistance R_L. The diodes D_1 and D_2 and R_L are connected in secondary circuit of centre tap transformer as shown in Figure 4.14. Input a.c. is applied across primary terminals of the transformer.

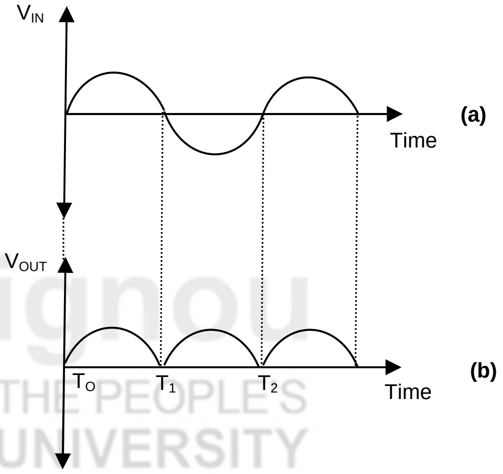


Figure 4.15: (a) Input Waveform (b) Output Waveform

Circuit Operation

During the positive half cycle of input a.c. sinusoidal signal V_{IN}, i.e. during the period T_0 to T_1, the end *A* is positive w.r.t. centre tap *C*, where as the end *B* is negative w.r.t. *C*. This makes diode D_1 forward biased and diode D_2 reverse biased. Since during this period D_1 conducts, a forward bias current I_F flows through D_1 to the load resistance R_L and produces voltage V_{OUT} as shown in Figure 4.15 (a) and 4.15 (b). During the negative half cycle of input a.c. voltage i.e. during period T_1 to T_2, the end *A* is negative w.r.t., centre tap *C* but the end *B* is positive w.r.t. *C*, which makes diode D_1 in reverse bias and diode D_2 in forward bias condition. Since D_2 conducts, during the period T_1 and T_2 the forward current I_F now flows via diode D_2 to the load resistance R_L and generates a voltage V_{OUT}. We see, therefore, that the current flows through R_L in the same direction during the positive, as well as, negative half cycle of input voltage and the output voltage V_{OUT} is full wave rectified as seen in Figure 4.15 (b).

Efficiency of Centre-Tap Full Wave Rectifier

$$\text{Rectifier efficiency } \eta = \frac{Output\ d.c.\ power}{Input\ a.c.\ power}$$

$$\text{Output d.c. power } = I_{dc}^2 . R_L$$

For full wave centre tap rectifier $I_{dc} = \dfrac{2I_o}{\pi}$

where I_0 = peak current

$$\therefore \qquad \text{Output d.c. power} = \left(\frac{2I_o}{\pi}\right)^2 R_L$$

$$\text{Input a.c. power} = (I_{rms})^2 (r_f + R_L)$$

where I_{rms} is root mean square value of input a.c. and r_f is forward diode resistance. For full wave centre tap rectifier,

$$I_{rms} = \frac{I_o}{\sqrt{2}}$$

Therefore, $$\eta = \frac{\left(\frac{2I_o}{\pi}\right)^2 R_L}{\left(\frac{I_O}{\sqrt{2}}\right)^2 (r_f + R_L)} = \frac{(0.812)R_L}{(r_f + R_L)}$$

The efficiency will be maximum if r_f is negligible as compared to R_L.

Therefore, maximum efficiency of centre-tap full wave rectifier is **81.2%.**

Example 4.4

A full wave rectifier in a d.c. backup supply system of a passenger vessel uses two diodes of forward resistance 18Ω. The transformer rms secondary voltage from centre tap to each end of secondary is 12 V and load resistance is 482Ω. Find.

(i) mean load current

(ii) rms value of load current

(iii) efficiency of the rectifier

Solution

Given $V_{rms} = 12$ V

$R_L = 482\ \Omega$

$r_f = 18\ \Omega$

$$I_o = \frac{V_o}{r_f + R_L} = \frac{\sqrt{2}V_{rms}}{r_f + R_L}$$

i.e. $$I_o = \frac{\sqrt{2} \times 12}{18 + 482} = 0.0339\text{A}$$

(i) $$I_{dc} = \frac{2I_o}{\pi} = 0.0216\text{A}$$

(ii) $$I_{rms} = \frac{I_o}{\sqrt{2}} = 0.024\text{A}$$

(iii) $$\text{Efficiency} = \frac{0.812 R_L}{r_f + R_L}$$

$$= \frac{0.812 \times 482}{500}$$

$$= 0.7827$$

$$= 78.27\ \%$$

SAQ 3

A full wave rectifier in a d.c. backup supply system of a passenger vessel uses two diodes of forward resistance 18Ω. The transformer rms secondary voltage from centre tap to each end of secondary is 12V and load resistance is 48Ω. Find

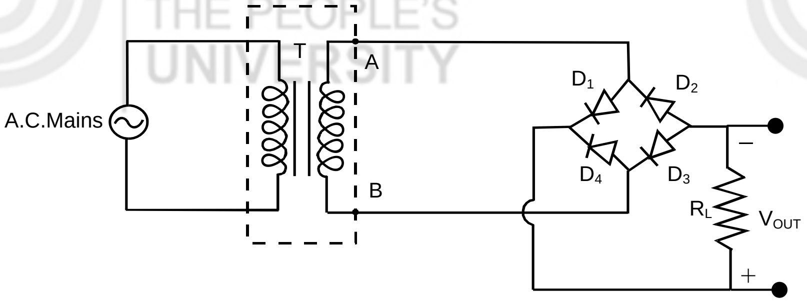
(i) mean load current

(ii) rms value of load current

(iii) efficiency of the rectifier

4.5.3 Full Wave Bridge Rectifier

Circuit Diagram



T : Transformer (Step up or Step Down)

R_L : Load Resistance

D_1, D_2, D_3 & D_4 : Semiconductor Diodes

Figure 4.16: Circuit Schematic of a Full-Wave Bridge Rectifier.

Circuit Detail

The circuit of a full wave bridge rectifier is shown in Figure 4.16. It consists of a transformer T which may either be a step-down or a step-up. The secondary of the transformer is connected to four diodes D_1, D_2, D_3, and D_4 which are connected in a bridge configuration, and the load resistance R_L. It may be noted that the secondary of the transformer has no centre tap in this circuit of the full-wave rectifier.

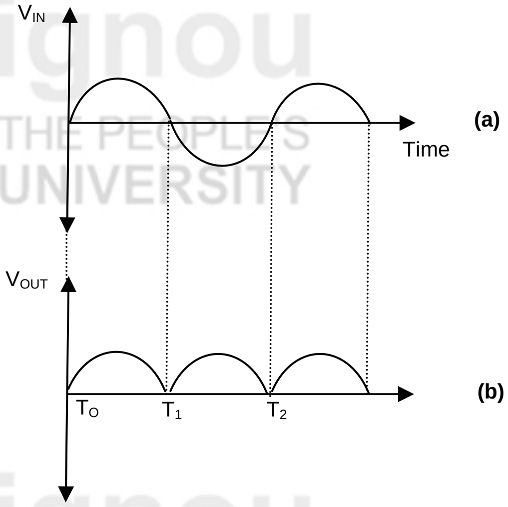


Figure 4.17: (a) Input Waveform (b) Output Waveform

Circuit Operation

During +ve half cycle of input a.c. i.e. during period T_0 to T_1, end A becomes +ve w.r.t. end B. This makes diodes D_1 and D_3 forward biased and D_2 and D_4 reverse biased. Since D_1 and D_3 conduct a forward bias current flows through the load resistance RL and generates voltage V_{OUT} with the shown polarity.

During –ve half cycle of input a.c. i.e. during period T_1 to T_2 end A becomes –ve w.r.t. end B. This makes diodes D_2 and D_4 forward biased and D_1 and D_3 reverse biased. Since D_2 and D_4 conduct during the time period T_1 and T_2, a forward bias current flows through the resistance R_L and generate V_{OUT} with the shown polarity. The full wave recitified waveform is shown in Figure 4.17(b).

Efficiency of Full Wave Bridge Rectifier

$$\text{Rectifier efficiency, } \eta = \frac{\textit{Output d.c. power}}{\textit{Input a.c. power}}$$

$$\text{Output d.c. power} = I_{dc}^2 . R_L$$

$$\text{For full wave bridge rectifier } I_{dc} = \frac{2I_o}{\pi}$$

where I_o= peak current

$$\therefore \qquad \text{Output d.c. power} = \left(\frac{2I_o}{\pi}\right)^2 R_L$$

$$\text{Input a.c. power} = (I_{rms})^2 (2r_f + R_L)$$

where I_{rms} is root mean square value of input a.c. and r_f is forward diode resistance

$$\text{For full wave bridge rectifier,} \quad I_{rms} = \frac{I_o}{\sqrt{2}}$$

$$\therefore \eta = \frac{\left(\frac{2I_o}{\pi}\right)^2 R_L}{\left(\frac{I_o}{\sqrt{2}}\right)^2 (2r_f + R_L)} = \frac{0.812\, R_L}{(2r_f + R_L)}$$

In the ideal case of r_f equal to zero, the efficiency would be maximum and would be 81.2%.

SAQ 4

A bridge rectifier is used in the exciter circuit of an alternator. The forward resistance of each diode is 1Ω. The rms value of a.c. supply is 220V and load resistance is 98Ω. (Assume each diode has infinite reverse resistance). Calculate

(i) d.c. current

(ii) rms value of load current

(iii) power dissipation in each diode

4.6 FILTERS

The output current of a rectifier is unidirectional but pulsating. To convert pulsating unidirectional current into d.c., we make use of some sort of filter circuit, that filters out the a.c. component as far as possible.

4.6.1 Capacitor Filter

Figure 4.18 depicts schematic of a simple capacitor filter. The output voltage of rectifier is pulsating unidirectional as sown in Figure 4.19 (a). This contains d.c. component, as well as, a.c. component (ripple). The reactance offered to a.c. component by the capacitor is quit low. Therefore, most of the a.c. component is bypassed through the capacitor to ground. But capacitor offers infinite resistance to d.c. component. Hence capacitor blocks d.c. component and d.c. component is sent to load resistance and is available as V_{OUT} which is smoothened of variations as shown in Figure 4.19 (b).

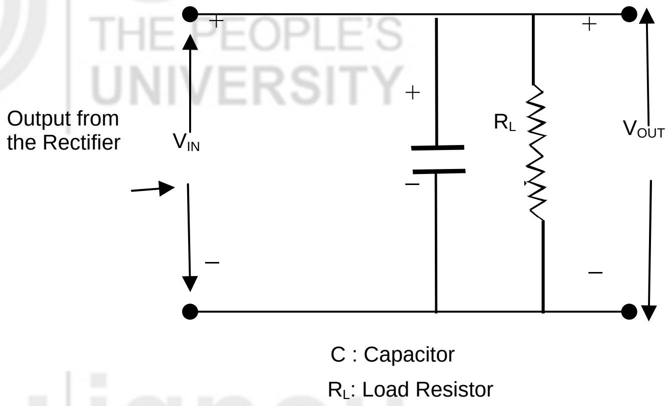


Figure 4.18 : Circuit Schematic of a Simple Capacitor Filter

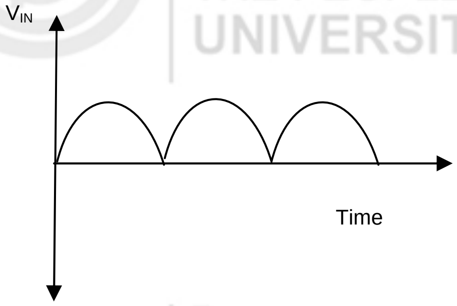


Figure 4.19 (a): Rectifier Output

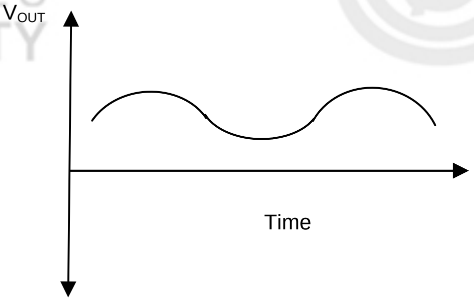


Figure 4.19 (b): Filter Output

4.6.2 Inductor Input Filter

Circuit Diagram

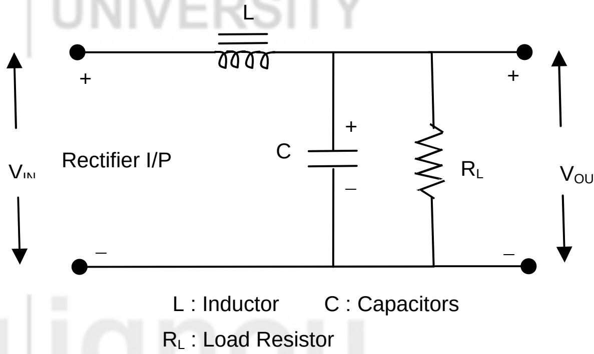
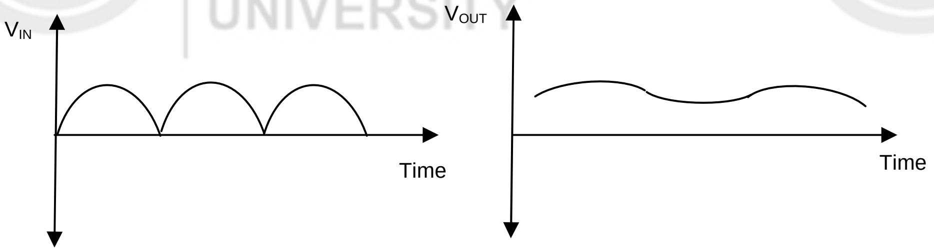


Figure 4.20: Circuit schematic of an Inductor Input Ffilter



(a) **(b)**

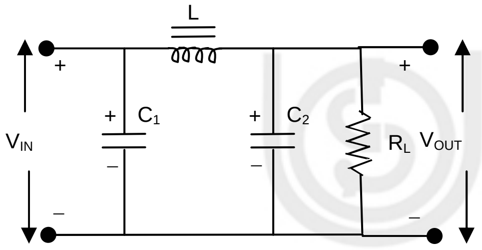
Figure 4.21: (a) Rectifier Output or Input to Filter; (b) Output from the Filter

Working

The output voltage of rectifier, which contains a.c. component as well as d.c. component are given to *LC* filter shown in Figure 4.20. The inductance coil offers high reactance to a.c. component, but zero reactance to the d.c. component. Therefore, most of the a.c. component is blocked by the coil and d.c. component is passed through it. But capacitor offers very small reactance to a.c. component and infinite resistance to d.c. component. So a.c. component which escapes from the coil is bypassed through the capacitor. The d.c. component which is passed through the coil are blocked by the capacitor and is passed on to the load resistance R_L. The output voltage V_{OUT} is, therefore, smoothened as shown in Figure 4.21(b).

4.6.3 Capacitor Input Filter

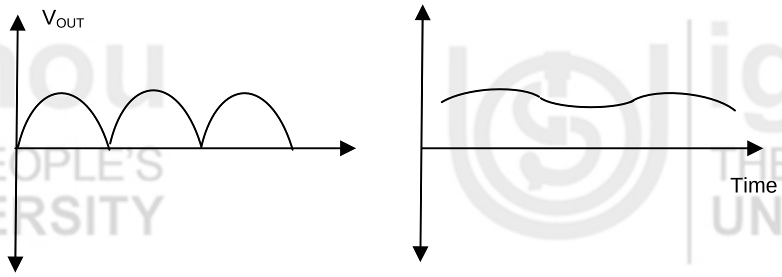
Circuit Diagram



L : Inductor C_1 and C_2 : Capacitors

R_L : Load Resistor

Figure 4.22 : Circuit Schematic of a Capacitor Input Filter



(a)

(b)

Figure 4.23: (a) Filter Input; (b) Filter Output

Working

In this circuit filtering action is done in three successive steps. As explained earlier the inductor *L* blocks the a.c. component but allows the d.c. component to pass on to the load resistance R_L. The capacitors C_1 and C_2 bypass the a.c. component to ground but allow the d.c. component to be presented to the load resistance R_L. V_{OUT} is, therefore, better smoothened, as shown in Figure 4.23(b).

4.7 ZENER DIODE

4.7.1 Zener Diode and its Circuit Symbol

A diode, which is designed with adequate power dissipation capability to operate in the breakdown region and which may be used as constant voltage device is called Zener diode. Zener diode normally operates in the reverse bias connection.

The circuit symbol of Zener diode is as shown in Figure 4.24.

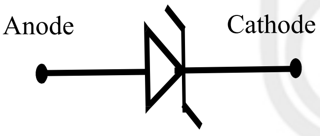


Figure 4.24 : Symbol of a Zener Diode

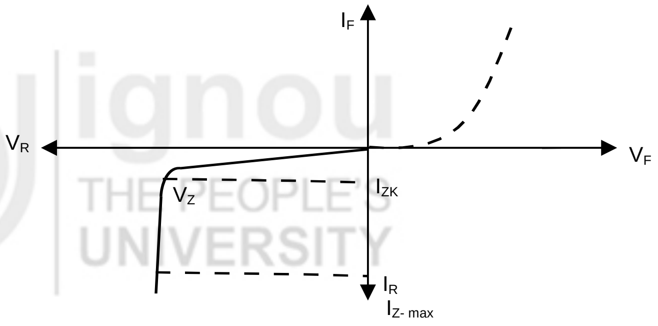
4.7.2 Zener Breakdown Mechanism

The electric field intensity at the junction increases as the impurity concentration increases for a fixed applied voltage. At a field of about 2×10^7 V/m, a sufficiently strong force may be exerted on a bound electron by the field to tear it out of its covalent bond. The new hole-electron pair, which is created, increases the reverse current through the junction. This process is called Zener breakdown. It does not involve collisions of charge carriers with atoms.

Usually Zener breakdown takes place for heavily doped diodes that are operating at low voltages.

4.7.3 V-I Characteristics of a Zener Diode

When a zener diode is forward biased, its *V-I* characteristic is similar to that of an ordinary diode. This is shown as forward voltage-forward current (V_F -I_F) characteristic in Figure 4.25. The Zener breakdown mechanism depicted in the reverse voltage reverse current characteristic (V_R - I_R) of Figure 4.25. The reverse current is very small before the break-down voltage V_Z is reached. A sharp increase in reverse current I_R is observed when Zener break-down voltage V_Z is reached. In the break-down region the voltage V_Z is almost constant with the increase of the reverse current I_R.



V_Z : Zener Breakdown Voltage

I_{ZK} : Zener Knee Current

$I_{Z\text{-}max}$: Maximum Zener Current Limited by Maximum Power Dissipation

Figure 4.25

4.7.4 Temperature Characteristics of a Zener Diode

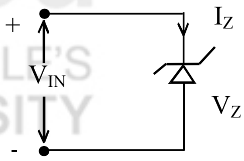
As temperature increases, the energies of the valence electrons also increase. This makes easier for electrons to escape from covalent bonds. Hence less applied voltage is required to pull these electrons from their positions in the crystal lattice and convert them into conduction electrons. Therefore the Zener breakdown voltage decreases with increase in temperature.

4.7.5 Equivalent Circuit of Zener Diode

The equivalent circuit of a Zener diode can be drawn as follows.

'ON' State

> When reverse voltage across a Zener diode is equal to or more than breakdown Voltage V_Z, the current increases very sharply. In this region, the curve is almost vertical. It means that voltage across Zener diode is constant at V_Z even though the current through it changes. Therefore in the breakdown region an ideal Zener diode can be represented by a battery of voltage V_Z as shown in Figure 4.26 (b). Under such conditions the Zener diode is said to be in the 'ON' state.



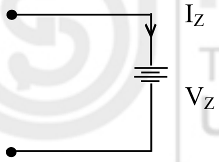
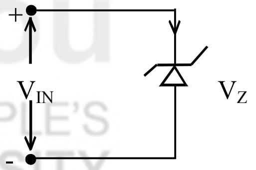


Figure 4.26 (a) **Figure 4.26 (b)**

'OFF' State

When the reverse voltage across the Zener diode is less than V_Z but greater than zero, the Zener diode is in the 'OFF' state. Under such conditions the Zener diode can be represented by an open circuit as shown in Figure 4.27 (b).



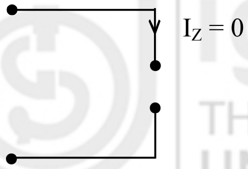


Figure 4.27 (a) **Figure 4.27 (b)**

4.7.6 Zener Diode as Voltage Stabilizer

A zener diode can be used as a voltage regulator to provide a constant voltage from a source whose voltage may vary over sufficient range. Figure 4.28 shows circuit arrangement of a Zener diode voltage regulator.

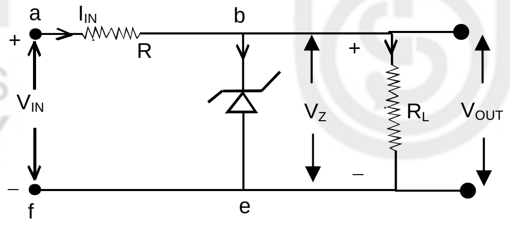


Figure 4.28

Working

When the circuit is properly designed the load voltage V_{out} remains constant even though the input voltage V_{in} and load resistance R_L may vary over a wide range.

A Zener diode can be employed as an elementary voltage regulating device when connected in the circuit of Figure 4.28. Voltage stabilization at the load can be because of either the input voltage variation or the load resistance variation. The output voltage regulation or stability due to the two causes is explained below:

Case (1)

When the input voltage V_{IN} varies:

Suppose the input voltage increases. Consider the circuit loop abef. In this loop we have

$$V_{IN} = I_{IN}.R + V_Z \qquad \text{...(I)}$$

Now since V_Z is to remain constant with any change in current, the increase in V_{IN} would cause increase in ($I_{IN}.R$) voltage drop. The I_{IN} current, therefore, increases, causing increase in I_Z which does not affect V_Z. The output voltage V_{OUT}, therefore, remains constant.

Case (2)

When the load resistance varies:

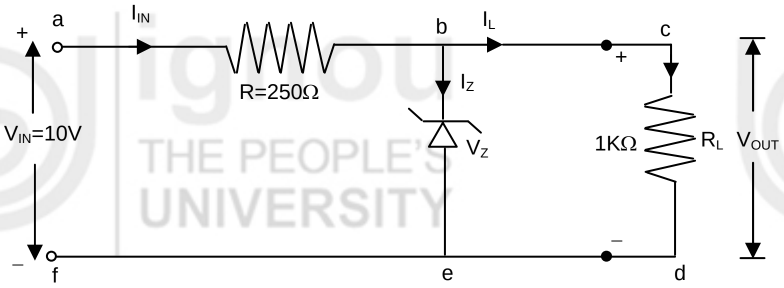
Suppose the input voltage V_{IN} is constant but the load resistant R_L decreases. From Eq. (I) we see that since V_Z and V_{IN} are constant therefore, I_{IN} would remain constant.

Now $I_{IN} = I_Z + I_L = \text{Constant}$ … (II)

The decrease in R_L would result in increase in load current I_L. From Eq. (II) we see that the extra current to I_L would be provided by the decrease in Iz. The increase in I_L keeps $I_L\ R_L = V_{out}$ constant.

Example 4.5

Consider the Zener reglator circuit of Figure 4.29 and the values of circuit as shown.



V_{IN} : 10 V
V_{out} : 5 V
R_L : 1K ohms
I_L : 5 mA
V_Z : 5 V
R : 250 ohms
I_Z : 15 mA

Figure 4.29

Calculate

(a) Input current I_{IN}

(b) If V_{IN} increases to 12 volt, compute the new value of I_{IN} and I_Z.

(c) If R_L decreses to 800 ohms compute the new value of I_L and I_Z.

Solution

(a) At the mode b, from the Kirchhoff's Current Law

$$I_{IN} = I_Z + I_L$$

$$= 15 + 5 = 20 \text{ mA}$$

(b) Consider the circuit loop abef

$$V_{IN} = I_{IN}.\ R + V_Z = 12 \text{ Volt}$$

Now, $V_Z = 5$ V

$R = 250$ Ohms

Therefore, $I_{IN}.\ R = 12 - 5 = 7\text{V}$

And $I_{IN} = {}^{7}\!/_{250} = .028\text{A} = 28 \text{ mA}$

Since load current I_L does not change, we have

$$I_Z = I_{IN} - I_L = 28 - 5 = 23 \text{ mA}$$

(c) In the circuit loop bcde

$$V_Z = I_L.R_L = 5 \text{ Volt}$$

Changed value of R_L= 800 Ohms

$\therefore \quad I_L = 5/800 = .00625 = 6.25$ mA

Therefore New value of $I_L = 6.25$ m A

Now since I_{IN} does not change and

$$I_{IN} = I_Z + I_L = 20 \text{ mA}$$

and value of $\quad I_Z = 20 - I_L$

$$= 20 - 6.25$$

$$= 13.75 \text{ mA}$$

SAQ 5

In the circuit of Figure 4.29, (a) if the input voltage V_{IN} reduces to 8 volts, compute (i) I_{IN} (ii) I_Z (b) if R_L increases to 1.2 K Ohms, compute the new value of

(i) I_L , (ii) I_Z

4.8 SUMMARY

In this unit, we have learnt the concept of electron emission and different types of electron emission. We have been exposed to intrinsic semiconductor, p-type, n-type semiconductor, *PN* junction and its characteristics and applications are discussed in detail. The filter circuit was highlighted.

In the last section of the unit, you learnt about Zener diode, its *V-I* characteristics and Zener as voltage stabilizer.

4.9 ANSWERS TO SAQs

SAQ 1

(a) 1163 amp/m^2

(b) 0.1616×10^{-7} A

(c) 0.4157 A

(d) 3.81 eV

SAQ 2

(a) (i) 19.4 mA, 30.5 mA

(ii) 0.763 W, 0.301 W

(iii) 15.52 V

(iv) 39.5 %

(b) 128.2 V

SAQ 3

(i) 0.163 A

(ii) 0.181 A

(iii) 59.05%

SAQ 4

(i) 1.98 amp

(ii) 2.20 amp

(iii) 4.84 W

SAQ 5

(a) (i) 12 mA

    (ii) 7 m A

(b) (i) 4.167 mA

    (ii) 15.833 mA