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PN Junction Diode and its Applications

In this Chapter,

- The basic aspects connected with Semiconductor Physics and the terms like Effective Mass, Semiconductors and their types are introduced, Intrinsic, Extrinsic, and Semiconductors are introduced.
- Atomic Structure, Configurations, Concept of Hole, Conductivity in ***p-type*** and ***n-type*** semiconductors are given. This forms the basis to study Semiconductor Devices in the following chapters.
- After p-type and n-type semiconductors, we shall study semiconductor devices formed using these two types of semiconductors.
- We shall also study the physical phenomena such as conduction, transport mechanism, electrical characteristics, and applications of semiconductor devices such as p-n diode, zener diode, tunnel diode and so on.
- Circuit applications of p-n junction diode namely Half Wave Rectifier (HWR), Full Wave Rectifier (FWR) and Bridge Rectifier circuits, for rectification applications are described.
- Inductor, L-section and π-section filter circuits are explained.

1.1 REVIEW OF SEMICONDUCTOR PHYSICS

1.1.1 ENERGY LEVELS AND ENERGY BANDS

To explain the phenomenon associated with conduction in metals and semiconductors and the emission of electrons from the surface of a metal, we have to assume that atoms have loosely bound electrons which can be removed from it.

Rutherford found that atom consists of a nucleus with electrons (each electron carrying a unit negative charge) rotating around it. The mass of the atom is concentrated in the nucleus. It consist of protons which are positively charged. In hydrogen atom, there is one positively charged nucleus (a proton) and a single electron. The charge on particle is positive and is equal to that of electron. So hydrogen atom is neutral in charge. The proton in the nucleus carries the charge of the atom, so it is immobile. The electron will be moving around it in a closed orbit. The force of attraction between electron and proton follows Coulombs Law. {directly proportional to product of charges and inversely proportional to (distance)^2}.

Assume that the orbit of the electron around nucleus is a circle. We can calculate the radius of this circle, in terms of total energy 'W' of the electron. The force of attraction between the electron and the nucleus is :

$$F \,\alpha\, e^2$$

(Therefore, the nucleus has the proton with electron charge equal to 'e')

$$F \,\alpha\, \frac{1}{r^2}$$

(r is the radius of the orbit)

$$\therefore \qquad F \,\alpha\, \frac{e^2}{r^2}$$

$$F = \frac{e^2}{4\pi \in_0 r^2}$$

$$\therefore \qquad F \,\alpha\, \frac{e^2}{r^2}$$

where $\in_0$ is the permitivity of free space. Its value is $\frac{10^{-9}}{36\pi}$ F/m.

As the electron is moving around the nucleus in a circular orbit with radius r, and with velocity v, then the force of attraction given by the above expression F should be equal to the centripetal force $\frac{mv^2}{r}$ (according to Newton's Second Law of Motion)

(F = m.a; m is the mass of electron and acceleration, $a = \frac{v^2}{r}$)

∴ The Potential Energy of the electron = $-\frac{e^2}{4\pi\varepsilon_0 r^2} \times r = -\frac{e^2}{4\pi\varepsilon_0 r}$

(–ve sign is because Potential Energy is by definition work done against the field)

$$\text{Kinetic Energy} = \frac{1}{2}\,mv^2$$

∴ Total Energy W possessed by the electron = $\frac{1}{2}\,mv^2 - \frac{e^2}{4\pi\varepsilon_0 r}$

But $mv^2 = \frac{e^2}{4\pi\varepsilon_0 r}$ reduces to

$$W = \frac{e^2}{8\pi\varepsilon_0 r} - \frac{e^2}{4\pi\varepsilon_0 r} = -\frac{e^2}{8\pi\varepsilon_0 r}$$

∴ Energy possessed by the electron $W = -\frac{e^2}{8\pi\varepsilon_0 r}$

W is the energy of the electron. Only for Hydrogen atom, W will also be the energy of atom since it has only one electron. The negative sign arises because the Potential Energy of the electron is

$$W = -\frac{e^2}{8\pi\varepsilon_0 r}$$

As radius r increases, Potential Energy decreases. When r is infinity, Potential Energy is zero. Therefore the energy of the electron is negative. If r is $< \infty$, the energy should be less. (Any quantity less than 0 is negative).

The above equation is derived from the classical model of the electron. But according to classical laws of electromagnetism, an accelerated charge must radiate energy. Electron is having charge = e. It is moving with velocity v or acceleration v^2/r around the nucleus. Therefore this electron should also radiate energy. If the charge is performing oscillations with a frequency 'f', then the frequency of the radiated energy should also be the same. Hence the frequency of the radiated energy from the electron should be equal to the frequency with the electron orbiting round the nucleus.

But if the electron is radiating energy, then its total energy 'W' must decrease by the amount equal to the radiation energy. So 'W' should go on decreasing to satisfy the equation,

$$W = -\frac{e^2}{8\pi\varepsilon_0 r}$$

If W decreases, r should also decrease. Since if $-\frac{e^2}{8\pi\varepsilon_0 r}$ should decrease, this quantity should become more negative. Therefore, r should decrease. So, the electron should describe smaller and smaller orbit and should finally fall into nucleus. So classical model of atom is not fairly satisfactory.

1.1.2 THE BOHR ATOM

The above difficulty was resolved by Bohr in 1913. He postulated three fundamental laws.

1. *The atom can possess only discrete energies. While in states corresponding to these discrete energy levels, electron does not emit radiation in stationary state.*
2. *When the energy of the electron is changing from W_2 to W_1 then radiation will be emitted. The frequency of radiation is given by*

   $$f = \frac{W_2 - W_1}{h}$$

   where 'h' is Plank's Constant.

   $$h = 6.626 \times 10^{-34}\ \text{J} - \text{sec.}$$

   i.e., when the atom is in stationary state, it does not emit any radiation. When its energy changes from W_2 to W_1 then the atom is said to have moved from one stationary state to the other. The atom remains in the new state corresponding to W_1. Only during transition, will some energy be radiated.
3. *A stationary state is determined by the condition that the angular momentum of the electron in this state must be an integral multiple of $h/2\pi$.*

   $$\text{So} \quad mvr = \frac{nh}{2\pi}$$

   where n is an integer, other than zero.

1.1.3 EFFECTIVE MASS

An electron mass 'm' when placed in a crystal lattice, responds to applied field as if it were of mass m*. The reason for this is the interaction of the electron even within lattice.

E = Kinetic Energy of the Free Electron
p = Momentum
v = Velocity
m = Mass
$p = mv$
m* = Effective mass of electron

$$E = \frac{p^2}{2m}$$

Electrons in a solid are not free. They move under the combined influence of an external field plus that of a periodic potential of atom cores in the lattice. An electron moving through the lattice can be represented by a wave packet of plane waves grouped around the same value of K which is a wave vector.

Electron velocity falls to zero at each band edge. This is because the electron wave further becomes standing wave at the top and bottom of a band i.e., $v_g = 0$.

Now consider an electronic wave packet moving in a crystal lattice under the influence of an externally applied uniform electric field. If the electron has an instantaneous velocity 'v_g' and moves a distance 'dx' in the direction of an accelerating force 'F', in time 'dt', it acquires energy δE where

$$\delta E = F \times \delta x = F \times v_g \times \delta t$$

$$\delta E = \frac{F}{\hbar} \times \frac{\delta E}{\delta k} \times \delta t$$

$$v_g = \frac{\delta E}{\hbar \delta k}$$

Within the limit of small increments in 'K', we can write,

$$\frac{dK}{dt} = \frac{F}{\hbar} \qquad \text{..........(1.1)}$$

But this is not the case for the electron in a solid because the externally applied force is not the only force acting on the electrons. Forces associated with the periodic lattice are also present.

Acceleration of an electronic wave packet in a solid is equal to the rate of change of its velocity.

$$\text{Acceleration of an electron in a solid} = \frac{dv_g}{dt} = \frac{d}{dt}\left(\frac{dE}{dp}\right) = \frac{d^2E}{(dp)(dt)}$$

$$\because \quad v_g = \frac{dE}{dp}$$

$$\frac{dk}{dt} = \frac{F}{\hbar}$$

$$F = \hbar \times \frac{dk}{dt}$$

$$\text{But} \quad \frac{dk}{dt} = \frac{F}{\hbar} \qquad \text{from Eq. (1.1)}$$

$$\therefore \quad \frac{dv_g}{dt} = \left(\frac{dp}{dt}\right)\frac{d^2E}{dp^2} = \frac{F}{\hbar^2} \cdot \frac{d^2E}{dp^2}$$

$$\text{or} \quad F = \hbar^2 \times \left(\frac{d^2E}{dp^2}\right)^{-1} \times \frac{dv_g}{dt}$$

This is of the form, F = ma, from Newton's Laws of Motion,

$$\text{where} \quad m^* = \hbar^2 \times \left(\frac{d^2E}{dp^2}\right)^{-1} \text{ and } a = \frac{dv_g}{dt}$$

$$\therefore \quad F = m^* \times \frac{dv_g}{dV}$$

where m* is the effective mass.

If an electric field 'ε' is impressed, the electron will accelerate and its velocity and energy will increase. Hence the electron is said to have positive mass. On the other hand, if an electron is at the upper end of a band, when the field is applied, its energy will increase and its velocity decreases. So the electron is said to have negative mass.

In an atom,

$$\text{Coulombs force of attraction} = \frac{e^2}{4\pi \epsilon_0 r^2}$$

$$\text{Centripetal Force} = \frac{mv^2}{r}$$

Equating these two forces in an atom,

$$\frac{e^2}{4\pi \epsilon_0 r^2} = \frac{mv^2}{r} \quad v = \text{velocity; } r = \text{radius of Orbit}$$

$$\therefore \quad \frac{e^2}{4\pi \epsilon_0} = \frac{mv^2}{r} \times r^2 = mv^2 r$$

$$\therefore \quad r = \frac{e^2}{4\pi \epsilon_0 mv^2} \qquad \text{..........(1.2)}$$

$$\text{But} \quad mvr = \frac{nh}{2\pi} \quad h = \text{Plank's Constant; } n = \text{Principle Quantum Number.}$$

$$\therefore \quad v = \frac{nh}{2\pi mr} \qquad \text{..........(1.3)}$$

Substituting the value of v in eq. (1.2),

$$r = \frac{e^2 \times 4\pi^2 m^2 r^2}{4\pi \epsilon_0 . m \times n^2 h^2}$$

$$\therefore \quad \boxed{r = \frac{n^2 h^2 \epsilon_0}{\pi m e^2}} \qquad \text{..........(1.4)}$$

This is the expression for radii of stable states.

Energy possessed by the atom in the stable state is

$$W = \frac{e^2}{8\pi \epsilon_0 r} \qquad \text{..........(1.5)}$$

Substituting the value of r in Eq. (1.5), then

$$W = -\frac{e^2 \times \pi m e^2}{8\pi \epsilon_0 n^2 h^2 \epsilon_0}$$

$$W = -\frac{me^4}{8h^2 \epsilon_0^2} \cdot \frac{1}{n^2}$$

Thus energy 'W' corresponds to only the coulombs force due to attraction between ground electron (negative charge) and proton (positive charge).

Problem 1.1

Determine the radius of the lowest state of Ground State.

Solution

$$n = 1$$

$$\because \quad r = \frac{n^2h^2 \in_0}{\pi me^2}$$

Plank's Constant, $h = 6.626 \times 10^{-34}$ J-sec

Permitivity, $\in_0 = 10^{-9}/36\pi$

Substituting the values and simplifying,

$$\therefore \quad r = 0.58 \text{ A}^0$$

1.1.4 ATOMIC ENERGY LEVELS

For different elements, the value of the free electron concentration will be different. By spectroscopic analysis we can determine the energy level of an element at different wavelengths. This is the characteristic of the given element.

The lowest energy state is called the normal level or ground level. Other stationary states are called ***excited***, ***radiating***, ***critical*** or ***resonance*** levels.

Generally, the energy of different states is expressed in (eV) electrovolts rather than in Joules (J), and the emitted radiation is expressed by its wavelength λ rather than by its frequency. This is only for convenience since Joule is a larger unit and the energy is small and is in electron volts.

$$F = \frac{W_2 - W_1}{h}$$

$$f = \frac{C}{\lambda}$$

C = Velocity of Light = 3×10^{10} cm / sec.

h = Plank's Constant = 6.626×10^{-34} J - sec.

f = Frequency of Radiation

λ = Wavelength of emitted radiation

W_1 and W_2 are the energy levels in Joules.

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

$$\therefore \quad \frac{C}{\lambda} = \frac{(E_2 - E_1) \times 1.6 \times 10^{-19}}{h}$$

$$\frac{3 \times 10^{10}}{\lambda} = \frac{(E_2 - E_1) \times 1.6 \times 10^{-19}}{6.626 \times 10^{-34}}$$

E_1 and E_2 are energy levels in eV.

or $$\lambda = \frac{3\times10^{10}\times6.626\times10^{-34}}{(E_2 - E_1)\times1.6\times10^{-19}}$$

$$\boxed{\lambda = \frac{12{,}400}{(E_2 - E_1)} A^0}$$

where 'λ' is in Armstrong, $1A^0 = 10^{-8}$ cm $= 10^{-10}$ m, and E_2 and E_1 in eV.

1.1.5 PHOTON NATURE OF LIGHT

An electron can be in the excited state for a small period of 10^{-7} to 10^{-10} sec. Afterwards it returns back to the original state. When such a transition occurs, the electrons will loose energy equal to the difference of energy levels $(E_2 - E_1)$. This loss of energy of the atom results in radiation of light. The frequency of the emitted radiation is given by

$$f = \frac{(E_2 - E_1)}{h}.$$

According to classical theory it was believed that atoms continuously radiate energy. But this is not true. Radiation of energy in the form of photons takes place only when the transition of electrons will take place from higher energy state to lower energy state, so that $(E_2 - E_1)$, is positive. This will not occur if the transition is from lower energy state to higher energy state. When such photon radiation takes place, the number of photons liberated is very large. This is explained with a numercial example given below.

Problem 1.2

For a given 50 W energy vapour lamp. 0.1% of the electric energy supplied to the lamp, appears in the ultraviolet line 2,537 A^0. Calculate the number of photons per second, of this wavelength emitted by the lamp.

Solution

$$\lambda = \frac{12{,}400}{(E_2 - E_1)}$$

λ = Wavelength of the emitted radiation.

E_1 and E_2 are the energy levels in eV.

$(E_2 - E_1)$ is the energy passed by each photon in eV of wavelength λ. In the given problem, $\lambda = 2{,}537\ A^0$. $(E_2 - E_1) = ?$

$$\therefore \quad (E_2 - E_1) = \frac{12{,}400}{2{,}537} = 4.88 \text{ eV/photon}$$

0.1% of 50W energy supplied to the lamp is,

i.e., $$\frac{0.1}{100} \times 50 = 0.05 \text{ W} = 0.05 \text{ J/Sec}$$

$$\because \quad 1W = 1 \text{ J/sec}$$

Converting this into the electron Volts,

$$\frac{0.05\ \text{J/sec}}{1.6\times10^{-19}\ \text{J/eV}} = 3.12 \times 10^{17}\ \text{eV/sec}$$

This is the total energy of all the photons liberated in the λ = Wavelength of 2,537 A^0.

$$\therefore \quad \text{Number of photons emitted per sec} = \frac{\text{total energy}}{\text{energy / photon}}$$

$$= \frac{3.12\times10^{17}\ \text{ev/sec}}{4.88\ \text{ev/photon}}$$

$$= 6.4 \times 10^{16}\ \text{photon/sec}$$

The lamp emits 6.4×10^{16} photons / sec of wavelength λ = 2, 537A^0.

1.1.6 IONIZATION POTENTIAL

If the most loosely bound electron (free electron) of an atom is given more and more energy, it moves to stable state (since it is loosely bound, its tendency is to acquire a stable state. Electrons orbiting closer to the nucleus have stable state, and electron orbiting in the outermost shells are loosely bound to the nucleus). But the stable state acquired by the electron is away from the nucleus of the atom. If the energy supplied to the loosely bound electron is enough large, to move it away completely from the influence of the parent nucleus, it becomes detached from it. ***The energy required to detach an electron is called Ionization Potential.***

1.1.7 COLLISIONS OF ELECTRONS WITH ATOMS

If a loosely bound electron has to be liberated, energy has to be supplied to it. Consider the case when an electron is accelerated and collides with an atom. If this electron is moving slowly with less energy, and collides with an atom, it gets deflected, i.e., its direction changes. But no considerable change occurs in energy. This is called ***Elastic Collision***.

If the electron is having much energy, then this electron transfers its energy to the loosely bound electron of the atom and may remove the electron from the atom itself. So another free electron results. If the bombarding electron is having energy greater than that required to liberate a loosely bound electron from atom, the excess energy will be shared by the bombarding and liberated electrons.

Problem 1.3

Argon resonance radiation, corresponding to an energy of 11.6 eV falls upon sodium vapor. If a photon ionizes an unexcited sodium atom, with what speed is the electron ejected ? The ionization potential of sodium is 5.12 eV.

Solution

Ionization potential is the minimum potential required to liberate an electron from its parent atom. Argon energy is 11.6 eV. Ionization Potential of Na is 5.12 eV.

$\therefore$ The energy possessed by the electron which is ejected is

$$11.6 - 5.12 = 6.48\ \text{eV}$$

or Potential, $V = 6.48$ volts ($\because$ 1eV energy, potential is 1V)

Its velocity $v = \sqrt{\frac{2eV}{m}} = 5.93 \times 10^5 \sqrt{6.48} = 1.51 \times 10^6$ m/sec.

Problem 1.4

With what speed must an electron be travelling in a sodium vapor lamp in order to excite the yellow line whose wavelength is 5,893 A°.

Solution

$$\text{Ee} \geq \frac{12{,}400}{5{,}893} \geq 2.11 \text{ eV}$$ (Corresponding to evergy of 2.11eV, the potential is 2.11 Volts)

$$V = 2.11 \text{ Volts}$$

$$\therefore \text{ Velocity,} \quad v = \sqrt{\frac{2eV}{m}} = 5.93 \times 10^5 \sqrt{2.11} = 8.61 \times 10^5 \text{ m/sec.}$$

Problem 1.5

A radio transmitter radiates 1000 W at a frequency of 10 MHz.

(a) *What is the energy of each radiated quantum in ev ?*

(b) *How many quanta are emitted per second ?*

(c) *How many quanta are emitted in each period of oscillation of the electromagnetic field ?*

Solution

(a) Energy of each radiated quantum = E = hf

$f = 10 \text{ MHz} = 10^7 \text{ Hz}, h = 6.626 \times 10^{-34}$ Joules / sec

$\therefore$ $E = 6.626 \times 10^{-34}\, 10^7 = 6.626 \times 10^{-27}$ Joules / Quantum

$$= \frac{6.626 \times 10^{-27}}{1.6 \times 10^{-19}} = 4.14 \times 10^{-8} \text{ eV / Quantum}$$

(b) 1 W = 1 Joule/sec

1000 W = 1000 Joules/sec = Total Energy

Energy possessed by each quantum = 6.626×10^{-27} Joules/Quantum.

$$\therefore \quad \text{Total number of quanta per sec, N} = \frac{1000}{6.626 \times 10^{-27}} = 1.5 \times 10^{29}/\text{sec}$$

(c) One cycle = 10^{-7} sec

$\therefore$ Number of quanta emitted per cycle $= 10^{-7} \times 1.51 \times 10^{29}$

$= 1.51 \times 10^{22}$ per cycle

Problem 1.6

(a) *What is the minimum speed with which an electron must be travelling in order that a collision between it and an unexcited Neon atom may result in ionization of this atom? The Ionization Potential of Neon is 21.5 V.*

(b) *What is the minimum frequency that a photon can have and still be able to cause Photo-Ionization of a Neon atom?*

Solution

(a) Ionization Potential is 21.5 V

$$\therefore \quad \text{Velocity} = \sqrt{\frac{2eV}{m}} = 5.93 \times 10^5 \sqrt{21.5} = 2.75 \times 10^6 \text{ m/sec}$$

Wavelength of radiation,

(b)
$$\lambda = \frac{12{,}400}{E_2 - E_1} = \frac{12{,}400}{21.5} = 577 \text{ A}^0$$

Frequency of radiation,

$$f = \frac{C}{\lambda} = \frac{3 \times 10^8}{577 \times 10^{-10}} = 5.2 \times 10^{15} \text{ Hz}$$

Problem 1.7

Show that the time for one revolution of the electron in the hydrogen atom in a circular path around the nucleus is

$$T = \frac{m^{1/2} e^2}{4\sqrt{2}\, \epsilon_0 \,(-W)^{\frac{3}{2}}}$$

Solution

$$v = \sqrt{\frac{e^2}{4\pi m \,\epsilon_0\, r}}$$

$$T = \frac{2\pi r}{v} = \frac{2\pi r (4\pi m\, \epsilon_0\, r)^{1/2}}{e} = \frac{2\pi r^{\frac{3}{2}} (4\pi m\, \epsilon_0)^{1/2}}{e}$$

But radius,
$$r = \frac{e^2}{4\pi\, \epsilon_0\, W}$$

$$\therefore \quad T = \frac{m^{1/2} e^2}{4\sqrt{2}\, \epsilon_0\, (-W)^{3/2}}$$

Problem 1.8

A photon of wavelength 1,400 A° is absorbed by cold mercury vapor and two other photons are emitted. If one of these is the 1,850 A° line, what is the wavelength λ of the second photon ?

Solution

$$(E_2 - E_1) = \frac{12{,}400}{\lambda} = \frac{12{,}400}{1400} = 8.86 \text{ eV}$$

1850^0 A° line is from 6.71 eV to 0 eV.

∴ The second photon must be from 8.86 to 6.71 eV.

So, $\Delta E = 2.15$ eV.

$$\lambda = \frac{12{,}400}{(E_2 - E_1)}$$

$$\lambda = \frac{12{,}400}{2.15} = 5767 \text{ A}^0$$

1.1.8 METASTABLE STATES

An atom may be elevated to an excited energy state by absorbing a photon of frequency 'f' and thereby move from the level of energy W_1 to the higher energy level W_2 where $W_2 = W_1 + hf$. But certain states may exist which can be excited by electron bombardment but not by photo excitation (absorbing photons and raising to the excited state). ***Such levels are called metastable states.*** A transition from a metastable level to a normal state with the emission of radiation has a very low probability of occurence. Transition from higher level to a metastable state are permitted, and several of these will occur.

An electron can be in the metastable state for about 10^{-2} to 10^{-4} sec. This is the mean life of a metastable state. Metastable state has a long lifetime because they cannot come to the normal state by emitting a photon. Then if an atom is in metastable state how will it come to the normal state? It cannot release a photon to come to normal state since this is forbidden. Therefore an atom in the metastable state can come to normal state only by colliding with another molecule and giving up its energy to the other molecule. Another possibility is the atom in the metastable state may receive additional energy by some means and hence may be elevated to a higher energy state from where a transition to normal state can occur.

1.1.9 WAVE PROPERTIES OF MATTER

An atom may absorb a photon of frequency 'f' and move from the energy level 'W_1' to the higher energy level 'W_2' where $W_2 = W_1 + hf$.

Since a photon is absorbed by only one atom, the photon acts as if it were concentrated in one point in space. So wave properties can not be attributed to such atoms and they behave like particles.

Therefore according to 'DeBroglie' hypothesis, dual character of wave and particle is not limited to radiation alone, but is also exhibited by particles such as electrons, atoms, and molecules. He calculated that a particle of mass 'm' travelling with a velocity 'v' has a wavelength 'λ' given by $\lambda = \frac{h}{mv} = \frac{h}{p}$ (λ is the wavelength of waves consisting of these particles).

Where 'p' is the momentum of the particle. Wave properties of moving electrons can be made use to explain Bohr's postulates. A stable orbit is one whose circumference is exactly equal to the wavelength 'λ' or '$n\lambda$' where 'n' is an integer other than zero.

Thus, $2\pi r = n\lambda$ r = radius of orbit, n = Principle Quantum Number.

But according to DeBroglie,

$$\lambda = \frac{h}{mv}$$

$$\therefore \quad 2\pi r = \frac{nh}{mv}$$

This equation is identical with Bohr's condition, $mvr = \frac{nh}{2\pi}$

1.1.10 SCHRODINGER EQUATION

Schrodinger carried the implications of the wave nature of electrons. A branch of physics called ***Wave Mechanics*** or ***Quantum Mechanics*** was developed by him. If deBroglie's concept of wave nature of electrons is correct, then it should be possible to deduce the properties of an electron system from a mathematical relationship called the ***Wave Equation*** or ***Schrodinger Equation***. It is

$$\nabla^2\phi - \frac{1}{v^2}\cdot\frac{\partial^2\phi}{\partial t^2} = 0, \qquad \text{..........(1.6)}$$

where $$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

'ϕ' can be a component of electric field or displacement or pressure. 'v' is the velocity of the wave, and 't' is the time.

The variable can be eliminated in the equation by assuming a solution.

$$\phi\,(x, y, z, t) = \psi\,(x, y, z)e^{jwt}$$

This represents the position of a particle at 't' in 3-D Motion.

ω = Angular Frequency = 2 πf

ω is regarded as constant, while differentiating.

ϕ is a function of x, y, z and t.

But ψ is a function of x, y and z only.

To get the independent ***Schrodinger Equation***

$$\frac{\partial\phi}{\partial t} = j\omega\psi(x, y, z)e^{j\omega t}$$

$$\frac{\partial^2\phi}{\partial t^2} = -\omega^2\psi(x, y, z)e^{j\omega t}$$

But $\omega = 2\pi f$

So, $\omega^2 = 4\pi^2 f^2$

Substituting this in the original ***Schrodinger's Equation***,

$$e^{jwt}\left\{\nabla^2\psi + \frac{1}{v^2}\times 4\pi^2 f^2\psi\right\} = 0$$

But $\lambda = \frac{v}{f}$; Wavelength = $\frac{\text{Velocity}}{\text{Frequency}}$

$$\therefore \quad \nabla^2\psi + \frac{4\pi^2}{\lambda^2}\psi = 0 \qquad \text{..........(1.7)}$$

But $\lambda = \frac{h}{mv} = \frac{h}{p}$ v = Velocity.

$\because$ p = mv

This is deBrogile's Relationship.

$$\frac{1}{\lambda^2} = \frac{p^2}{h^2}$$

But $p^2 = m^2 v^2 = 2$ (Kinetic Energy)m $\because$ K.E. = $\frac{1}{2}mv^2$

Kinetic Energy = Total Energy (W) – Potential Energy (U)

$\therefore$ $p^2 = 2(W - U) \cdot m$

$$\therefore \quad \frac{p^2}{h^2} = \frac{2m}{h^2}(W - U) \qquad \text{..........(1.8)}$$

Substituting Eq. (1.8) in Eq. (1.7) we get,

$$\nabla^2 \Psi + \frac{8\pi^2 m}{h^2}(W - U)\Psi = 0.$$

This is the Time Independent Schrodinger Equation Ψ is a function of 't', But this equation as such is not containing the term 't'.

1.1.11 WAVE FUNCTION

'Ψ' is called as the wave function, which describes the behavior of the particle. 'Ψ' is a quantity whose square gives the probability of finding an electron. $|\Psi|^2(dx \times dy \times dz)$ is proportional to the probability of finding an electron in volume dx, dy and dz at point P(x, y, z).

Four quantum numbers are required to define the wave function. They are :

1. ***The Principal Quantum Number 'n' :***

   It is an integer 1, 2, 3, ... This number determines the total energy associated with a state. It is same as the quantum number 'n' of Bohr atom.

2. ***The Orbital Angular Momentum Quantum Number l :***

   It takes values 0, 1, 2...l... $(n - l)$

   The magnitude of this angular momentum is $\sqrt{(l)(l+1)} \times \frac{h}{2\pi}$

   It indicates the shape of the classical orbit.

3. ***The orbital magnetic number m_l :***

   This will have values 0, ± 1, ±2 .... ± l. This number gives the orientation of the classical orbit with respect to an applied magnetic field.

   The magnitude of the Angular Momentum along the direction of magnetic field $= m_\ell\left(\frac{h}{2\pi}\right)$.

4. ***Electron Spin :***

   It was found is 1925 that in addition to assuming that electron orbits round the nucleus, it is also necessary to assume that electron also spins around itself, in addition to orbiting round the nucleus. This intrinsic electronic angular momentum is called ***Electron Spin***.

   When an electron system is subjected to a magnetic field, the spin axis will orbit itself either parallel or anti-parallel to the direction of the field. The electron angular momentum is given by $m_s\left(\frac{h}{2\pi}\right)$ where the spin quantum m_s number may have values +½ or –½.

1.1.12 ELECTRONIC CONFIGURATION

PAULI'S EXCLUSION PRINCIPLE

No two electrons in an electron system can have the same set of four quantum numbers n, l, m_l and m_s.

Electrons will occupy the lower most quantum state.

ELECTRONIC SHELLS (PRINCIPLE QUANTUM NUMBER)

All the electrons which have the same value of 'n' in an atom are said to belong to the same electron shell. These shells are identified by letters K, L, M, N corresponding to n = 1, 2, 3, 4..... A shell is subdivided into sub shells corresponding to values of l and identified as s, p, d, f, g, h,. for l = 0, 1, 2, 3... respectively. This is shown in Table 1.1.

Table 1.1

Shell ..... n	K 1	L 2		M 3			N 4			
l ..... subshell	0 s	0 s	1 p	0 s	1 p	2 d	0 s	1 p	2 d	3 f
No. of	2	2	6	2	6	10	2	6	10	14
electron	2	8		18			32			

ELECTRON SHELLS AND SUBSHELLS

Number of Electrons in a sub shell = $2(2l + 1)$

n = 1 corresponds to K shell

$l = 0$ corresponds to s sub shell

$\because$ $l = 0, \ldots, (n - 1)$ if $n = 1$,

$l = 0$ is the only possibility

Number of electrons in K shell = $2(2l + 1) = 2(0 + 1) = 2$ electrons.

$\therefore$ K shell will have 2 electrons.

This is written as $1s^2$ pronounced as "***one s two***" (1 corresponds to K shell, n = 1; s is the sub shell corresponds to $l = 0$ number of electron is 2. Therefore, $1s^2$)

If n = 2, it is 'l' shell

If $l = 0$, it is 's' sub shell

If $l = 1$, it is 'p' sub shell

Number of electron in 's' sub shell (i.e., $l = 0$) = $2 \times (2l + 1) = 2(0 + 1) = 2$

Number of electron is 'p' sub shell (i.e., $l = 1$) = $2[\,(1 \times 2) + 1)\,] = 6$

In l shell there are two sub shells, s and p.

$\therefore$ Total number of electron in l shell = 2 + 6 = 8

This can be represented as $2s^2\ 2p^6$

If n = 3, it is M shell

It has 3 sub shell s, p, d, corresponding to $l = 0, 1, 2$

In 's' sub shell number of electrons $(l = 0) = 2(\therefore l = 0)\ 2(2l + 1)$

In 'p' sub shell number of electrons $(l = 1) = 2(2 + 1) = 6$

In 'd' sub shell number of electrons $(l = 2) = 2(2 \times 2 + 1) = 10$

$\therefore$ Total number of electrons in M shell = 10 + 6 + 2 = 18

This can be represented as $3s^2\ 3p^6\ 3d^{10}$

$\therefore\ 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 4d^{10}$

ELECTRONIC CONFIGURATION

Atomic number 'z' gives the number of electrons orbiting round the nucleus. So from the above analysis, electron configuration can be given as $1s^2\ 2s^2\ 2p^6\ 3s^1$. First k shell (n = 1) is to be filled. Then l shell (n = 2) and so on.

In 'K' shell there is one sub shell (s) $(l = 0)$. This has to be filled.

In 'L' shell there are two sub shells and p. First – s and then p are to be filled and so on.

The sum of subscripts 2 + 2 + 6 + 1 = 11. It is the atomic number represented as Z.

For Carbon, the Atomic Number is 6., i.e., Z = 6.

$\therefore$ The electron configuration is $1s^2\ 2s^2\ 2p^2$

For the Ge Z = 32. So the electronic configuration of Germanium is,

$\therefore\ 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$

For the Si Z = 14. So the electronic configuration of Silicon is,

$\therefore\ 1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^2$

1.1.13 TYPES OF ELECTRON EMISSION

Electrons at absolute zero possess energy ranging from 0 to E_F the fermi level. It is the characteristic of the substance. But this energy is not sufficient for electrons to escape from the surface. They must posses energy $E_B = E_F + E_W$ where E_W is the work function in eV.

E_B = Barrier's Energy

E_F = Fermi Level

E_W = Work Function.

Different types of Emission by which electrons can emit are

(1) *Thermionic Emission*

(2) *Secondary Emission*

(3) *Photoelectric Emission*

(4) *High field Emission.*

1. THERMIONIC EMISSION

Suppose, the metal is in the form of a filament and is heated by passing a current through it. As the temperature is increased, the electron energy distribution starts in the metal changes. Some electrons may acquire energy greater than E_B sufficient to escape from the metal.

E_W : ***Work function of a metal. It represents the amount of energy that must be given for the electron to be able to escape from the metal.***

It is possible to calculate the number of electrons striking the surface of the metal per second with sufficient energy to be able to surmount the surface barriers and hence escape. Based upon that, the thermionic current is,

$$I_{th} = S \times Ao\,T^2\ e^{-E_w/KT} \qquad \text{.......... (1.9)}$$

It is also written as

$$\frac{I_{th}}{S} = J = AoT^2\ e^{\frac{-E_w}{kT}} = AT^2\ e^{\frac{-B}{T}}$$

where $A = A_o$ and $B = \frac{E_W}{k}$

where
S = Area of the filament in m^2 (Surface Area)
Ao= Constant whose dimensions are $A/m^2\ {}^oK$
T = Temperature in ^oK
K = Boltzman's constant $eV/^oK$
E_w= Work function in eV

This equation is called ***Thermionic Emission Current*** or ***Richardson - Dushman Equation***. E_w is also called as latent heat of evaporation of electrons similar to evaporation of molecules from a liquid.

Taking logarithms

$$\log I_{th} = \log (S\,A_o) - \frac{E_w}{kT}\ \log e + \log T^2$$

$$\log I_{th} - 2 \log T = \log S\,Ao - 0.434 \left(\frac{E_W}{kT}\right)$$

$$\because \quad \log e = 0.434$$

So if a graph is plotted between ($\log I_{th} - 2 \log T$) V_S $\frac{1}{T}$, the result will be a straight line having a slope = $- 0.434 \left(\frac{E_W}{kT}\right)$ from which E_W can be determined.

$\because$ I_{th} and T can be determined experimentally.

I_{th} is a very strong function of T. For Tungsten, $E_W = 4.52$ eV.

CONTACT POTENTIAL

Consider two metals in contact with each other forming junction at 'C' as in Fig 1.1 . The contact difference of potential is defined as the Potential Difference V_{AB} between a point A, just out side metal1 and a point B just outside metal2. The reason for the difference of potential is, when two metals are joined, electrons will flow from the metal of lower Work Function, say 1 to the metal of higher Work Function say 2. ($\because$ $E_W = E_B - E_F$ electrons of lower work function means E_W is small or E_F is large). Flow of electrons from metal 1 to 2 will continue till metal 2 has acquired sufficient negative charge to repel extra new electrons. 'E_B' value will be almost same for all metals. But E_F differs significantly.

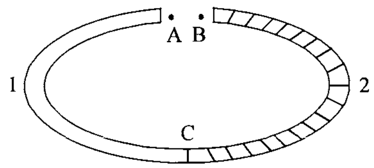


Fig 1.1 Contact Potential

In order that the fermi levels of both the metals are at the same level, the potential energy difference $E_{AB} = E_{W2} - E_{W1}$, that is, ***the contact difference of potential energy between two metals is equal to the difference between their work functions.***

If metals 1 and 2 are similar then contact potential is zero. If they are dissimilar, the metal with lower work function becomes positive, since it looses electrons.

ENERGIES OF EMITTED ELECTRONS

At absolute zero, the electrons will have energies ranging from zero to E_F. So the electrons liberated from the metal surface will also have different energies. The minimum energy required is the barrier potential to escape from the metal surface, But the electrons can acquire energy greater than E_B to escape from the surface. This depends upon the initial energy, the electrons are possessing at room temperature.

Consider a case where anode and cathode are plane parallel. Suppose the voltage applied to the cathode is lower, and the anode is indirectly heated. Suppose the minimum energy required to escape from the metal surface is 2 eV. As collector is at a potential less than 2V, electrons will be collected by the collector. If the voltage of cathode is lower, below 2V, then the current also decreases exponentially, but not abruptly. If electrons are being emitted from cathode with 2eV energy, and the voltage is reduced below 2V, then there must be abrupt drop of current to zero. But it doesn't happen This shows that electrons are emitted from surface of the emitter with different velocities. The decrease of current is given by $I = I_{th}.e^{-V_T}$ where V_T is the retarding potential applied to the collector and V_T is Volt equivalent of temperature.

$$V_T = \frac{kT}{e} = \frac{T}{11,600} \qquad \text{.......... (1.10)}$$

T = Temperature in °K

K = Boltzman's Constant in J/°K

SCHOTTKY EFFECT

If a cathode is heated, and anode is given a positive potential, then there will be electron emission due to thermionic emission. There is accelerating field, since anode is at a positive potential. This accelerating field tends to lower the Work Function of the cathode material. It can be shown that under the condition of accelerating field E is

$$I = I_{th}\; e^{+0.44\ \varepsilon 1/2/T}$$

where I_{th} is the zero field thermionic current and T is cathode temperature in 0 °K.

The effect that thermionic current continues to increase as E is increased (even though T is kept constant) is known as ***Schottky Effect.***

2. SECONDARY EMISSION

This emission results from a material (metal or dielectric) when subjected to electron bombardment.

It depends upon,

1. *The energy of the primary electrons.*
2. *The angle of incidence.*
3. *The type of material.*
4. *The physical condition of surface ; whether surface is smooth or rough.*

Yield or secondary emission ratio S is defined as the ratio of the number of secondary electrons to primary electrons. It is small for pure metals, the value being 1.5 to 2. By contamination or giving a coating of alkali metal on the surface, it can be improved to 10 or 15.

3. PHOTO ELECTRIC EMISSION

Photo-Electric Emission consists of liberation of electrons by the incidence of light, on certain surfaces. The energy possessed by photons is 'hf' where 'h' is Plank's Constant and 'f' is frequency of incident light. When such a photon impinges upon the metal surface, this energy **hf** gets transferred to the electrons close to the metal surface whose energy is, very near to the barrier potential. Such electrons gain energy, to overcome the barrier potential and escape from the surface of the metal resulting in photo electric emission.

For photoelectric emission to take places, the energy of the photon must at least be equal to the work function of the metal. That is $hf \geq e\phi$ where ϕ is the voltage equivalent Work Function, (i.e. Work Function expressed in Volts). ***The minimum frequency that can cause photo-electric emission is called threshold frequency*** and is given by

$$f_T = \frac{e\phi}{h}$$

The wavelength corresponding to threshold frequency is called the ***Threshold Wavelength***.

$$\lambda_t = \frac{C}{f_t} = \frac{h_C}{\phi e}$$

If the frequency of radiation is less than f_T, then additional energy appears as kinetic energy of the emitted electron

$$\therefore \quad hf = \phi e + \frac{1}{2} m v^2$$

ϕ is the Volt equivalent of Work Function.

$$v = \sqrt{\frac{2eV}{m}}$$

v is the Velocity of electrons in m/sec.

$$\therefore \quad \boxed{hf = = \phi e + eV} \qquad \text{..........} \ (1.11)$$

LAWS OF PHOTO ELECTRIC EMISSION

1. *For each photo sensitive material, there is a threshold frequency below which emission does not take place.*
2. *The amount of photo electric emission (current) is proportional to intensity.*

3. *Photo electric emission is instantaneous. (But the time lag is in nano-sec).*
4. *Photo electric current in amps/watt of incident light depends upon 'f'.*

4. HIGH FIELD EMISSION

Suppose a cathode is placed inside a very intense electric field, then the Potential Energy is reduced. For fields of the order of 10^9 V/m, the barrier may be as thin as 100 A°. So the electron will travel through the barrier. This emission is called as ***High Field Emission*** or ***Auto Electronic Emission.***

Problem 1.9

Estimate the percentage increase in emission from a tungsten filament when its temperature is raised from 2400 to 2410 °K.

$$A_0 = 60.2 \times 10^4\ \text{A/m}^2/{}^\circ\text{K}^2$$
$$B = 52{,}400\ {}^\circ\text{K}$$

A and B are constants in the equation for current density J

Solution

$$JS_1 = A\,T_1^2 = 1142\ \text{A / m}^2$$
$$JS_2 = AT_2^2\, e^{-B/T} = 1261\ \text{A / m}^2.$$

$$\text{Percentage Increase} = \frac{1261-1142}{1142}\times 100 = 10.35\%$$

Problem 1.10

A photoelectric cell has a cesium cathode. When the cathode is illuminated with light of $\lambda = 5500 \times 10^{-10}$ m, the minimum anode voltage required to inhibit built anode current is 0.55 V. Calculate

(a) *The work function of cesium*

(b) *The longest λ for which photo cell can function.*

by applying –0.55V to anode the emitted electrons are repelled. So the current can be inhibited

Solution

(a) $hf = e\phi + eV$ V = 0.55 volts ϕ = Work Function (WF) = ?

$$f = \frac{C}{\lambda}$$

$$\therefore \quad \frac{h.C}{\lambda} = e(\phi + V)$$

Plank's Constant, $h = 6.63 \times 10^{-34}$ J sec.

Charge of Electron, $e = 1.6 \times 10^{-19}$ C

Velocity of Light, $C = 3 \times 10^8$ m/sec

$$= \frac{6.63\times10^{-34}\times3\times10^{8}}{5500\times10^{-10}} = 1.6 \times 10^{-19}(\phi + 0.55)$$

$$\phi = 1.71\ \text{Volts}$$

(b) ***Threshold Wavelength :***

$$\lambda_o = \frac{Ch}{e\phi}$$

$$\therefore \qquad \lambda_o = \frac{12{,}400}{\phi} = \frac{12{,}400}{1.71} = 7{,}250\ A^o$$

Problem 1.11

If the temperature of a tungsten filament is raised from 2300 to 2320 ^oK, by what percentage will the emission change ? To what temperature must the filament be raised in order to double its energy at 2300 ^oK. E_W for Tungsten = 4.52 eV. Boltzman's Constant K = 8.62×10^5 eV/^oK.

Solution

(a) $$I_{th} = S.A_o\ T^2\ e^{-Ew/kT}$$

Taking Logarithms,

$$ln\ I_{th} - 2 \log T = ln\ S\ A_o - \frac{E_w}{kT}$$

Differentiating, $$\left(\frac{2}{T} + \frac{E_W}{KT^2}\right)\frac{dT}{T^2}$$

$$\frac{dI_{th}}{I_{th}} = \left(2 + \frac{E_W}{kT}\right)\frac{dT}{T} = \left(2 + \frac{4.52}{(8.62\times10^{-5})2310}\right)\frac{20}{2310} = 21.4\%$$

(b) $$I_{th} = S.Ao\ (2300)^2\ e^{\frac{-4.52}{8.62\times10^{-5}\times2300}}$$

$$2I_{th} = S\ Ao\ (T)^2\ e^{\frac{-4.52}{8.62\times10^{-5}}}$$

Ratio of these two equation is

$$2 = \left(\frac{T}{2300}\right)^2 e^{-\frac{52{,}400}{T}+22.8}$$

Taking log to the base 10,

$$\log 2 = 2 \log\left(\frac{T}{2300}\right) - \left(\frac{52{,}400}{T} + 22.8\right)\log e$$

$$\log 2 = 2 \log\left(\frac{T}{2300}\right) - \frac{52400}{T}\times 0.434 - 22.8 \times 0.434$$

$$9.6 + 2 \log\left(\frac{T}{2300}\right) = \frac{22{,}800}{T}$$

This is solved by Trail and Error Method to get $T = 2370^0K$

Problem 1.12

In a cyclotron, the magnetic field applied is 1 Tesla. If the ions (electrons) cross the gap between the D shaped discs dees twice in each cycle, determine the frequency of the R.F. voltage. If in each passage through the gap, the potential is increased by 40,000 volts how many passages are required to produce a 2 million volts particle? What is the diameter of the last semicircle?

Solution

$$B = 1 \text{ Tesla} = 1 \text{Wb/m}^2$$

Time taken by the particle to describe one circle is $T = \dfrac{35.5\mu\text{sec}}{B}$

$$T = \frac{35.5 \times 10^{-6}}{1} \text{ sec,}$$

when it describes one circle, the particle passes through the gap twice.

$\therefore$ The frequency of the R.F voltage should be the same.

$$\therefore \quad f = \frac{1}{T} = \frac{1}{35.5 \times 10^{-6}} = 2.82 \times 10^{10} \text{ Hz}$$

Number of passages required :

In each passage it gains 40,000 volts.

To gain 2 million electron volts $= \dfrac{2 \times 10^6 \text{V}}{40 \times 10^3 \text{V}} = 50$

Diameter of last semicircle :

The initial velocity for the 50th revolution is the velocity gained after 49th revolution.

$\therefore$ Accelerating potential $V_0 = 49 \times 40{,}000 = 1{,}960$ KV 49th revolution

Radius of the last semicircle $= R = \dfrac{3.37 \times 10^{-6}}{B}\sqrt{V_0}$

$$R = \frac{3.37 \times 10^{-6}}{1}\sqrt{1960 \times 10^3} = 47.18 \times 10^{-4} \text{ m}$$

$$\text{Diameter} = 2R = 94.36 \times 10^{-4} \text{ m}$$

Problem 1.13

The radiated power density necessary to maintain an oxide coated filament at 110 °K is found to be 5.8×10^4 W/m^2. Assume that the heat loss due to conductor is 10% of the radiation loss. Calculate the total emission current and the cathode efficiency η in ma/w.

Take

$E_W = 1.0$ eV
$A_0 = 100$ A/m^2 / °K^2
$S = 1.8$ cm^2

$\bar{K}$ = Boltzman's Constant in eV / °K = 8.62×10^{-5}eV / °K

Solution

Power Density = 5.8×10^4 W/m^2

If 10% is lost by conductor, then the total input power density is $1.1 \times 5.8 \times 10^4 = 6.38$ W/m^2 and the total input power is $6.38 \times 10^4 \times$ Area $(1.8 \times 10^{-4}) = 11.5$ W.

$$I_{th} = S\,Ao\,T^2\,e^{-Ew/kT}$$

$$= 1.8 \times 10^{-4} \times 100 \times (1100)^2\,e^{-\frac{1}{8.62\times10^{-5}\times1100}}$$

$$I_{th} = 2.18 \times 10^4\,e^{-10.55}$$

$$I_{th} = 0.575\ \text{A}$$

$$\text{Cathode Efficiency, } \eta = \frac{0.575}{11.5} = 50\ \text{mA} / {}^{\text{o}}\text{K}$$

1.2 n-TYPE AND p-TYPE SEMICONDUCTORS

1.2.1 n-TYPE OR DONOR TYPE SEMICONDUCTORS

Intrinsic or pure semiconductor is of no use since its conductivity is less and it can not be charged much. If a pure semiconductor is doped with impurity it becomes extrinsic. Depending upon impurity doped, the semiconductor may become ***n-type, where electrons are the majority carriers or donor type***, since it donates an electron. On the other hand ***if the majority carriers are holes, it is p-type or acceptor type semiconductor***, because it accepts an electron to complete the broken covalent bond.

Germanium atom with its electrons arranged in shells will have configuration as

$$1s^2\,2s^2\,2p^2\,3s^2\,3p^6\,3d^{10}\,4s^2\,4p^2$$

Ge is tetravalent (4). 'Ge' becomes *n-type* if a pentavalent (5), impurity atoms such as Phosphorus (P), or Arsenic are added to it.

The impurity atoms have size of the same order as that of Ge atoms. Because of the energy supplied while doping, the impurity atom dislodges one from its normal position in the crystal lattices takes up that position. But since the concentration of impurity atoms is very small (about 1 atom per million of Ge atoms), the impurity atom is surrounded by Ge atoms. The impurity atom is pentavalent. That is, it has 5 electrons in the outermost orbit (5 valence electrons). Now 4 of these are shared by Ge atoms, surrounding the impurity atom and they form covalent bonds. So one electron of the impurity atom is left free. The energy required to dislodge this fifth electron from its parent impurity atom is very little of the order of 0.01 eV to 0.05 eV. This free electron is in excess to the free electrons that will be generated because of breaking of covalent bonds due to thermal agitation. Since an excess electron is available for each impurity atom, or it can ***denote an electron it is called n-type, or donor type semiconductor.***

1.2.2 p-TYPE OR ACCEPTOR TYPE SEMICONDUCTORS

An intrinsic semiconductor when doped with trivalent (3) impurity atoms like Boron, Gallium Indium, Aluminium etc., becomes p-type or acceptor type.

Because of the energy supplied while doping, the impurity atom dislodges one Ge atom from the crystal lattice. The doping level is low, i.e., there is one impurity atom for one million Ge atoms, the impurity atom is surrounded by Ge atom. Now the three valence electrons of impurity atom are shared by 3 atoms. The fourth Ge atom has no electron to share with the impurity atom. So the covalent bond is not filled or a hole exists. The impurity atom tries to steal one electron from the neighboring Ge atoms and it does so when sufficient energy is supplied to it. So hole moves.

There will be a natural tendency in the crystal to form 4 covalent bonds. The impurity atom (and not just 3) since all the other Ge atoms have 4 covalent bonds and the structure of Ge semiconductor is crystalline and symmetrical. The energy required for the impurity atom to steal one Ge electron is 0.01 eV to 0.08 eV. This hole is in excess to the hole created by thermal agitation.

1.3 MASS ACTION LAW

In an intrinsic Semiconductor number of free electrons $n = n_i$ = No. of holes $p = p_i$

Since the crystal is electrically neutral, $n_i p_i = n_i^2$.

Regardless of individual magnitudes of n and p, the product is always constant,

$$\therefore \quad np = n_i^2$$

$$n_i = AT^{\frac{3}{2}}\, e^{\frac{-E_{GO}}{2KT}} \qquad \text{.......... (1.12)}$$

This is called ***Mass Action Law***.

1.4 CONTINUITY EQUATION

Thus Continuity Equation describes how the carrier density in a given elemental volume of crystal varies with time.

If an intrinsic semiconductor is doped with n-type material, electrons are the majority carriers. Electron - hole recombination will be taking place continuously due to thermal agitation. So the concentration of holes and electrons will be changing continuously and this varies with time as well as distance along the semiconductor. We now derive the differential. equation which is based on the fact ***that charge is neither created nor destroyed***. This is called ***Continuity Equation***.

Consider a semiconductor of area A, length dx (x + dx – x = dx) as shown in Fig. 1.2. Let the average hole concentration be 'p'. Let E_p is a factor of x. that is hole current due to concentration is varying with distance along the semiconductor. Let 'I_p' is the current entering the volume at 'x' at time 't', and $(I_p + dI_p)$ is the current leaving the volume at (x + dx) at the same instant of time 't'. So when only I_p colombs is entering, ($I_p + dI_p$) colombs are leaving. Therefore effectively there is a decrease of $(I_p + dI_p - I_p) = dI_p$ colombs per second within the volume. Or in other words, since more hole current is leaving than what is entering, we can say that more holes are leaving than the no. of holes entering the semiconductor at 'x'.

If dI_p is rate of change of total charge that is

$$dI_p = d\left(\frac{n \times q}{t}\right)$$

$\frac{dI_p}{q}$ gives the decrease in the number of holes per second with in the volume A × dx. Decrease in holes per unit volume (hole concentration) per second due to I_p is

$$\frac{dI_p}{A \times dx} \times \frac{1}{q}$$

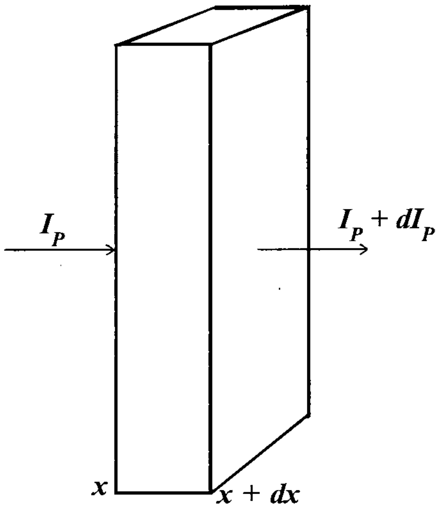


Fig 1.2 Charge flow in semiconductor

But $\frac{dI_p}{A}$ = Current Density

$$= \frac{1}{q} \times \frac{dJ_p}{dx}.$$

But because of thermal agitation, more number of holes will be created. If 'p_0' is the thermal equilibrium concentration of holes, (the steady state value reached after recombination), then, the increase per second, per unit volume due to thermal generation is,

$$g = \frac{p}{\tau_p}$$

Therefore, increase per second per unit volume due to thermal generation,

$$g = \frac{p_o}{\tau_p}$$

But because of recombination of holes and electrons there will be decrease in hole concentration.

The decrease $= \frac{p}{\tau_p}$

Charge can be neither created nor destroyed. Because of thermal generation, there is increase in the number of holes. Because of recombination, there is decrease in the number of holes. Because of concentration gradient there is decrease in the number of holes.

So the net increase in hole concentration is the algebraic sum of all the above.

$$\frac{\partial p}{\partial t} = \frac{p_o - p}{\tau_p} - \frac{1}{q} \times \frac{\partial J_p}{\partial x}$$

Partial derivatives are used since 'p' and 'Jp' are functions of both time t and distance x.

$\frac{dp}{dt}$ gives the variation of concentration of carriers with respect to time 't'.

If we consider unit volume of a semiconductor (*n-type*) having a hole density p_n, some holes are lost due to recombination. If p_{no} is equilibrium density, (i.e., density in the equilibrium condition when number of electron = holes).

The recombination rate is given as $\frac{p_n - p_{no}}{\tau}$. ***The expression for the time rate of change in carriers density is called the Continuity Equation.***

$$\text{Recombination rate } R = \frac{dp}{dt}$$

Life time of holes in n-type semiconductors

$$\tau_p = \frac{\Delta P}{R} = \frac{p_n - p_{no}}{dp/dt}$$

or

$$\frac{dp}{dt} = \left(\frac{p_n - p_{no}}{\tau_p}\right)$$

where p_n is the original concentration of holes in n-type semiconductors and p_{no} is the concentration after holes and electron recombination takes place at the given temperature. In other word p_{no} is the thermal equilibrium minority density. Similarly for a p-type semiconductors, the life time of electrons

$$\tau_n = \frac{n_p - n_{po}}{dx/dt} \; ; \; \frac{dx}{dt} = \frac{n_p - n_{no}}{\tau_n} .$$

1.5 THE HALL EFFECT

If a metal or semiconductor carrying a current I is placed in a perpendicular magnetic field B, an electric field E is induced in the direction perpendicular to both I and B. This *phenomenon is known as the **Hall Effect**. It is used to determine whether a semiconductor is p-type or n-type. By measuring conductivity σ, the mobility μ can be calculated using **Hall Effect**.*

In the Fig. 1.3 current 'I' is in the positive 'X'-direction and 'B' is in the positive 'Z'-direction. So a force will be exerted in the negative 'Y'-direction. If the semiconductor is *n-type*, so that current is carried by electrons, these electrons will be forced downward toward side 1. So side 1 becomes negatively charged with respect to side 2. Hence a potential V_H called the ***Hall Voltage*** appears between the surface 1 and 2.

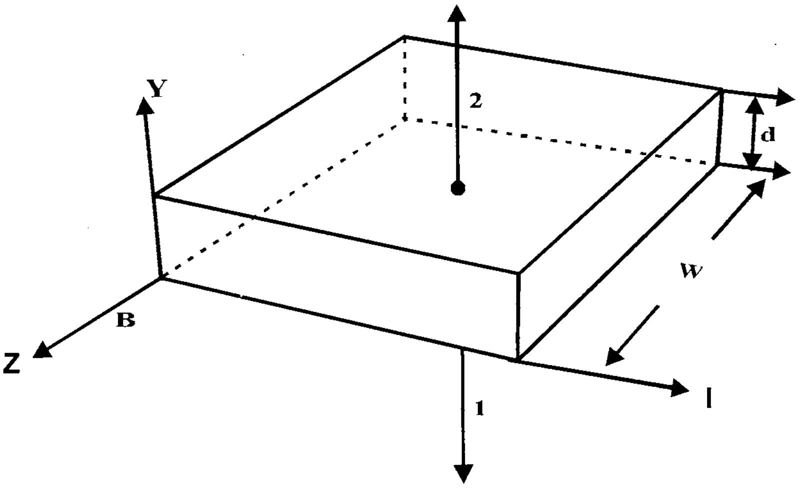


Fig 1.3 Hall effect.

In the equilibrium condition, the force due to electric field intensity 'E', because of Hall effect should be just balanced by the magnetic force or

$$e\varepsilon = B\,ev$$

v = Drift Velocity of carriers in m / sec

B = Magnetic Field Intensity in Tesla (wb/m^2)

or

$$\varepsilon = Bv \qquad \text{.......... (a)}$$

But $\varepsilon = V_H/d$

where V_H = Hall Voltage

d = Thickness of semiconductors.

J = nev or $J = \rho v$

ρ = charge density.

J = Current Density (Amp / m^2)

or $$J = \frac{I}{\omega . d}$$

ω = width of the semiconductor; ωd = cross sectional area

I = current

$$\therefore \quad J = \text{Current Density} = \frac{I}{\omega d}$$

$$\varepsilon = V_H/d$$

or $V_H = \varepsilon d$

But $\varepsilon = Bv$ From Equation (a)

$\therefore$ $V_H = B \times v \times d$ But $v = J/\rho$

$$= \frac{B.J.d}{\rho} \quad \text{But } J = \frac{I}{\omega d}$$

$$V_H = \frac{B.I.d}{\rho.\omega.d} = \frac{B.I}{\rho\omega}$$

$$V_H = \frac{B.I}{\rho\omega} \qquad \text{.......... (1.13)}$$

If the semiconductor is n-type, electrons the majority carriers under the influence of electric field will move towards side 1, side 2 becomes positive and side 1 negative. If on the other hand terminal 1 becomes charged positive then the semiconductor is p-type.

$\rho = n \times e$ (For n - type semiconductor)

or $\rho = p \times e$ (for p-type semiconductor)

and ρ = Charge density.

$$\because \quad V_H = \frac{B.I}{\rho\omega}$$

$$\rho = \frac{B.I}{V_H.\omega}$$

$$\therefore \quad R_H = \frac{V_H.\omega}{BI} \qquad \text{.......... (1.14)}$$

The Hall Coefficient, R_H is defined as $R_H = \frac{1}{\rho}$. Units of R_H are m^3 / coulombs

If the conductivity is due primarily to the majority carriers conductivity, $\sigma = ne\mu$ in n-type semiconductors.

$$n.e = \rho = \text{charge density.}$$

$$\therefore \quad \sigma = \rho \times \mu$$

$$\text{But} \quad \frac{1}{\rho} = R_H$$

$$\therefore \quad \sigma = \frac{1}{R_H} \times \mu$$

$$\text{or} \quad \mu = R_H \times \sigma = \frac{V_H.\omega}{B.I} \times \sigma$$

We have assumed that the drift velocity 'v' of all the carriers is same. But actually it will not be so. Due to the thermal agitation they gain energy, their velocity increases and also collision with other atoms increases. So for all particles v will not be the same. Hence a correction has to be made and it has been found that satisfactory results will be obtained if $\frac{1}{R_H}$ is taken as $\frac{3\pi}{8\rho}$.

$$\therefore \quad \mu = \left(\frac{8\sigma}{3\pi}\right) R_H \qquad \text{.......... (1.15)}$$

Multiply R_H by $\frac{8}{3\pi}$. Then it becomes ***Modified Hall Coefficient***. Thus mobility of carriers (electrons or holes) can be determined experimentally using Hall Effect.

The product (Bev) is the ***Lorentz Force***, because of the applied magnetic field B and the drift velocity 'v'. So the majority carriers in the semiconductors, will tend to move in a direction perpendicular to B. But since there is no electric field applied in that particulars direction, there will develop a Hall voltage or field which just opposes the Lorentz field.

So with the help of Hall Effect, we can experimentally determine

1. *The mobility of Electrons or Holes.*
2. *Whether a given semiconductor is* p-type *or* n-type *(from the polarity of Hall voltage V_H)*

Problem 1.14

The Hall Effect is used to determine the mobility of holes in a p-type Silicon bar. Assume the bar resistivity is 200,000 Ω-an, the magnetic field $B_z = 0.1$ Wb/m^2 and d = w = 3mm. The measured values of the current and Hall voltage are 10mA and 50 mv respectively. Find μ_p mobility of holes.

Solution

$B = 0.1$ Wb / m^2 (or Tesla)

$V_H = 50$ mv.

$I = 10$ mA;

$\rho = 2 \times 10^5\ \Omega$ - cm ;

$d = w = 3$mm $= 3 \times 10^{-3}$ meters

$$\frac{1}{R_H} = \frac{B.I}{V_H.w} = \frac{0.1 \times 10 \times 10^{-3}}{50 \times 10^{-2} \times 3 \times 10^{-3}} = \frac{1}{150} = 0.667.$$

$$\text{Conductivity} = \frac{1}{\rho} = \frac{1}{2 \times 10^5 \times 10^{-2}} = \frac{1}{2000} \text{ mhos / meter.}$$

$\mu = \sigma \times R_H$

$$\mu_p = \frac{1}{0.667} \times \frac{1}{2000} = 750 \text{ cm}^2\text{/ V - sec}$$

1.6 FERMI LEVEL IN INTRINSIC AND EXTRINSIC SEMICONDUCTORS

1.6.1 Fermi Level

Named after ***Fermi, it is the Energy State, with 50% probability of being filled if no forbidden band exists***. In other words, it is the mass energy level of the electrons, at 0°K.

If $E = E_f$,

$$f(E) = ½$$

If a graph is plotted between ($E - E_F$) and f(E), it is shown in Fig. 1.4

At $T = 0$°K, if $E > E_F$ then, $f(E) = 0$.

That is, there is no probability of finding an electron having energy $> E_F$ at $T = 0^0$ K. Since fermi level is the max. energy possessed by the electrons at 0°k. f(E) varies with temperature as shown in Fig. 1.4.

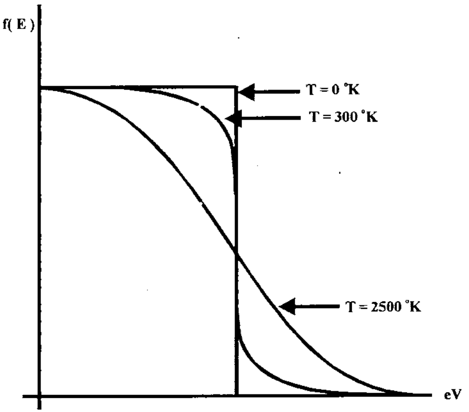


Fig. 1.4 Fermi level variation with temperature.

1.6.2 THE INTRINSIC CONCENTRATION

$$f(\mathrm{E}) = \frac{1}{1+e^{(\mathrm{E}-\mathrm{E_F})/\mathrm{KT}}} \qquad \text{.......... (1.16)}$$

$$1 - f(\mathrm{E}) = \frac{e^{(\mathrm{E}-\mathrm{E_F})/\mathrm{KT}}}{1+e^{(e-\mathrm{E_F})/\mathrm{KT}}} \simeq e^{-(\mathrm{E_F}-\mathrm{E})/\mathrm{KT}}$$

$$e^{(\mathrm{E}-\mathrm{E_F})/\mathrm{KT}}\left[1+e^{(\mathrm{E}-\mathrm{E_f})/\mathrm{KT}}\right]^{-1} \simeq e^{-(\mathrm{E_f}-\mathrm{E})/\mathrm{KT}}$$

Fermi function for a hole = $1 - f(\mathrm{E})$.

$$(\mathrm{E_F} - \mathrm{E}) >> \mathrm{KT} \text{ for } \mathrm{E} \leq \mathrm{Ev}$$

the number of holes per m^3 in the Valence Band is,

$$p = \int_{-\infty}^{\mathrm{E_V}} \gamma(\mathrm{E_V} - \mathrm{E})^{1/2} e^{-(\mathrm{E_F}-\mathrm{E})/\mathrm{KT}} \times d\mathrm{E}$$

$$= \mathrm{N_V} \times e^{-(\mathrm{E_F}-\mathrm{E_V})/\mathrm{KT}}$$

where $$\mathrm{N_V} = 2\left(\frac{2\pi m_p \overline{\mathrm{K}}\mathrm{T}}{h^2}\right)^{\frac{3}{2}}$$

Similarly $$n = \mathrm{N_e}\, e^{-(\mathrm{E_C}-\mathrm{E_F})/\mathrm{KT}}$$

$$n \times p = \mathrm{N_V} \times \mathrm{N_e}\, e^{-\mathrm{E_G}/\mathrm{KT}}$$

Substituting the values of $\mathrm{N_C}$ and $\mathrm{N_V}$,

$$n \times p = n_i^2 = \mathrm{AT}^3\, e^{-\mathrm{E_G}/\mathrm{KT}}$$

1.6.3 CARRIER CONCENTRATIONS IN A SEMICONDUCTOR

$d\eta$ = $\mathrm{N}(\mathrm{E}) \times f(\mathrm{E}) \times d\mathrm{E}$

dn = number of conduction electrons per cubic meter whose energy lies between E and E + dE

$f(\mathrm{E})$ = The probability that a quantum state with energy E is occupied by the electron.

N(E) = Density of States.

$$f(\mathrm{E}) = \frac{1}{1+e^{(\mathrm{E}-\mathrm{E_F})/\mathrm{KT}}}$$

The concentration of electrons in the conduction band is

$$n = \int_{\mathrm{E_C}}^{\infty} \mathrm{N}(\mathrm{E}) \times f(\mathrm{E}) \times d\mathrm{E}$$

for $\mathrm{E} \geq \mathrm{E_C}$

$(\mathrm{E} - \mathrm{E_s})$ is >> KT.

$\therefore$ $f(\mathrm{E}) = e^{-(\mathrm{E}-\mathrm{E_f})/\mathrm{KT}}$

$$\because \qquad e^{(E-E_F)/KT} >> 1$$

$$\therefore \qquad n = \int_{E_C}^{\infty} \gamma (E-E_C)^{1/2} \times e^{-(E-E_F)KT} . dE$$

Simplifying this integral, we get,

$$n = N_C \times e^{-(E_C-E_F)/KT}$$

where $$N_C = 2\left(\frac{2\pi m_n \overline{K}T}{h^2}\right)^{\frac{3}{2}}$$

$\overline{K}$ = Boltzman's Constant in J/°K

'N_i' is constant.

where m_n = effective mass of the electron.

Similarly the number of holes / m^3 in the Valence Band

$$p = N_V\ e^{-(E_F-E_V)/KT}$$

where $$N_V = 2\left(\frac{2\pi m_p \overline{K} \times T}{h^2}\right)^{\frac{3}{2}}$$

Fermi Level is the maximum energy level that can be occupied by the electrons at 0 °K. ***Fermi Level*** or characteristic energy represents the energy state with 50% probability of being filled if no forbidden bond exists. If E = E_F, then f(E) = ½ for any value of temperature. f(E) is the probability that a quantum state with energy E is occupied by the electron.

1.6.4 FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

$$n = p = n_i$$

$$n = N_C\ e^{-(E_C-E_F)/KT}$$

$$p = N_V\ e^{-(E_F-E_V)/KT}$$

$$n = p$$

or $$N_C\ e^{-(E_C-E_F)/KT} = N_V\ e^{-(E_F-E_V)/KT}$$

Electrons in the valence bond occupy energy levels up to 'E_F'. 'E_F' is defined that way. Then the additional energy that has to bo supplied so that free electron will move from valence band to the conduction band is E_C

$$\frac{N_C}{N_V} = e^{\frac{-(E_F-E_V)}{KT} + \frac{(E_C+E_F)}{KT}}$$

$$= e^{\frac{-2E_F+E_C+E_V}{KT}}$$

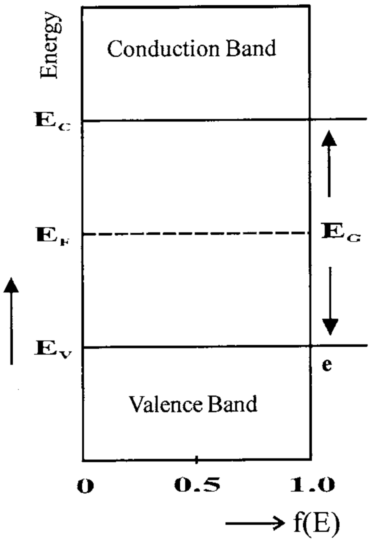


Fig. 1.5 Energy band diagram.

Taking logarithms on both sides,

$$\ln \frac{N_C}{N_V} = \frac{E_C + E_V - 2E_F}{KT}$$

$$\therefore \qquad E_F = \frac{E_C + E_V}{2} - \frac{KT}{2} \ln \frac{N_C}{N_V}$$

$$N_C = 2\left(\frac{2\pi m_n \overline{KT}}{h^2}\right)^{\frac{3}{2}} \qquad \text{.......... (1.17)}$$

$$N_V = 2\left(\frac{2\pi m_p.\overline{KT}}{h^2}\right)^{\frac{3}{2}} \qquad \text{.......... (1.18)}$$

where $m_n$and m_p are effective masses of holes and electrons. If we assume that $m_n = m_p$, (though not valid),

$$N_C = N_V$$

$$\therefore \qquad \ln \frac{N_C}{N_V} = 0$$

$$\therefore \qquad E_F = \frac{E_C + E_V}{2} \qquad \text{.......... (1.19)}$$

The graphical representation is as shown in Fig. 1.5. ***Fermi Level in Intrinsic Semiconductor lies in the middle of Energy gap E_G.***

Problem 1.15

In p-type Ge at room temperature of 300 °K, for what doping concentration will the fermi level coincide with the edge of the valence bond ? Assume $\mu_p = 0.4$ m.

Solution

$$E_F = E_V$$

when $\qquad N_A = N_V$

$$\therefore \qquad E_F = E_V + kT \ln . \frac{N_V}{N_A}$$

$$\therefore \qquad N_V = 4.82 \times 10^{15}\left(\frac{mp}{m}\right)^{\frac{3}{2}} \times T^{3/2} = 4.82 \times 10^{15}(0.4)^{3/2}(300)^{3/2}$$

$$= 6.33 \times 10^{18}.$$

$\therefore$ Doping concentration $N_A = 6.33 \times 10^{18}$ atoms/cm^3.

Problem 1.16

If the effective mass of an electron is equal to twice the effective mass of a hole, find the distance in electron volts (ev) of fermi level in as intrunsic semiconductor from the centre of the forbidden bond at room temperature.

Solution

For Intrunsic Semiconductor,

$$E_F = \left[\left(\frac{E_C + E_V}{2}\right) - \frac{KT}{2}\ln\left(\frac{N_C}{N_V}\right)\right]$$

If $m_p = m_n$

then $N_C = N_V$.

Hence E_F will be at the centre of the forbidden band. But if $m_p \neq m_n$. E_F will be away from the centre of the forbidden band by

$$\frac{KT}{2}\ln.\frac{N_C}{N_V} = \tfrac{3}{4}\frac{kT}{2}.\ln\frac{m_n}{m_p}$$

$$\therefore \quad N_C = 2\left(\frac{2\pi m_n \overline{K}T}{n^2}\right)^{3/2}$$

$$N_V = 2\left(\frac{2\pi m_p \overline{k}T}{n^2}\right)^{3/2}$$

$$= \frac{3}{4} \times 0.026\, ln\,(2)$$

$$= 13.5 \text{ m. eV}$$

1.7 p-n DIODE EQUATION

The hole current in the *n-side* ***Ipn(x)*** is given as

$$Ipn(x) = \frac{Ae \times Dp}{L_p} p_n(0)\, e^{-x/L_p}$$

But $p_n(0) = p_{no}\left(e^{V/V_T} - 1\right)$

$$Ipn(0) = \frac{Ae \times Dp}{L_p} \times p_{no}\left(e^{V/V_T} - 1\right)$$

D_p = Diffusion coefficient of holes

D_n = Diffusion coefficient of electrons.

$\therefore$ e^{-x/L_p} at $x = 0$ is 1.

Similarly the electron current due to the diffusion of electrons from *n-side* to *p-side* is obtained from the above equation itself, by interchanging n and p.

$$\therefore \quad Inp(0) = \frac{Ae \times Dn}{L_n} \times n_{po}\left(e^{V/V_T} - 1\right)$$

The total diode current is the sum of ***Ipn (0)*** and ***Inp(0)***

or $$I = I_o\left(e^{V/V_T} - 1\right) \qquad \text{.......... (1.20)}$$

where $$I_0 = \frac{AeDp}{Lp} \times p_{no} + \frac{AeDn}{L_n} \times n_{po}$$

In this analysis we have neglected charge generation and recombination. Only the current that results as a result of the diffusion of the carriers owing to the applied voltage is considered.

Reverse Saturation Current

$$I = I_0 \times \left(e^{V/V_T} - 1\right)$$

This is the expression for current I when the diode is forward biased. If the diode is reverse biased, V is replaced by –V. V_T value at room temperature is ~ 26 mV. If the reverse bias voltage is very large, $e^{\frac{-V}{V_T}}$ is very small. So it can be neglected.

$$\therefore \qquad I = -I_0$$

I_0 will have a small value and I_0 is called the ***Reverse Saturation Current.***

$$I_0 = \frac{AeD_p p_{no}}{L_p} + \frac{AeD_n n_{po}}{L_n}.$$

In *n-type* semiconductor,

$$n_n = N_D$$

But $$n_n \times p_n = n_i^2 \qquad \therefore\ p_n = \frac{n_i^2}{N_D}$$

In *p-type* semiconductor,

$$p_p = N_A \qquad \therefore\ n_p = \frac{n_i^2}{N_A}$$

Substituting these values in the expression for I_0,

$$I_0 = Ae\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n . N_A}\right) \times n_i^2$$

where $$n_i^2 = A_0\,T^3\,e^{-E_G/KT}$$

E_G is in electron volts = e.V_G, where V_G is in Volts.

$$\therefore \qquad n_i^2 = A_0\,T^3\,e^{-\frac{E_{GO}}{KT}}$$

$$E_{G_O} = V_G\,.\,e$$

But $$\frac{KT}{e} = \text{Volt equivalent of Temperature } V_T.$$

For Germanium, D_p and D_n decrease with temperature and n_i^2 increases with T. Therefore, temperature dependance of I_0 can be written as,

$$I_0 = K_1 T^2 \ e^{-V_G / V_T}$$

For Germanium, the current due to thermal generation of carriers and recombination can be neglected. But for Silicon it cannot be neglected. So the expression for current is modified as

$$I = I_0 \left(e^{\frac{V}{\eta V_T}} - 1 \right)$$

where n = 2 for small currents and n = 1 for M large currents.

1.8 VOLT-AMPERE (V-I) CHARACTERISTICS

The general expression for current in the *p-n junction* diode is given by

$$I = I_0 \left(e^{\frac{V}{\eta V_T}} - 1 \right)$$

$\eta = 1$ for Germanium and 2 for Silicon. For Silicon, ‘I’ will be less than that for Germanium.

$$V_T = 26 \text{ mV}.$$

If ‘V’ is much larger than V_T, 1 can be neglected. So ‘I’ increases exponentially with forward bias voltage ‘V’. In the case of reverse bias, if the reverse voltage $-V >> V_T$, then e^{-V/V_T} can be neglected and so reverse current is $-I_0$ and remains constant independent of ‘V’. So the characteristics are as shown in Fig. 1.6 and not like theoretical characteristics. The difference is that the practical characteristics are plotted at different scales. If plotted to the same scale, (reverse and forward) they may be similar to the theoretical curves. Another point is, in deriving the equations the breakdown mechanism is not considered. As ‘V’ increases **Avalanche multiplication** sets in. So the actual current is more than the theoretical current.

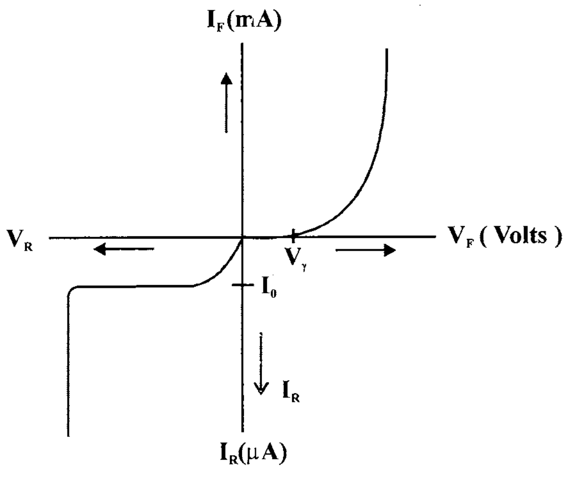


Fig 1.6 V-I Characteristics of p-n junction diode.

CUT IN VOLTAGE V_γ

In the case of Silicon and Germanium, diodes there is a ***Cut In*** or ***Threshold*** or ***Off Set*** or ***Break Point Voltage***, below which the current is negligible. It's magnitude is 0.2V for Germanium and 0.6V for Silicon (Fig. 1.7).

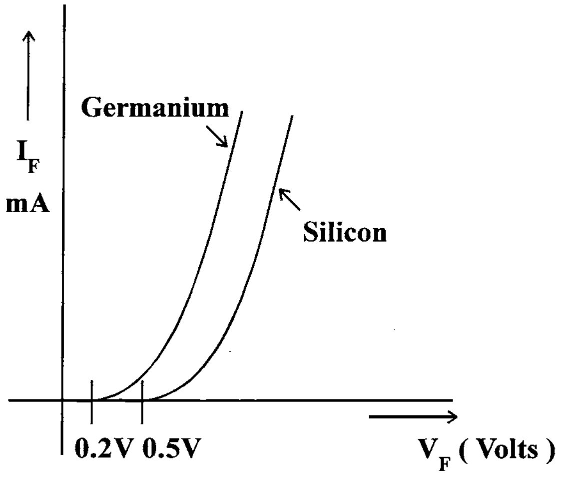


Fig 1.7 Forward characteristics of a diode.

1.9 TEMPERATURE DEPENDENCE OF V-I CHARACTERISTICS

$$\sigma = (\mu_n n + \mu_p p)e,$$

So the electrical characteristics of a semiconductor depends upon '***n***' and '***p***', the concentration of holes and electrons.

The expression for $n = N_C\ e^{-(E_C - E_F)/KT}$ and the expression for $p = N_V\ e^{-(E_F - E_V)/KT}$

These are valid for both intrinsic and extrinsic materials.

The electrons and holes, respond to an external field as if their mass is m^*($m^* = 0.6m$) and not 'm'. So this m^* is known as ***Effective Mass***.

With impurity concentration, only E_F will change. In the case of intrinsic semiconductors, E_F is in the middle of the energy gap, indicating equal concentration of holes and electrons.

If donor type impurity is added to the intrinsic semiconductor it becomes n-type. So assuming that all the atoms are ionized, each impurity atom contributes at least one free electron. So the first N_D states in the conduction band will be filled. Then it will be more difficult for the electrons to reach Conduction Band, bridging the gap between Covalent Bond and Valence Bond. So the number of electron hole pairs, thermally generated at that temperature will be decreased. ***Fermi level is an indiction of the probability of occupancy of the energy states.*** Since Because of doping, more energy states in the ConductionBand are filled, the fermi level will move towards the Conduction Band.

EXPRESSION FOR E_G

$$n = N_C \times e^{\frac{-(E_C - E_F)}{KT}}$$

$$p = N_V \cdot e^{\frac{-(E_F - E_V)}{KT}}$$

$$n \times p = N_C \times N_V \times e^{\frac{-(E_C - E_V)}{KT}}$$

But $\quad (E_C - E_V) = E_G$

and $\quad n \times p = n_i^2$

$\therefore \quad n_i^2 = N_C \times N_V \times e^{-\frac{E_G}{KT}}$

$$\frac{n_i^2}{N_C \times N_V} = e^{-\frac{E_G}{KT}}$$

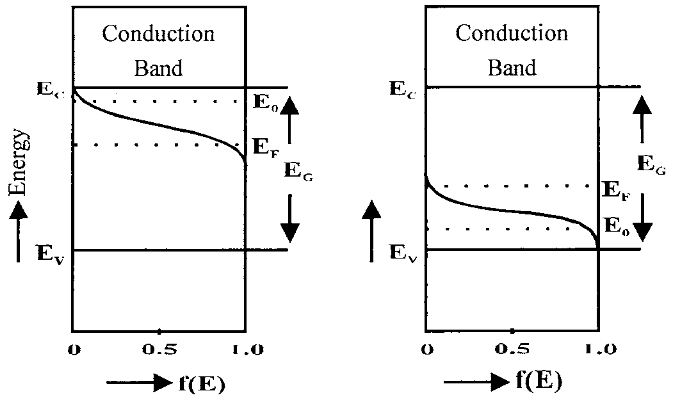
Taking logarithms,

$$\ln\left(\frac{n_i^2}{N_C N_V}\right) = -\frac{E_G}{KT}$$

or $\quad -\ln\left(\frac{N_C N_V}{n_i^2}\right) = -\frac{E_G}{KT}$

or $\quad E_G = KT \ln\left(\frac{N_C N_V}{n_i^2}\right)$ .... (1.21)

The position of Fermi Level is as shown in Fig. 1.8.



For n-type semiconductor *For p-type semiconductor*

Fig. 1.8

Similarly, in the case of *p-type* materials, the Fermi level moves towards the valence band since the number of holes has increased. In the case of *n-type* semiconductor, the number of free electrons has increased. So energy in Covalent Bond has increased. Fermi Level moves towards conduction band. ***Similarly in p-type semiconductors, fermi Level moves towards Valence Band.*** So it is as shown in Fig. 1.8.

To calculate the exact position of the Fermi Level in n-type Semiconductor:

In *n-type* semiconductor,

$$n \simeq N_D$$

But $$n = N_C \times e^{-(E_C - E_F)/KT}$$

$$\therefore \quad N_D = N_C \times e^{-(E_C - E_F)/KT}$$

or $$\frac{N_D}{N_C} = e^{-(E_C - E_F)/KT}$$

Taking logarithms,

$$\ln \frac{N_D}{N_C} = \frac{-(E_C - E_F)}{KT}$$

or $$KT \times \left\{ \ln \frac{N_D}{N_C} \right\} = -(E_C - E_F)$$

or $$E_F = E_C - KT \times \left\{ \ln \frac{N_C}{N_D} \right\} \qquad \text{.......... (1.22)}$$

So Fermi Level E_F is close to Conduction Band E_C in n-type semiconductor.

Similarly for p-type material,

$$p = N_A$$

But $$p = N_V \times e^{-(E_F - E_V)/KT}$$

$$\therefore \quad \frac{N_A}{N_V} = e^{-(E_F - E_V)/KT}$$

Taking Logarithms,

$$\ln \frac{N_A}{N_V} = -\frac{(E_F - E_V)}{KT}$$

$$KT \times \ln \frac{N_A}{N_V} = E_V - E_F$$

or $$E_F = E_V + KT \times \ln \frac{N_V}{N_A} \qquad \text{.......... (1.23)}$$

$$\therefore \quad N_A = N_V$$

Fermi Level is close to Valance Band E_V in p-type semiconductor.

Problem 1.17

In n type silicon, the donor concentration is 1 atom per 2 × 10^8 silicon atoms. Assuming that the effective mass of the electron equals true mass, find the value of temperature at which, the fermi level will coincide with the edge of the conduction band. Concentration of Silicon = 5 × 10^{22} atom/ cm3.

Solution

Donor atom concentration = 1 atom per 2 × 10^8 Si atom.

Silicon atom concentration = 5 × 10^{22} atoms/cm^3

$$\therefore \quad N_D = \frac{5\times10^{22}}{2\times10^8} = 2.5 \times 10^{14}/\text{cm}^3.$$

For n-type, Semiconductor,

$$E_F = E_C - KT \ln\left(\frac{N_C}{N_D}\right)$$

If E_F were to coincide with E_C, then

$$N_C = N_D.$$

$$N_D = 2.5 \times 10^{14}\ /\text{cm}^3.$$

$$N_C = 2\left\{\frac{2\pi m_n \overline{K} T}{h^2}\right\}^{\frac{3}{2}}$$

h = Plank's Constant; $\overline{K}$ = Boltzman Constant

m_n the effective mass of electrons to be taken as = m_E

$$\therefore \quad N_C = 2\left\{\frac{2\times3.14\times9.1\times10^{-31}\times\overline{K}\times T}{h^2}\right\}^{\frac{3}{2}}$$

$$= 4.28 \times 10^{15}\ T^{\frac{3}{2}}$$

$$\because \quad N_C = N_D,$$

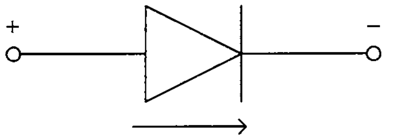
$$4.28 \times 10^{15}\ T^{\frac{3}{2}} = 2.5 \times 10^{14}$$

$$\therefore \quad T = 0.14\ ^\circ K$$

that *p-side* of the p-n junction is heavily doped. If *n-side* is heavily doped, it would be N_D.

1.10 IDEAL VS PRACTICAL

Ideal: The p-n junction diode allows flow of heavy current during forward bias condition and allows a small level of current when it is reverse biased. The direction of the arrow in the following Fig.1.9(a) depicts the direction of flow of current when the diode is forward biased. Similarly the direction of the arrow in Fig.1.9 (b) depicts the flow of current direction when the diode is reversed biased.



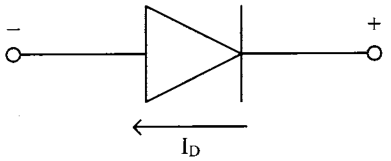


Fig.1.9(a) Illustration of flow of current when the diode is forward biased

Fig. 1.9(b) Illustration of flow of current when the diode is Reverse biased

ANALOGY

A common analogy that can be employed to describe the behaviour of a p-n junction diode is Mechanical switch.

During the forward bias the p-n junction diode allows flow of heavy currents through the junction. And hence the amount of resistance offered by the p-n junction diode during forward bias condition is very small and assumed to be zero. Thus the pn junction diode acts as a closed switch when the diode is forward biased. On the other hand when the diode is reverse biased it offers a flow very small level of current across the junction which is assumed to be zero. In otherwords it offers very high amount of resistance during its reverse bias (prevents flow of current across the junction i.e., offer ∞ resistance). Thus the p-n junction diode acts on a open switch during the reverse bias.

The following Fig.1.10(a) shows the analogy of closed switch of p-n junction diode and Fig. 1.10(b) shows the analogy of open switch of p-n junction diode.

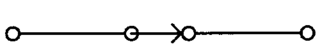


Fig. 1.10(a) Analogy of p-n junction diode as closed switch

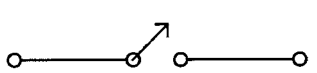


Fig.1.10(b) Analogy of p-n junction diode as open switch

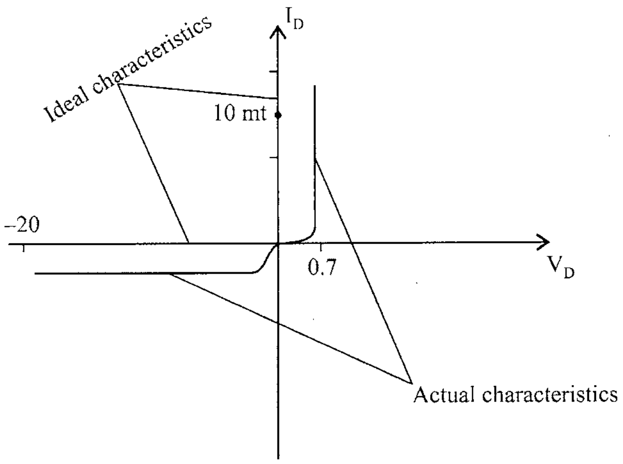
PRACTICAL

Even though the p-n junction diode offers a flow of heavy currents during forward bias, a small amount of current (which is due to presence of minority charge carriers across the junction) opposes the flow of forward biased current (I_D). In otherwords the p-n junction diode offers a small amount of forward resistance (r_f) which opposes the flow forward biased current (I_D).

Similarly when the diode is reverse biased the switch is assumed to be open but in practical the p-n junction diode allows the flow small amounts of currents through the junction which can be refered as leakage current (or) minority charge carrier current.

IDEAL VS PRACTICAL

The following figure shows super imposition of practical characteristics in ideal characteristics. From the figure we can observe that the ideal diode does not offer any forward resistance and hence it does not require any additional voltage to make I_D to flow through the diode. In otherwords the forward bias current I_D starts flowing through the diode even when applied forward bias voltage is at 0V.



Where as in case of practical diode as it offers a small amount of forward resistance (r_f) it requires a knee voltage (or) threshold voltage of 0.6 in case of silicon (0.3 of germanium) to make forward current I_D to flow through the junction.

ANALOGY: CLOSED SWITCH

Ideal: When the switch is closed, the resistance between the contacts is assumed to be zero. In the plot a point chosen in vertical axis where the diode current 10 mA and voltage across diode is 0V. According to Ohm's law.

$$R_F = \frac{V_D}{I_D} = \frac{0V}{10\ \text{mA}} = 0\ \Omega$$

Practical: In practical diode the minimum voltage required to obtain I_D is 0.6 (for Si). Hence

$$R_F = \frac{V_D}{I_D} = \frac{0.6}{10\ \text{mA}} = 60\ \Omega$$

ANALOGY: OPEN SWITCH

Ideal: For any value of voltage on horizontal axis (any point on X-axis has zero coordinate) the current is zero. Applying ohm's law. In plot V_D is taken as 20.

$$R_r = \frac{V_D}{I_D} = \frac{20}{0\text{ mA}} = \infty$$

Practical: For practical diode a small level of current (usually in order of ηA for si and μA for Ge) flows when the diode is reverse biased. Hence

$$R_r = \frac{20}{10\text{ mA (assume)}} = \frac{20}{10 \times 10^{-9}} = 2000\text{ M}\,\Omega \text{ for si}$$

	Ideal	Practical
When switch is closed	$R_f = 0$	$R_f = R_f$ (in order of ohms)
When switch is open	$R_r = \infty$	$R_r = R_r$ (in order of M Ω)

1.11 DIODE EQUIVALENT CIRCUITS

An equivalent circuit is a combination of elements that are chosen to represent actual characteristics of device for particular operating region.

***Piecewise Linear Equivalent Circuit*:** The best method of obtaining equivalent circuit is to approximate its characteristics with straight line segments. The forward bias characteristics of p-n junction diode is shown in following Fig. 1.11.

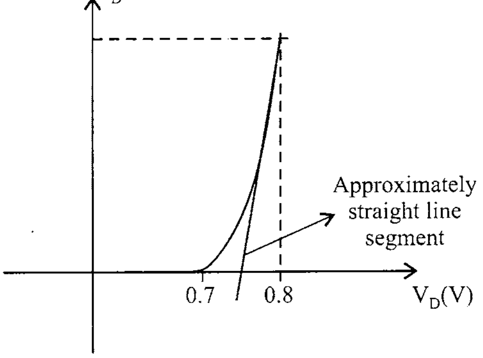
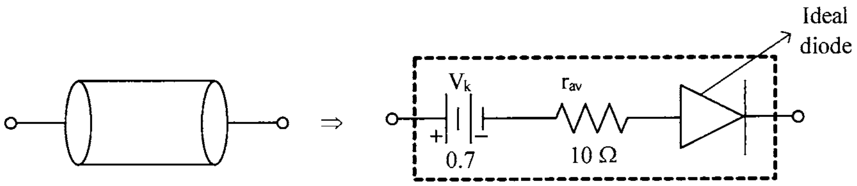


Fig. 1.11 Approximation of diode characteristics

The above Fig. 1.11 represent approximation of exact characteristics of p-n junction diode. From the figure it is clear that this approximation does not yield the exact duplication of actual characteristics of p-n junction diode. However these approximation yields sufficiently close to actual curve to represent the behaviour of the diode.

The actual characteristics have knee voltage of 0.7 V but the approximate model has knee voltage greater than 0.7 V. To achieve this 0.7 V of knee voltage connect a battery of 0.7 V to the p-n junction diode assuring its polarity is in opposition with the applying voltage as show in following Fig.1.12 and assuming the diode to be ideal, the ideal diode does not conduct any current when it is in reverse bias condition hence approximation of reverse bias characteristics of diode can be neglected.



(a) *(b)*

Fig. 1.12 Equivalent circuit of diode

The above Fig. 1.12 assures that the diode is not conducted until voltage across it reaches greater than its knee voltage i.e., 0.7. And once the diode starts conducting it offers a specified value of resistance r_{av}.

The approximate value of r_{av} can be obtained from the operating point of the diode. Assuming its operating point to be (10, 0.8) i.e., the current through the diode is 10 mA when applied voltage is 0.8 (show in Fig. 1.12(a)). We get

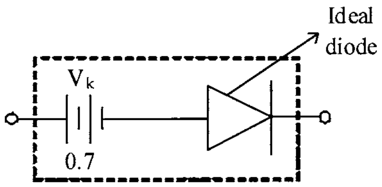
$$r_{av} = \left.\frac{\Delta V_d}{\Delta I_d}\right|_{\text{pt to pt}} = \frac{0.8 - 0.7}{10\text{ mA} - 0\text{ mA}} = \frac{0.1}{10\text{ mA}} = 10\ \Omega$$

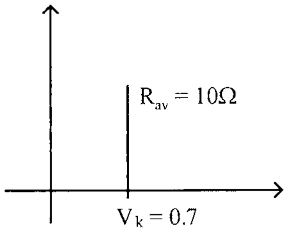
$$\therefore \quad r_{av} = 10\ \Omega$$

The 0.7 V is knee voltage i.e., minimum voltage required to make diode ready for conducting and at exact knee point the diode will be ready to conduct, but it will not be conducting hence I_D at knee voltage is 0 mA. When the voltage across the diode just crosses its knee voltage the diode starts conducting and hence I_D starts increasing. But at point when applied voltage is equal to knee voltage the diode will be in equilibrium resulting $I_D = 0$.

SIMPLIFIED EQUIVALENT CIRCUIT

In general the value of r_{av} is very small in comparison with the other elements of the circuit and hence it can be neglected. Removing r_{av} from diode equivalent circuits give simplified equivalent diode circuit. The following shows the simplified equivalent circuit of the diode and its characteristics.





1.12 BREAK DOWN MECHANISMS IN SEMICONDUCTOR DIODES

There are three types of breakdown mechanisms in semiconductor devices.

1. Avalanche Breakdown 2. Zener Breakdown 3. Thermal Breakdown

1.12.1 AVALANCHE BREAKDOWN

When there is no bias applied to the diode, there are certain number of thermally generated carriers. When bias is applied, electrons and holes acquire sufficient energy from the applied potential to produce new carriers by removing valence electrons from their bonds. These thermally generated carriers acquire additional energy from the applied bias. They strike the lattice and impart some energy to the valence electrons. So the valence electrons will break away from their parent atom and become free carriers. These newly generated additional carriers acquire more energy from the potential (since bias is applied). So they again strike the lattice and create more number of free electrons and holes. This process goes on as long as bias is increased and the number of free carriers gets multiplied. This is known as ***avalanche multiplication***, Since the number of carriers is large, the current flowing through the diode which is proportional to free carriers also increases and when this current is large, avalanche breakdown will occur.

1.12.2 ZENER BREAKDOWN

Now if the electric field is very strong to disrupt or break the covalent bonds, there will be sudden increase in the number of free carriers and hence large current and consequent breakdown. Even if thermally generated carriers do not have sufficient energy to break the covalent bonds, the electric field is very high, then covalent bonds are directly broken. This is ***Zener Breakdown***. A junction having narrow depletion layer and hence high field intensity will have zener breakdown effect. ($\simeq 10^6$ V/m). If the doping concentration is high, the depletion region is narrow and will have high field intensity, to cause Zener breakdown.

1.12.3 THERMAL BREAKDOWN

If a diode is biased and the bias voltage is well within the breakdown voltage at room temperature, there will be certain amount of current which is less than the breakdown current. Now keeping the bias voltage as it is, if the temperature is increased, due to the thermal energy, more number of carriers will be produced and finally breakdown will occur. This is ***Thermal Breakdown***.

In zener breakdown, the covalent bonds are ruptured. But the covalent bonds of all the atoms will not be ruptured. Only those atoms, which have weak covalent bonds such as an atom at the surface which is not surrounded on all sides by atoms will be broken. But if the field strength is not greater than the critical field, when the applied voltage is removed, normal covalent bond structure will be more or less restored. This is Avalanche Breakdown. But if the field strength is very high, so that the covalent bonds of all the atoms are broken, then normal structure will not be achieved, and there will be large number of free electrons. This is ***Zener Breakdown***.

In Avalanche Breakdown, only the excess electron, loosely bound to the parent atom will become free electron because of the transfer of energy from the electrons possessing higher energy.

1.13 ZENER DIODE CHARACTERISTICS

This is a *p-n junction* device, in which zener breakdown mechanism dominates. ***Zener diode is always used in Reverse Bias.***

Its constructional features are:

1. *Doping concetration is heavy on* p *and* n *regions of the diode, compared to normal* p-n junction *diode.*
2. *Due to heavy doping, depletion region width is narrow.*
3. *Due to narrow depletion region width, electric field intensity* $E = \frac{V}{d} = \frac{V_Z}{W}$ *will be high, near the junction, of the order of* 10^6 *V/m. So Zener Breakdown mechanism occurs.*

In normal *p-n junction* diode, avalanche breakdown occurs if the applied voltage is very high. The reverse characteristic of a p-n junction diode is shown in Fig. 1.13.

When the Zener diode is reverse biased, the current flowing is only the reverse saturation current I_0 which is constant like in a reverse biased diode. At $V_i = V_Z$, due to high electric field $\left(\frac{V_Z}{W}\right)$, Zener breakdown occurs. Covalent bonds are broken and suddenly the number of free electrons increases. So I_Z increases sharply and V_Z remains constant, since, I_Z increases through Zener resistance R_Z decreases. So the product $V_Z = R_Z \cdot I_Z$ almost remains constant. If the input voltage is decreased, the Zener diode regains its original structure. (But if V_i is increased much beyond V_Z, electrical breakdown of the device will occur. The device looses its semiconducting properties and may become a short circuit or open circuit. ***This is what is meant by device breakdown.***)

Applications

1. *In Voltage Regulator Circuits*
2. *In Clipping and Clamping Circuits*
3. *In Wave Shaping Circuits.*

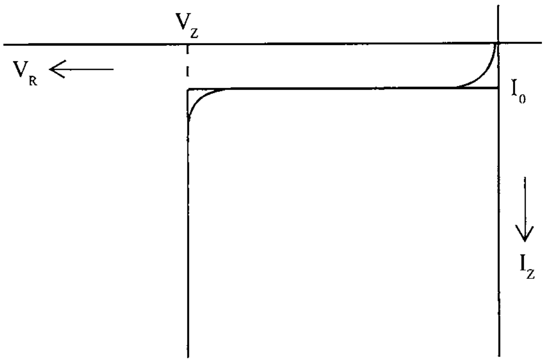


Fig 1.13 Reverse characteristic of a Zener diode.

1.14 p-n JUNCTION DIODE AS RECTIFIER

The electronic circuits require a D.C. source of power. For transistor A.C. amplifier circuit for biasing, D.C supply is required. The input signal can be A.C. and so the output signal will be amplified A.C. signal. But without biasing with D.C. supply, the circuit will not work. So more or less all electronic A.C. instruments require D.C. power. To get this, D.C. batteries can be used. But they will get dried quickly and replacing them every time is a costly affair. Hence it is economical to convert A.C. power into D.C.

Rectifier is a circuit which offers low resistance to the current in one direction and high resistance in the opposite direction.

Rectifier converts sinusoidal signal to unidirectional flow and not pure D.C.

Filter converts unidirectional flow into pure D.C.

If the input to the rectifier is a pure sinusoidal wave, the average value of such a wave is zero, since the positive half cycle and negative half cycle are exactly equal.

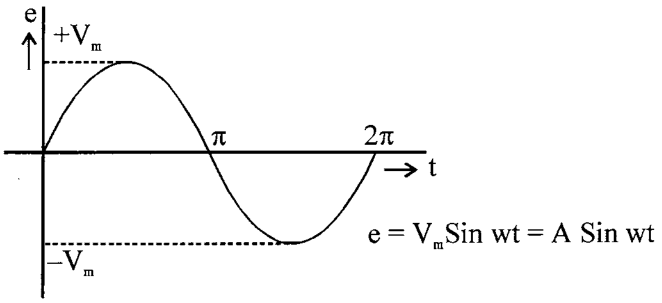


Fig 1.14 AC input wave form.

$$T_{av} = \frac{1}{2\pi}\int_{0}^{2\pi} A\,\mathrm{Sin}(\omega t)\,dt$$

1.15 HALF-WAVE RECTIFIER

If this signal is given to the rectifier circuit, say Half Wave Rectifier Circuit, the output will be as shown in Fig. 1.15.

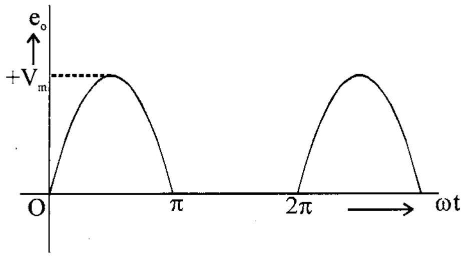


Fig. 1.15 Half wave rectified output (unidirectional flow).

Now the average value of this waveform is *not zero,* since there is no negative half. Hence a rectifier circuit converts A.C. Signal with zero average value to a unidirectional wave form with non zero average value.

The rectifying devices are semiconductor diodes for low voltage signals and vacuum diodes for high voltage circuit. A basic circuit for rectification is as shown in Fig. 1.16.

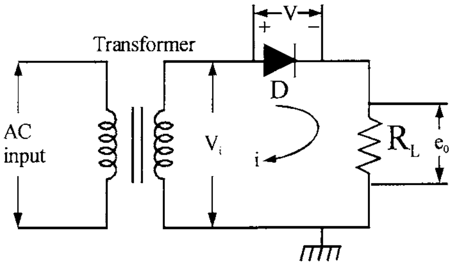
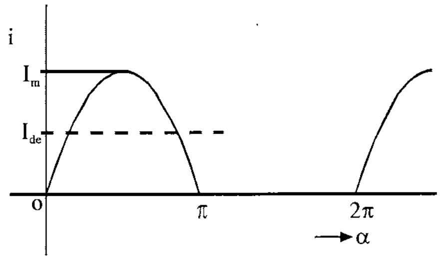


Fig 1.16 Halfwave Rectifier (HWR) circuit.

A.C input is normally the A.C. main supply. Since the voltage is 230V, and such a high voltage cannot be applied to the semiconductor diode, step down transformer should be used. If large D.C. voltage is required vacuum tubes should be used. Output voltage is taken across the load resistor R_L. Since the peak value of A.C. signal is much larger than V_γ, we neglect V_γ, for analysis.

1.15.1 MAXIMUM OR PEAK CURRENT

The output current waveform for half wave rectification is shown in Fig. 1.17.



$i = I_m \text{ Sin } \alpha$ between $0 \le \alpha \le \pi$

$i = 0$ between $\pi \le \alpha \le 2\pi$

Fig 1.17 Half wave rectified output.

$$\therefore \quad i = I_m \text{ Sin } \alpha \qquad \alpha = \omega t \qquad 0 \le \alpha \le \pi$$

$$i = 0 \qquad \pi \le \alpha \le 2\pi$$

$$I_m = \frac{V_m}{R_f + R_L}$$

R_f is the forward resistance of the diode. R_L is the load resistance

1.15.2 READING OF D.C. AMMETER

If a D.C. Ammeter is connected in the rectifier output circuit, what reading will it indicate? Is it the peak value or will the needle oscillate from zero to maximum and then to zero and so on, or will it indicate average value? The meter is so constructed that it reads the average value.

$$\text{By definition, average value} = \frac{\text{Area of the curve}}{\text{Base}}$$

∴ For Half wave rectified output, base value is 2π for one cycle,

$$I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \text{Sin}\alpha \, d\alpha = \frac{I_m}{2\pi} . \left|-\text{Cos}\alpha\right|_0^{\pi}$$

$$I_{DC} = \frac{I_m}{2\pi}[1+1] = \frac{I_m}{\pi}$$

Upper limit is only π, because the signal is zero from π to 2π. The complete cycle is from 0 to 2π.

1.15.3 READING OF A.C. AMMETER

An A.C. ammeter is constructed such that the needle deflection indicates the effective or RMS current passing through it.

Effective or RMS value of an A.C. quantity is the equivalent D.C. value which produces the same heating effect as the alternating component. If some A.C. current is passed through a resistor, during positive and negative half cycles, also because of the current, the resistor gets heated, or there is some equivalent power dissipation. What is the value of D.C. which produces the same heating effects as the A.C. quantity? The magnitude of this equivalent D.C. is called the RMS or Effective Value of A.C.

By definition $$I_{rms} = \sqrt{\frac{I}{2\pi}\int_0^{2\pi}(I_m \text{Sin}\alpha)^2 d\alpha} = \sqrt{\frac{I_m^2}{2\pi}\int_0^{2\pi}\text{Sin}^2\alpha.d\alpha}$$

$$= \frac{I_m}{\sqrt{2\pi}}\sqrt{\int_0^{2\pi}\left\{\frac{1-\text{Cos}2\alpha}{2}\right\}d\alpha} = \frac{I_m}{\sqrt{2\alpha}}\sqrt{\left.\frac{\alpha}{2}\right|_0^{2\pi} + \left.\frac{\text{Sin}2\alpha}{4}\right|_0^{2\pi}}$$

$\therefore$ RMS value of a sine wave $= \dfrac{I_m}{\sqrt{2\pi}} \times \sqrt{\dfrac{2\pi}{2} + 0}$

$$= \frac{I_m\sqrt{\pi}}{\sqrt{2}\sqrt{\pi}} = \frac{I_m}{\sqrt{2}} = 0.707\, I_m$$

$$\text{Form Factor} = \frac{\text{RMS Value}}{\text{Average Value}}$$

For a sine wave, $$I_{average} = 0.636 I_m = 2 \times \frac{1}{2\pi}\int_0^{\pi}(I_m\ \text{Sin}\alpha)d\alpha$$

$$I_{rms} = \frac{I_m}{\sqrt{2}} = 0.707 I_m$$

$$\text{Form factor} = \frac{\left(\frac{I_m}{\sqrt{2}}\right)}{\left(\frac{I_m}{\pi}\right)} = \frac{0.707 I_m}{0.636 I_m} = 1.11$$

1.15.4 PEAK INVERSE VOLTAGE

For the circuit shown, the input is A.C. signal. Now during the positive half cycle, the diode conducts. The forward resistance of the diode R_f will be small.

$\therefore$ The voltage across the diode $v = i \times R_f$

$i = I_m \text{ Sin } \alpha \qquad 0 \le \alpha \le \pi.$

$\therefore$ $v = I_m R_f \text{ Sin } \alpha \qquad 0 \le \alpha \le \pi.$

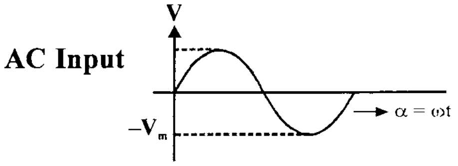


Fig. 1.18

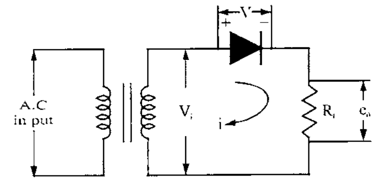


Fig. 1.19 Half wave rectifier circuit

Since R_f is small, the voltage across the diode 'V' during positive half cycle will be small, and the waveform is as shown. But during the negative half cycle, the diode will not conduct. Therefore, the current 'i' through the circuit is zero. So the voltage across the diode is not zero but the voltage of the secondary of the transformer V_i will appear across the diode ($\because$ effectively the diode is across the secondary of the transformer.)

$$\therefore \quad v = V_m \operatorname{Sin} \alpha \qquad \pi \leq \alpha \leq 2\pi.$$

The waveform across the diode is Fig. 1.20.

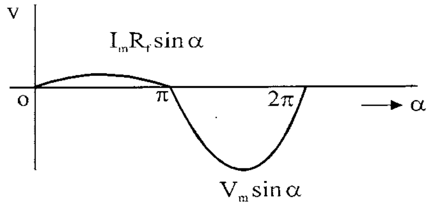


Fig 1.20 Voltage waveform across the diode

So the D.C. Voltage that is read by a D.C. Voltmeter is the average value.

$$V_{DC} = \frac{1}{2\pi}\left[\int_0^{\pi} I_m R_f . \operatorname{Sin}\alpha \, d\alpha + \int_{\pi}^{2\pi} V_m \operatorname{Sin}\alpha \, d\alpha\right]$$

$$= \frac{1}{2\pi}\left[(2)I_m R_f - (2)I_m (R_f + R_L)\right]$$

$$\because \quad V_m = I_m (R_f + R_c)$$

$$\therefore \quad \boxed{V_{DC} = \frac{-I_m R_L}{\pi}} \qquad \text{.......... (1.24)}$$

If we connect a CRO across the diode, this is the waveform that we see is as shown in Fig. 1.20. So in the above circuits the diode is being subjected to a maximum voltage of V_m. It occurs when the diode is not conducting. Hence it is called the ***Peak Inverse Voltage*** (**PIV**)

1.15.5 REGULATION

The variation of D.C output voltage as a function of D.C load current is called '*regulation*'.

$$\% \text{ Regulation} = \frac{V_{\text{No Load Voltage}} - V_{\text{Full Load}}}{V_{\text{Full Load}}} \times 100\,\%$$

For an ideal power supply output voltage is independent of the load or the output in voltage remains constant even if the load current varies, like in Zener diode near breakdown. Therefore, ***regulation is zero or it should be low for a given circuit.***

EXPRESSION FOR V_{DC} THE OUTPUT DC VOLTAGE

For half wave rectifier circuit (Fig. 1.21), I_{DC} the average value is :

$$I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} i.d\alpha$$

$$= \frac{1}{2\pi}\int_0^{\pi} I_m \sin\alpha.d\alpha = \frac{I_m}{\pi}$$

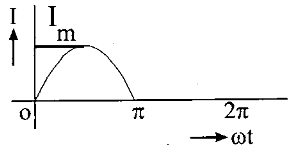


Fig 1.21 HWR current output

$$I_{DC} = \frac{I_m}{\pi} \qquad \text{.......... (1.25)}$$

But $I_m = \dfrac{V_m}{R_f + R_L}$

R_L = Load Resistance

R_f = Forward Resistance of the Diode.

$$V_{DC} = I_{DC} R_L$$

$$\therefore \quad I_{DC} = \frac{V_m/\pi}{R_f + R_L}$$

But $$I_{DC} = \frac{V_m}{\pi(R_f + R_L)}$$

$$\therefore \quad V_{DC} = \frac{V_m.R_L}{\pi(R_f + R_L)}$$

Adding and Subtracting R_f,

$$V_{DC} = \frac{V_m.(R_L + R_f - R_f)}{\pi(R_f + R_L)} = \frac{V_m}{\pi} - \frac{V_m.R_f}{\pi(R_f + R_L)}$$

$$I_{DC} = \frac{V_m}{\pi(R_f + R_L)}$$

I_{DC} is determined by R_L. Hence V_{DC} depends upon R_L.

$$\boxed{V_{DC} = \frac{V_m}{\pi} - I_{DC} \times R_f} \quad \text{.......... (1.26)}$$

This expression indicates that V_{DC} is $\frac{V_m}{\pi}$ at ***no load or when the load current is zero***, and it decreases with increase in I_{DC} linearly since R_f is more or less constant for a given diode. The larger the value of R_f, the greater is the decrease in V_{DC} with I_{DC}. But, the series resistance of the secondary winding of the transformer R_s should also be considered.

For a given circuit of half wave rectifier, if a graph is plotted between V_{DC} and I_{DC} the slope of the curve gives ($R_f + R_s$) where R_f is the forward resistance of diode and R_s the series resistance of secondary of transformer.

REGULATION FOR HWR

The regulation indicates how the DC voltage varies as a function of DC load current. In general, the percentage of regulation for ideal power supply is zero. The percentage of regulation is defined as

$$\% \text{ Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

As we know that,

$$V_{DC} = \frac{V_m}{\pi} - I_{DC} \cdot R_f$$

$$V_{NL} = \frac{V_m}{\pi} \text{ and } V_{FL} = \frac{V_m}{\pi} - I_{DC} \cdot R_f$$

$$\therefore \% \text{ Regulation} = \frac{\frac{V_m}{\pi} - \frac{V_m}{\pi} + I_{DC}.R_f}{\frac{V_m}{\pi} - I_{DC}.R_f} \times 100$$

$$= \frac{I_{DC}.R_f}{\frac{V_m}{\pi} - I_{DC}.R_f} = \frac{1}{\frac{V_m}{\pi\,(I_{DC}.R_f) - 1}} \times 100$$

$$= \frac{1}{\frac{V_m}{\pi} \times \frac{\pi}{V_m} \frac{(R_f + R_L)}{R_f} - 1} \times 100 \left[\because I_{DC} = \frac{V_m}{\pi(R_f + R_L)}\right]$$

$$\boxed{\% \text{ Regulation} = \frac{R_f}{R_L} \times 100}$$

Suppose for a given rectifier circuit, the specifications are 15V and 100 mA, i.e., the no load voltage is 15V and max load current that can be drawn is 100 mA. If the value of ($R_f + R_s$) = 25 Ω then the percentage regulation of the circuit is :

No Load Voltage = 15V

Drop across Diode = $I_m (R_f + R_s)$

R_S = Transformer Secondary Resistance

Max. Voltage with load = $15V - (I_m \times (R_f + R_s))$

$= 15 - 100 \text{ mA} \times 25\Omega$

$= 15 - 2.5$ volts = 12.5V

$$\therefore \quad \text{Percentage Regulation} = \frac{15-12.5}{12.5} \times 100 = \frac{2.5}{12.5} \times 100 \simeq 20\%.$$

1.15.6 RIPPLE FACTOR

The purpose of a rectifier circuit is to convert A.C. to D.C. But the simple circuit shown before will not achieve this. Rectifier converts A.C. to unidirectional flow and not D.C. So filters are used to get pure D.C. Filters convert unidirectional flow into D.C. Ripple factor is a measure of the fluctuating components present in rectifier circuits.

$$\text{Ripple factor, } \gamma = \frac{\text{RMS Value of alternating components of the waveform}}{\text{Average Value of the waveform}}$$

$$\gamma = \frac{I'_{rms}}{I_{DC}} = \frac{V'_{rms}}{V_{DC}}$$

I'_{rms} and V'_{rms} denote the value of the A.C components of the current and voltage in the output respectively. While determining the ripple factor of a given rectifier system experimentally, a voltmeter or ammeter which can respond to high frequencies (greater than power supply frequency 50 Hz) should be used and a capacitor should be connected in series with the input meter in order to block the D.C. component. Ripple factor should be small. (Total current $i = I_m \operatorname{Sin} \omega t$ according to Fourier Series, only A.C. is sum of D.C. and harmonics).

We shall now derive the expression for the ripple factor. The instantaneous current is given by $i' = i - I_{DC}$.

'i' is the total current. In a half wave rectifier, some D.C components are also present. Hence A.C component is,

$$i' = (i - I_{DC}) \ [(\text{Total current} - I_{DC})]$$

$$\text{RMS value is } I'_{rms} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} (i - I_{DC})^2 \, d\alpha}$$

$$\therefore \qquad I'_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi}\left(i^2 - 2I_{DC}.i + I_{DC}^{\ 2}\right)d\alpha}$$

Now, $\frac{1}{2\pi}\int_0^{2\pi} i^2 d\alpha$ = Square of the rms value of a sine wave by definition.

$$= (I_{rms})^2$$

$\frac{1}{2\pi}\int_0^{2\pi} i.d\alpha$ = The average value or D.C value I_{DC}.

I_{DC} is constant. So taking this term outside,

$$\frac{I_{DC}^{\ 2}}{2\pi}\int_0^{2\pi} d\alpha = \frac{I_{dc}}{2\pi}[2\pi]$$

$$\therefore \qquad I'_{rms} = \sqrt{(I_{rms})^2 - 2I_{DC}^{\ 2} + I_{DC}^{\ 2}}$$

The rms ripple current is

$$I'_{rms} = \sqrt{(I_{rms})^2 - I_{DC}^{\ 2}}$$

Ripple factor, $\gamma = \frac{I'_{rms}}{I_{dc}} = \frac{\sqrt{(I_{rms})^2 - I_{DC}^{\ 2}}}{I_{DC}}$

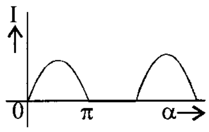
$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{DC}}\right)^2 - 1} \qquad \text{.......... (1.27)}$$

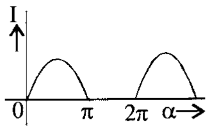
This is independent of the current waveshape and is not restricted to a half wave configuration. If a capacitor is used to block D.C. and then I_{rms} or V_{rms} is measured,

Then, $\gamma = \frac{I_{rms}}{I_{DC}}$

$\because \qquad I'_{rms} = \sqrt{I_{rms}^{\ 2} - I_{DC}}$

and $\qquad I_{DC} = 0$ (blocked by Capacitor) output waveform





For Half Wave Rectifier Circuit (HWR),

$$I = I_m \sin\alpha$$

$$I_{av} = I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin\alpha.d\alpha = \frac{I_m}{\pi}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \text{Sin}^2(\alpha)\, d\alpha} = \frac{I_m}{2}$$

$$I_{DC} = \frac{I_m}{\pi};\ V_{DC} = \frac{V_m}{\pi} \quad \text{Peak Inverse Voltage (PIV)} = V_m$$

Ripple Factor $\gamma = \dfrac{\text{RMS value of ripple current}}{\text{Average value of the current}} = \dfrac{I'_{rms}}{I_{DC}}$

Total current $I = I_{DC} + I'(\text{ripple})$

$I'(\text{ripple}) = (I - I_{DC})$

$$I'_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi}\left(I - I_{DC}\right)^2 d\alpha} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi}\left(I^2 - 2I.I_{DC} + I_{DC}{}^2\right).d\alpha}$$

$$= \sqrt{\left(I_{rms}\right)^2 - 2I_{DC}{}^2 + I_{DC}{}^2}$$

$$\therefore \quad I'_{rms} = \sqrt{\left(I_{rms}\right)^2 - I_{DC}{}^2}$$

$$\gamma = \frac{I'_{rms}}{I_{DC}} = \sqrt{\left(\frac{I_{rms}}{I_{DC}}\right)^2 - 1}$$

for Half Wave Rectifier, $\gamma = \sqrt{\left(\dfrac{I_m \times \pi}{2 \times I_m}\right)^2 - 1} = \sqrt{\left(\dfrac{\pi}{2}\right)^2 - 1} = 1.21$

1.15.7 RATIO OF RECTIFICATION (η)

$$\text{Ratio of Rectification} = \frac{\text{DC power delivered to the load}}{\text{AC input power from transfer secondary}}$$

$$P_{DC} = I_{DC}^2 \times R_L$$

But I_{DC} for HWR $= \dfrac{I_m}{\pi}$

$$\therefore \quad P_{DC} = \left(\frac{I_m}{\pi}\right)^2 \times R_L$$

P_{AC} is what a Wattmeter would indicate if placed in the HWR circuit with its voltage terminal connected across the secondary of the transformer.

From $\pi - 2\pi$ the diode is not conducting. Hence $I_{ac} = 0$.

$$P_{ac} = (I_{rms})^2\,(R_f + R_L)$$

Q from $\pi - 2\pi$ the AC is not being converted to D.C. So this power is wasted, as heat across diode and transformer.

$$\therefore \quad I_{rms}(\pi - 2\pi) \text{ portion of AC is } = \sqrt{\frac{1}{2\pi}\int_{\pi}^{2\pi} I_m^2 \sin^2 \alpha d\alpha} = \frac{I_m}{2}$$

I_{rms} for HWR is $I_m/2$. During negative half cycle, diode is not conducting and current I in the loop is zero even though Voltage V is present.

$$\therefore \quad P_{AC} = \left(\frac{I_m}{2}\right)^2 (R_f + R_L) = \left(\frac{I_m}{2}\right)^2 \times R_L$$

$$\therefore \quad \frac{P_{DC}}{P_{AC}} = \frac{I_m^2 . R_L \times 4}{\pi^2 I_m^2 \times R_L} = \frac{4}{\pi^2} = 0.406$$

$\therefore$ Ratio of rectification for HWR = 0.406

Considering ideal diode. If we consider R_f also, the expression $= \dfrac{0.406}{1 + \left(\dfrac{R_f}{R_L}\right)}$

The AC input power is not converted to D.C. Only part of it is converted to D.C and is dissipated in the load. The balance of power is also dissipated in the load itself as AC power. We have to consider the rating of the secondary of the transformer. In ratio of rectification we have considered only the A.C output as the secondary of the transformer.

1.15.8 TRANSFORMER UTILIZATION FACTOR

$$\text{Transformer Utilization Factor (TUF)} = \frac{\text{D.C power delivered to the load}}{\text{AC rating of transformer secondary}}$$

$$= \frac{P_{DC}}{P_{AC} \text{ rated}}$$

This term TUF is not ratio of rectification, because all the rated current of the secondary is not being drawn by the circuit.

$$P_{ac} = I_{DC}^2 . R_L - \left(\frac{I_m}{\pi}\right)^2 . R_L$$

$$P_{ac} = V_{rms} \times I_{rms}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}} = \text{Rated voltage of (Secondary Transformer)}$$

$$I_{rms} = I_m/2$$

$$P_{ac} = V_{rms} \times I_{rms}$$

But $\quad V_m = I_m (R_f + R_L) \simeq I_m R_L$ (R_f is small)

$$\text{TUF} = \frac{I_m^2}{\pi^2} \times R_L \Big/ \frac{I_m R_L}{\sqrt{2}} \times \frac{I_m}{2} = \frac{2\sqrt{2}}{\pi^2} = 0.287$$

Transformer Utilization Factor for Half Wave Rectifier is 0.287

1.15.9 DISADVANTAGES OF HALF WAVE RECTIFIER

1. High Ripple Factor (1.21)
2. Low ratio of rectification (0.406)
3. Low TUF (0.287)
4. D.C saturation of transformer.

For half wave configuration,

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2 \alpha.d\alpha} = \frac{I_m}{2}$$

Because during negative half cycle the diode will not conduct hence i = 0 in the loop from $\pi - 2\pi$. So integration is from $0 - \pi$ only. Even though V is present, i = 0 for one half cycle. Therefore, Power is zero ($V \times I = P = 0$, since, $I = 0$)

$$I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin\alpha.d\alpha = \frac{I_m}{2\pi}\left|-\cos\alpha\right|_0^{\pi} = \frac{I_m}{2\pi}\left|1+1\right| = \frac{I_m}{\pi}$$

$\therefore$ Ripple Factor for Half Wave Rectification $\frac{I_{rms}}{I_{DC}} = \frac{I_m/2}{I_m/\pi} = \frac{\pi}{2}$

$$\gamma = \sqrt{(1.57)^2 - 1} = 1.21$$

$$\because \quad \frac{\pi}{2} = 1.57$$

$$\therefore \quad \gamma > 1$$

So the ripple voltage exceeds D.C voltage. Hence HWR is a poor circuit for converting AC to DC.

1.15.10 POWER SUPPLY SPECIFICATIONS

The input characteristics which must be specified for a power supply are :

1. *The required output D.C voltage*
2. *Regulation*
3. *Average and peak currents in each diode*
4. *Peak inverse voltage (**PIV**)*
5. *Ripple factor.*

1.16 RIPPLE FACTOR

The purpose of a rectifier circuit is to convert A.C. to D.C. But the simple circuit shown before will not achieve this. Rectifier converts A.C. to unidirectional flow and not D.C. So filters are used to get pure D.C. Filters convert unidirectional flow into D.C. Ripple factor is a measure of the fluctuating components present in rectifier circuits.

$$\text{Ripple factor, } \gamma = \frac{\text{RMS Value of alternating components of the waveform}}{\text{Average Value of the waveform}}$$

$$\gamma = \frac{I'_{rms}}{I_{DC}} = \frac{V'_{rms}}{V_{DC}}$$

I'_{rms} and V'_{rms} denote the value of the A.C components of the current and voltage in the output respectively. While determining the ripple factor of a given rectifier system experimentally, a voltmeter or ammeter which can respond to high frequencies (greater than power supply frequency

50 Hz) should be used and a capacitor should be connected in series with the input meter in order to block the D.C. component. Ripple factor should be small. (Total current $i = I_m \sin \omega t$ according to Fourier Series, only A.C. is sum of D.C. and harmonics).

We shall now derive the expression for the ripple factor. The instantaneous current is given by $i' = i - I_{DC}$.

i is the total current. In a half wave rectifier, some D.C components are also present. Hence A.C component is,

$$i' = (i - I_{DC}) \; [\text{(Total current} - I_{DC})]$$

$$\text{RMS value is } I'_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (i - I_{DC})^2 \, d\alpha}$$

$$\therefore \quad I'_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} \left(i^2 - 2I_{DC}.i + I_{DC}{}^2\right) d\alpha}$$

Now, $\frac{1}{2\pi}\int_0^{2\pi} i^2 d\alpha$ = Square of the rms value of a sine wave by definition.

$$= (I_{rms})^2$$

$\frac{1}{2\pi}\int_0^{2\pi} i.d\alpha$ = The average value or D.C value I_{DC}.

I_{DC} is constant. So taking this term outside,

$$\frac{I_{DC}{}^2}{2\pi}\int_0^{2\pi} d\alpha = \frac{I_{dc}}{2\pi}[2\pi]$$

$$\therefore \quad I'_{rms} = \sqrt{(I_{rms})^2 - 2I_{DC}{}^2 + I_{DC}{}^2}$$

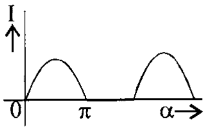
The rms ripple current is

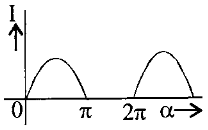
$$I'_{rms} = \sqrt{(I_{rms})^2 - I_{DC}{}^2}$$

Ripple factor, $\gamma = \frac{I'_{rms}}{I_{dc}} = \frac{\sqrt{(I_{rms})^2 - I_{DC}{}^2}}{I_{DC}}$

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{DC}}\right)^2 - 1} \qquad \text{.......... (1.28)}$$

This is independent of the current waveshape and is not restricted to a half wave configuration. If a capacitor is used to block D.C. and then I_{rms} or V_{rms} is measured,





Then, $\gamma = \frac{I_{rms}}{I_{DC}}$

∵ $I'_{rms} = \sqrt{{I_{rms}}^2 - I_{DC}}$

and $I_{DC} = 0$ (blocked by Capacitor) output waveform

For Half Wave Rectifier Circuit (HWR),

$$I = I_m \sin\alpha$$

$$I_{av} = I_{DC} = \frac{1}{2\pi}\int_0^{\pi} I_m \sin\alpha . d\alpha = \frac{I_m}{\pi}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \text{Sin}^2(\alpha)\, d\alpha} = \frac{I_m}{2}$$

$I_{DC} = \frac{I_m}{\pi}$; $V_{DC} = \frac{V_m}{\pi}$ Peak Inverse Voltage (PIV) = V_m

Ripple Factor $\gamma = \frac{\text{RMS value of ripple current}}{\text{Average value of the current}} = \frac{I'_{rms}}{I_{DC}}$

Total current $I = I_{DC} + I'(\text{ripple})$

$I'(\text{ripple}) = (I - I_{DC})$

$$I'_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (I - I_{DC})^2\, d\alpha} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} (I^2 - 2I.I_{DC} + {I_{DC}}^2).d\alpha}$$

$$= \sqrt{(I_{rms})^2 - 2{I_{DC}}^2 + {I_{DC}}^2}$$

∴ $I'_{rms} = \sqrt{(I_{rms})^2 - {I_{DC}}^2}$

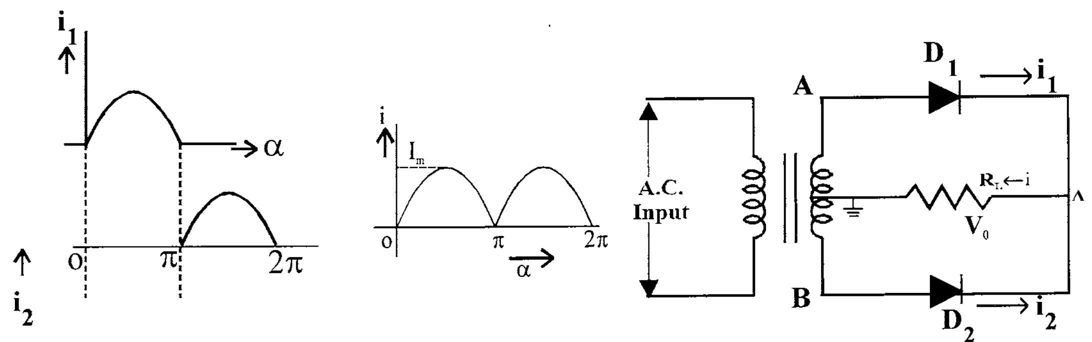
$$\gamma = \frac{I'_{rms}}{I_{DC}} = \sqrt{\left(\frac{I_{rms}}{I_{DC}}\right)^2 - 1}$$

for Half Wave Rectifier, $\gamma = \sqrt{\left(\frac{I_m \times \pi}{2 \times I_m}\right)^2 - 1} = \sqrt{\left(\frac{\pi}{2}\right)^2 - 1} = 1.21$

1.17 FULL WAVE RECTIFIER (FWR)

Since half wave rectifier circuit has poor ripple factor, for ripple voltage is greater than DC voltage, it cannot be used. So now analyze a full wave rectifier circuit.

The circuit is as shown in Fig. 1.22.



Waveforms **FWR Circuit**

Fig 1.22

During the +ve half cycle, D_1 conducts and the current through D_2 is zero

During the – ve half cycle, D_2 conducts and the current through D_1 is zero

A centre tapped transformer is used.

The total current i flows through the load resistor R_L and the output voltage V_0 is taken across R_L.

For half wave rectifier, circuit, $I_{DC} = \frac{1}{2\pi}\int_0^{2\pi} I_m \sin\alpha d\alpha = \frac{I_m}{\pi}$

For full wave rectifier, circuit, I_{DC} = Twice that of half wave rectifier circuit

$\therefore \quad I_{DC} = 2\, I_m/\pi$

For half wave rectifier circuit , $I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin\alpha d\alpha} = \frac{I_m}{2}$

For full wave rectifier circuit, $I_{rms} = \sqrt{2\times\frac{1}{2\pi}\int_0^{\pi} I_m^2 \sin^2\alpha d\alpha}$

$$I_{rms} = \sqrt{2} \times \frac{I_m}{2} = \frac{I_m}{\sqrt{2}}$$

$$I_m = \frac{V_m}{R_f + R_L}$$

R_f is the forward resistance of each diode.

A centre tapped transformer is essential to get full wave rectification. So there is a phase shift of 180^0, because of centre tapping. So D_1 is forward biased during the input cycle of 0 to π, D_2 is forward biased during the period π to 2π since the input to D_2 has a phase shift of 180^0 compared to the input to D_1. So positive half cycle for D_2 starts at a full wave rectifier circuit, while the D.C. current starts through the load resistance R_L is twice that of the Half Wave Rectifier Circuit.

Therefore, for Half Wave Rectifier Circuit,

$$I_{DC} = \frac{I_m}{\pi}$$

For Full Wave Rectifier Circuit,

$$I_{DC} = \frac{2I_m}{\pi}$$

Hence, Ripple Factor is improved.

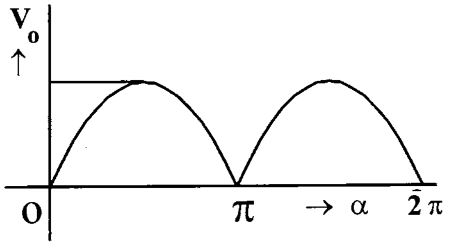


Fig 1.23 FWR voltage output.

1.17.1 RIPPLE FACTOR

$$\frac{I'_{rms}}{I_{DC}} = \frac{I_m/\sqrt{2}}{2I_m/\pi} = \frac{\pi}{2\sqrt{2}} = 1.11$$

$$I'_{rms} = \sqrt{I_{rms}{}^2 - I_{DC}{}^2}\ ; \quad \gamma = \frac{\sqrt{I_{rms}{}^2 - I_{DC}{}^2}}{I_{DC}}$$

Therefore, $\gamma = 1.21$ for HWR, and it is is 0.482 for FWR.

1.17.2 REGULATION FOR FWR

The regulation indicates how D.C voltage varies as a function of load current. The percentage of regulation is defined as

$$\%\ \text{Regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

The variation of DC voltage as a function of load current is as follows

$$V_{DC} = I_{DC}\, R_L$$

$$= \frac{2I_m}{\pi} \,.\, R_L \quad \left[\because I_m = \frac{V_m}{R_f + R_L}\right]$$

$$= \frac{2V_m}{\pi(R_f + R_L)} \,.\, R_L \quad \left[\because I_m = \frac{V_m}{R_f + R_L}\right]$$

$$= \frac{2V_m}{\pi}\left[1 - \frac{R_f}{R_f + R_L}\right]$$

$$= \frac{2V_m}{\pi} - \frac{2V_m}{\pi(R_f + R_L)} \times R_f$$

$$V_{DC} = \frac{2V_m}{\pi} - I_{DC} \cdot R_f$$

$$V_{NL} = \frac{V_m}{\pi}, \qquad V_{FL} = \frac{V_m}{\pi} - I_{DC} \cdot R_f$$

$$\% \text{Regulation} = \frac{\frac{2V_m}{\pi} - \frac{2V_m}{\pi} + I_{DC} \cdot R_f}{\frac{2V_m}{\pi} - I_{DC} \cdot R_f} \times 100$$

$$= \frac{I_{DC} R_f}{\frac{2V_m}{\pi} - I_{DC} . R_f} \times 100$$

$$= \frac{I_{DC} R_f}{I_{DC} R_f \left(\frac{2V_m}{\pi I_{DC} . R_f} \right) - 1} \times 100$$

$$= \frac{1}{\left(\frac{2V_m}{\pi} \times \frac{(R_f + R_L)}{\frac{2V_m}{\pi} . R_f} - 1 \right)} \times 100$$

$$\% \text{ Regulation} = \frac{R_f}{R_L} \times 100$$

1.17.3 RATIO OF RECTIFICATION

$$\frac{\text{D.C. power delivered to Load}}{\text{A.C. input power from transformer secondary}}$$

$$p_{DC} = I_{DC}^2 \times R_L \text{ for FWR,}$$

$$I_{DC} = \frac{2I_m}{\pi} = \frac{4.I_m^2}{\pi^2} R_L.$$

P_{AC} is what a Wattmeter would indicate if placed in the FWR Circuit with its voltage terminals connected across the transformer secondary.

$$P_{ac} = (I_{rms})^2 . (R_F + R_L);\ I_{rms} \text{ for FWR} = \frac{I_m}{\sqrt{2}}$$

$$= \left(\frac{I_m}{\sqrt{2}} \right)^2 .(R_F + R_L).$$

$$= \frac{I_m^2}{2} (R_F + R_L).$$

If we assume that R_f is the forward resistance of the diode is very small, compared to R_L.

$$R_f + R_L \cong R_L.$$

$$\therefore \quad P_{AC} = \frac{I_m^2}{2} (R_L).$$

$$\text{Ratio of Rectification} = \frac{p_{DC}}{p_{AC}} = \frac{4 I_m^2 R_L \times 2}{\pi^2 I_m^2 \times R_L} = \frac{8}{\pi^2} = 0.812$$

For HWR it is 0.406. Therefore, for FWR the ratio of rectification is twice that of HWR.

1.17.4 TRANSFORMER UTILIZATION FACTOR

In fullwave rectifier using center-tapped transformer, the secondary current flows through each half separately in every half cycle. While the primary of transformer carries current continuously. Hence TUF is calculated for primary and secondary windings separately and then the average TUF is determined.

$$\text{Secondary TUF} = \frac{\text{DC power delevered to load}}{\text{AC rating of transformer secondary}}$$

$$= \frac{(I_{DC})^2 R_L}{V_{rms} I_{rms}} = \frac{\left(\frac{2 I_m}{\pi}\right)^2 . R_L}{\frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}}}$$

$$= \frac{4I_m^2}{\pi^2} \times \frac{2R_L}{I_m^2(R_f + R_L)} = \frac{8}{\pi^2} \times \frac{1}{1+\frac{R_f}{R_L}}$$

if $R_f << R_L$, then secondary TUF = 0.812.

The primary of the transformer in feeding two HWR's separately. These two HWR's work independently of each other but feed a common load. Therefore,

$$\text{TUF for primary} = 2 \times \text{TUF of HWR} = 2 \times \frac{0.287}{1+\frac{R_f}{R_L}}$$

if $R_f << R_L$, then TUF for primary = 0.574

The average TUF for FWR using center tapped transformer

$$= \frac{\text{TUF of primary + TUF of secondary}}{2} = \frac{0.812 + 0.574}{2} = 0.693$$

Therefore, the transformer is utilized 69.3% in FWR using center tapped transformer.

1.17.5 PEAK INVERSE VOLTAGE FOR FULL WAVE RECTIFIER

With reference to the FWR circuit, during the –ve half cycle, D_1 is not conducting and D_2 is conducting. Hence maximum voltage across R_L is V_m, since voltage is also present between A and O of the transformer, the total voltage across $D_1 = V_m + V_m = 2V_m$ (Fig. 1.22).

1.17.6 D.C. SATURATION

In a FWR, the D.C. currents I_1 and I_2 flowing through the diodes D_1 and D_2 are in opposite direction and hence cancel each other. So there is no problem of D.C. current flowing through the core of the transformer and causing saturation of the magnetic flux in the core.

PIV is 2 V_m for each diode in FWR circuit because, when D_1 is conducting, the drop across it is zero. Voltage delivered to R_L is V_m. D_2 is across R_L. During the same half cycle, D_2 is not conducting. Therefore, peak voltage across it is V_m from the second half of the transformer. The total voltage across D_2 is $V_m + V_m = 2V_m$.

1.18 BRIDGE RECTIFIERS

The circuit is shown in Fig. 1.24. During the positive half cycle, D_1 and D_2 are forward biased. D_3 and D_4 are open. So current will flow through D_1 first and then through R_L and then through D_2 back to the ground. During the –ve half cycle D_4 and D_3 are forward biased and they conduct. The current flows from D_3 through R_L to D_4. Hence the direction of current is the same. So we get full wave rectified output.

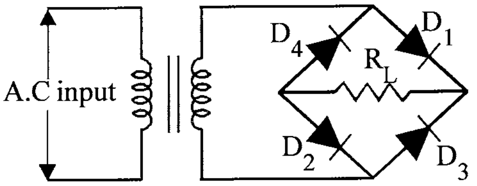


Fig 1.24 Bridge rectifier circuit.

In Bridge rectifier circuit, there is no need for centre tapped transformer. So the transformer secondary line to line voltage should be one half of that, used for the FWR circuit, employing two diodes.

$$I_{DC} = \frac{2I_m}{\pi}$$

where $$I_m = \frac{V_m}{R_S + 2R_f + R_L}$$

$$V_{DC} = \frac{2V_m}{\pi} - I_{DC}(R_S + 2R_F)$$

R_S = Resistance of Transformer Secondary.

R_f = Forward Resistance of the Diode.

R_L = Load Resistance.

$2R_f$ should be used since two diodes in series are conducting at the same time. The ripple factor and ratio of rectification are the same as for Full Wave Rectifier.

1.18.1 ADVANTAGES OF BRIDGE RECTIFIER

1. *The peak inverse voltage (PIV) across each diode is V_m and not $2V_m$ as in the case of FWR. Hence the Voltage rating of the diodes can be less.*
2. *Centre tapped transformer is not required.*
3. *There is no D.C. Current flowing through the transformer since there is no centre tapping and the return path is to the ground. So the transformer utilization factor is high.*

1.18.2 DISADVANTAGES

1. *Four diodes are to be used.*
2. *There is some voltage drop across each diode and so output voltage will be slightly less compared to FWR. But these factors are minor compared to the advantages.*

Bridge rectifiers are available in a package with all the 4 diodes incorporated in one unit. It will have two terminals for A.C. Input and two terminals for DC output. Selenium rectifiers are also available as a package.

1.19 THE HARMONIC COMPONENTS IN RECTIFIER CIRCUIT

The analytical representation of output current wave of halfwave rectifier using fourier series is given by

$$i = I_m \left[\frac{1}{\pi} + \frac{1}{2} \sin \omega t - \frac{2}{\pi} \sum_{k=\text{even}} \frac{\cos \omega t}{(k+1)(k-1)} \right] \qquad .....(1.29)$$

The lowest angular frequency present in eq. (1.29) is of a.c source. And all other terms present in above equation are of even harmonic of power source.

Similarly in case of full wave rectifier in which one diode conducts for positive half cycle and the other diode conducting for negative half cycle and the net output current is difference of the currents conducted in positive half cycle ($i_1(\alpha)$) and the current conducted in negative half cycle ($i_2(\alpha)$). i.e.,

$$\text{Net current } i = i_1(\alpha) + i_2(\alpha) \qquad (i_2(\alpha) = i_2(\alpha + \pi)) \qquad ....(1.30)$$

Here both $i_1(\alpha)$ and $i_2(\alpha)$ are same in magnitude but opposite in polarity. The difference $i_1(\alpha) + i_2(\alpha)$ results in cancellation of lowest angular frequency of power source present in eq. (1.29). And hence the total current.

$i = i_1 + i_2$ attains of form

$$i = I_m \left[\frac{2}{\pi} - \frac{4}{\pi} \sum_{\substack{k \text{ even} \\ k \neq 0}} \frac{\cos k\omega t}{(k+1)(k-1)} \right] \qquad .....(1.31)$$

Here in eq. (1.31) the fundamental frequency 'ω' has been eliminated from the equation. And hence lowest frequency in the output being 2ω, i.e., the second hormonic term. This offers an definite advantage in the effectiveness of filtering the output.

The other advantage of fullwave rectifier is that the direction of the current during two halfs of cycle is of opposite in nature, thus the magnetic cycle through which iron core is take is essentially that of the altering current and this eliminates d.c. saturation of the transformer, which would yield additional hormonics in the output.

1.20 INDUCTOR FILTER

FILTERS

A power supply must provide ripple free source of power from an A.C. line But the output of a rectifier circuit contains ripple components in addition to a D.C. term. It is necessary to include a filter between the rectifier and the load in order to eliminate these ripple components. Ripple components are high frequency A.C. Signals in the D.C output of the rectifier. These are not desirable, so they must be filtered. So filter circuits are used.

Flux linkages per ampere of current $L = \frac{N\phi}{I}$. The ability of a component to develop induced voltage when alternating current is flowing through the element is the property of the inductor. Types of Inductors are :

1. *Iron Cored* 2. *Air Cored*

An inductor opposes any change of current in the circuit. So any sudden change that might occur in a circuit without an inductor are smoothed out with the presence of an inductor. In the case of AC, there is change in the magnitude of current with time.

Inductor is a short circuit for DC and offers some impedance for A.C. ($X_L = j\omega L$). So it can be used as a filter. AC voltage is dropped across the inductors, where as D.C. passes through it. Therefore, A.C is minimized in the output.

Inductor filter is used with FWR circuit. Therefore, HWR gives 121% ripple and using filter circuit for such high ripple factor has no meaning. FWR gives 48% ripple and by using filter circuit we can improve it. According to Fourier Analysis, current, 'i' in HWR Circuit is

$$i = \frac{I_m}{\pi} + \frac{I_m}{2} \text{Sin}\,\omega t - \frac{2I_m}{\pi} \frac{\text{Cos}\,4\omega t}{3}$$

Current in the case of FWR is $i \cong \frac{2I_m}{\pi} - \frac{4I_m}{3\pi}\cos 2\omega t - \frac{4I_m \cos 4\omega t}{15\pi}$

The reactance offered by inductor to higher order frequencies like $4\omega t$ can be neglected. So the output current is

$$i \cong \frac{2I_m}{\pi} - \frac{4I_m}{3\pi}\cos 2\omega t$$

the fundamental harmonic ω is eliminated.

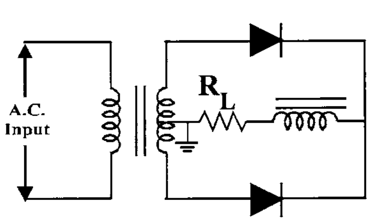


Fig 1.25 Inductor filter circuit.

The circuit for FWR with inductor filter is as shown in Fig. 1.25.

One winding of transformer can be used as 'L'. For simplification, diode and choke (inductor) resistances can be neglected, compared with R_L. The D.C. component of the current is

$$I_m = \frac{V_m}{R_L}$$

Impedance due to L and R_L in Series $|Z| = \sqrt{R_L{}^2 + (2\omega L)^2}$

For second Harmonic, the frequency is 2ω.

Therefore, A.C. Component of current $I_m = V_m / \sqrt{R_L{}^2 + 4\omega^2 L^2}$. So substituting these values in the expression, for current,

$$I = \frac{2I_m}{\pi} - \frac{4I_m}{3\pi} \text{Cos } 2\omega t$$

by inductor to higher order frequencies like $4\omega t$ etc., we get,

$$i = \frac{2V_m}{\pi R_L} - \frac{4V_m}{3\pi\sqrt{R_L{}^2 + 4\omega L^2}} \cos(2\omega t - \theta)$$

where θ is the angle by which the load current lags behind the voltage and is given by

$$\theta = \text{Tan}^{-1} \frac{2\omega L}{R_L}.$$

1.20.1 RIPPLE FACTOR

$$\gamma = I_{r \cdot rms}/I_{D.C.} = I'_{rms}/I_{DC}\ I_{DC} = 2V_m/\pi\ R_L$$

$$I_{rrms} = \frac{I_m}{\sqrt{2}} = \frac{4V_m}{3\sqrt{2\pi}\sqrt{R_L^2 + 4\omega^2 L^2}}$$

$$\therefore \quad \text{Ripple factor} = \frac{4v_m \times \pi R_L}{3\sqrt{2\pi}\sqrt{R_L^2 + 4\omega^2 L^2 \times 2V_m}}$$

$$= \frac{2}{3\sqrt{2}} \times \frac{1}{\sqrt{1 + \frac{4\omega^2 L^2}{R_L{}^2}}}$$

If $\frac{4\omega^2 L^2}{R_L{}^2} >> 1$, then

$$\text{Ripple Factor } r = \frac{R_L \times 2}{3\sqrt{2} \times 2\omega L}$$

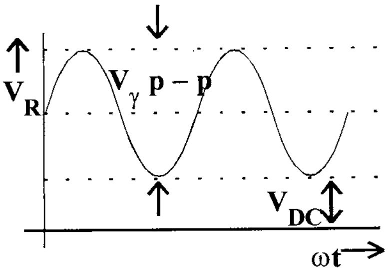


Fig 1.26 Ripple voltage V_V

$$\therefore \quad \text{Ripple factor} = \frac{R_L}{3\sqrt{2}\omega L} \qquad \text{..........} (1.32)$$

Therefore, for higher values of L, the ripple factor is low. If R_L is large, then also γ is high. Hence inductor filter should be used where the value of R_L is low. Suppose the output wave form from FWR supply is as shown in Fig. 1.26, then,

$V_{\gamma p-p}$ is the peak to peak value of the ripple voltage. Suppose

$V_{DC} = 300V$, and $V_{\gamma p-p}$ is 10V.

then V_R maximum = $\frac{10}{2} = 5V$. Therefore, $V_\gamma rms = \frac{V_\gamma \max}{\sqrt{2}} = \frac{5}{\sqrt{2}} = 3.54V$

$$\therefore \quad \text{Ripple Factor } \gamma = \frac{V_r rms}{V_x} = \frac{3.54}{300} = 0.0118.$$

$$\% \text{ ripple} = \text{Ripple factor} \times 100\ \% = 1.18$$

1.20.2 REGULATION

$$V_{DC} = I_{DC}.R_L; \qquad I_{DC} \text{ for F W R is } \frac{2I_m}{\pi}$$

$$V_{DC} = \frac{2I_m R_L}{\pi} = \frac{2V_m}{\pi}$$

$$I_m.R_L = V_m$$

Therefore, V_{DC} is constant irrespective of R_L. But this is true if L is ideal. In practice

$$V_{DC} = \frac{2V_m}{\pi} - I_{DC}.R_f$$

where R_f is the resistance of diode.

An inductor stores magnetic energy when the current flowing through it is greater than the average value and releases this energy when the current is less than the average value.

Another formula that is used for Inductor Filter for

$$\text{Ripple Factor} = 0.236\ \frac{R_C + R_L}{\omega_L} \qquad \text{.......... (1.33)}$$

where R_L is load resistance R_c is the series resistance of the inductors. This is the same as the above formula $\frac{R_L}{3\sqrt{2}\omega_L}$

$$\because \quad \frac{1}{3\sqrt{2}} = 0.236.$$

Problem 1.18

A FWR is used to supply power to a 2000Ω Load. Choke Inductors of 20 H inductance and capacitors of 16μf are available. Compute the ripple factor using **1**. One Inductor filter **2**. One capacitor filter **3**. Single L type filter.

Solution

1. One Inductor Filter :

$$I = \frac{2I_m}{\pi} - \frac{4I_m}{3\pi} \cos(2\omega t - \phi) \text{ where } \phi = \mathrm{Tan}^{-1}\left(\frac{2\omega L}{R}\right)$$

$$I_{DC} = \frac{2V_m}{\pi R_L}$$

$$V = \frac{I \text{ ripple}}{I_{DC}} = \frac{R_L}{3\sqrt{2}\omega_L} = \frac{100}{3 \times 1.414 \times 2} = 0.074$$

2. Capacitor filter :

The ripple voltage for a capacitor filter is of Triangular waveform approximately. The rms value for Triangular wave is $\frac{E_d}{2\sqrt{3}}$ or $\frac{V_{rms}}{2\sqrt{3}}$.

$$\therefore \quad E_{rms} = \frac{E_d}{2\sqrt{3}}$$

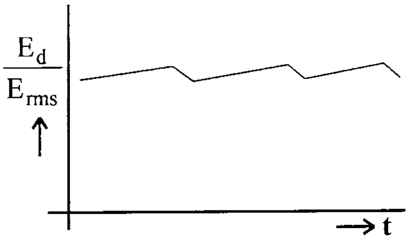


Fig 1.27** V_0 **of capacitor filter.

Suppose the discharging of the capacitor will cut one for one full half cycle .then the change last by the capacitor

$$Q = \omega t = I_{DC} \times \frac{1}{2f}.$$

$$\therefore \quad \text{voltage} = \frac{Q}{c}$$

$$\therefore \quad E_d = \frac{I_{DC}}{2fc}$$

$$\gamma = \frac{I_{DC}}{2fc \times 2\sqrt{3} \times I_{DC}} = \frac{1}{4fc\sqrt{3}R_L} = \frac{1}{4 \times \sqrt{3} \times 50 \times 16 \times 10^{-6} \times 2000} = 0.09$$

3. L Type filter :

$$\gamma = \frac{\sqrt{2}}{3} \times \frac{1}{4\omega^2 LC} = 0.0037$$

Problem 1.19

A diode whose internal resistance is 20 Ω is to supply power to a 1000Ω load from a 110V ((rms) source of supply. Calculate **(a)** The peak load current. **(b)** The DC load current **(c)** AC Load Current **(d)** The DC diode voltage. **(e)** The total input power to the circuit. **(f)** % regulation from no load to the given load.

Solution

Since only one diode is being used, it is for HWR Circuit.

(a) $$I_m = \frac{V_m}{R_f + R_L} = \frac{110\sqrt{2}}{1020} = 152.5\text{mA}.$$

(b) $$I_{DC} = \frac{I_m}{\pi} = \frac{152.5}{\pi} = 48.5\text{mA}.$$

(c) $$I_{rms} = \frac{I_m}{2} = \frac{152.5}{2} = 76.2\text{mA}.$$

(d) $$V_{dc} = \frac{-I_m.R_L}{\pi} = -48.5 \times 1 = -48.5\text{V}.$$

(e) $$P_i = I_{rms} \times (R_f + R_L) = 5.92\Omega.$$

(f) $$\%\ \text{regulation} = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\% = \frac{\frac{V_m}{\pi} - I_{DC}.R_L}{I_{DC}.R_L} = 2.06\%$$

Problem 1.20

Show that the maximum DC output power $P_{DC} = V_{DC}\, I_{DC}$ in a half wave single phase circuit occurs when the load resistance equals the diode resistance R_f.

Solution

$$P_{DC} = I_{DC}^2.R_L = \frac{V_m^{\ 2}.R_L}{\pi^2(R_F + R_L)}$$

when R_L is very large, $V_{DC} \cong \frac{V_m}{\pi}$; $I_{DC} = \frac{V_{DC}}{R_L} = \frac{V_m}{\pi.R_L}$

for P_{DC} to be maximum, $\frac{dp_{DC}}{dR_L} = 0.$

or $$\frac{V_m^{\ 2}}{\pi^2}\left(\frac{(R_F + R_L)^2 - (R_F + R_L).R_L}{(R + R_L)^4}\right) = 0.$$

$$R_F + R_L = 2R_L \text{ or } R_L = R_F.$$

Therefore, P_{DC} is maximum when R_L is equal to R_F

Problem 1.21

A 1mA meter whose resistance is 10Ω is calibrated to read rms volts when used in a bridge circuit with semiconductor diodes. The effective resistance of each element may be considered to be zero in the forward direction and ∞ in the reverse direction. The sinusoidal input voltage is applied in series with a 5 - KΩ resistance. What is the full scale reading of this meter?

Solution

$$I_{DC} = \frac{2I_m}{\pi} \text{ for bridge rectifier circuit.}$$

$$I_m = \frac{V_m}{R_L};$$

$$V_m = \sqrt{2}V_{rms}$$

$$\therefore \quad I_{DC} = \frac{2\sqrt{2} \times V_{rms}}{\pi R_L};$$

$$R_L = 5K\Omega + 10\ \Omega = (\ 5000 + 10\ )\Omega = 5010\ \Omega$$

$$1mA = \frac{2\sqrt{2} \times V_{rms}}{\pi \times 5010}$$

$$\therefore \quad V_{rms} = \frac{1 \times 10^{-3} \times \pi \times 5010}{2\sqrt{2}} = 5.56V.$$

1.21 L-SECTION FILTER

In an inductor filter, ripple decreases with increase in R_L. In a capacitor filter, ripple increases with increase in R_L. A combination of these two into a choke ***input or L-Section Filter*** should then make the ripple independent of load resistance.

If L is small, the capacitor will be charged to V_m, the diodes will be cut off allowing a short pulse of current. As L is increases, the pulses of current are smoothed and made to flow for a larger period, but at reduced amplitude. But for a critical value of inductance L_c, either one diode

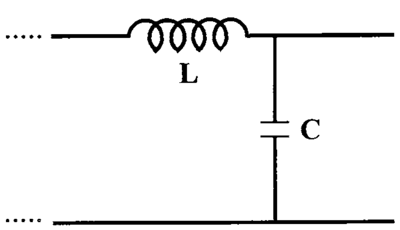


Fig 1.28 (a) Circuit.

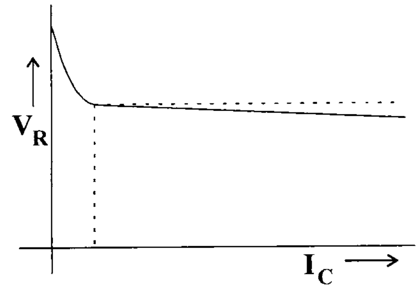


Fig 1.28 (b) LC filter characteristic.

or the other will be always conducting, with the result that the input voltage V and I to the filter are full wave rectified sine waves.

The circuit and graph of DC output voltage for LC Filter is as shown in Fig. 1.28(a) and (b) respectively.

$$V_{DC} = \frac{2V_m}{\pi}$$

for Full Wave Rectifier Circuit. Considering ideal elements, conduction angle is increased when inductor is placed because there is some drop across 'L'. So C cannot charge to V_m. Therefore, the diode will be forward biased for a longer period.

The ripple circuit which passes through 'L', is not allowed to develop much ripple voltage across R_L, if X_c at ripple frequency is small compared to R_L. Because the current will pass through C only. Since X_c is small and Capacitor will get charged to a constant voltage. So V_o across R_L will not vary or ripple will not be there. Since for a properly designed LC Filter,

$$X_c << R_L$$

and $$X_L >> X_c \quad \text{at } \omega = 2\pi f$$

X_L should be greater than X_c because, all the AC should be dropped across X_L itself so that AC Voltage across C is nil and hence ripple is low.

1.21.1 RIPPLE FACTOR IN LC FILTER

AC Component of current through L is determined by X_L.

$$X_L = 2\omega L$$

RMS value of ripple current for Full Wave Rectifier with L Filter is,

$$I'\text{rms} = \frac{4V_m}{3\pi\sqrt{2}X_L} = \text{RMS Value of Ripple Current for L Filter}$$

$$I'\text{rms} = \frac{2}{3\sqrt{2}X_L} = \frac{2V_m}{\pi}$$

$$\therefore \quad I'\text{rms} = \frac{2}{3\sqrt{2}X_L} \cdot V_{DC} = \frac{\sqrt{2}V_{DC}}{3X_L}$$

The ripple voltage in the output is developed by the ripple current flowing through X_C.

$$\therefore \quad V'\text{rms} = I'\text{rms} \cdot X_C = \frac{\sqrt{2}}{3} \cdot \frac{X_C}{X_L} \cdot V_{DC}$$

$$\text{Ripple factor} = \frac{V'\text{rms}}{V_{DC}}$$

$$\gamma = \frac{\sqrt{2}.X_C}{3X_L}$$

$$X_C = \frac{1}{j2\omega fc} \; . \; X_L = jL\omega L = 2\,\pi fL$$

$$\therefore \qquad \gamma = \frac{\sqrt{2}}{3}.\frac{1}{2\omega C}.\frac{1}{2\omega L}$$

$X_L = 2wL$ since ripple is being considered at a frequency, twice the line frequency.

If $\quad f = 60\text{ Hz}, \quad \gamma = \frac{0.83}{LC}$

1.21.2 BLEEDER RESISTANCE

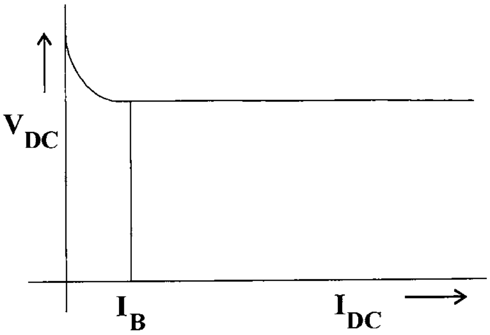


Fig 1.29 LC filter characteristic.

For the LC filter, the graph between I_{DC} and V_{DC} is as shown in Fig. 1.29. For light loads, i.e., when the load current is small, the capacitor gets charged to the peak value and so the no load voltage is $2V_m/\pi$. As the load resistance is decreased, I_{DC} increases so the drop across other elements V_{iz} diodes and choke increases and so the average voltage across the capacitor will be less than the peak value of $2V_m/\pi$. The output voltage remains constant beyond a certain point I_B and so the regulation will be good. The voltage V_{DC} remains constant even if I_{DC} increases, because, the capacitor gets charged every time to a value just below the peak voltage, even though the drop across diode and choke increases. So for currents above I_B, the filter acts more like an inductor filter than C filter and so the regulation is good. Therefore, for LC filters, the load is chosen such that, the $I_{DC} \geq I_B$. The corresponding resistance is known as ***Bleeder Resistance*** (R_B). So Bleeder Resistance is the value for which $I_{DC} \geq I_B$ and good regulation is obtained, and conduction angle is 180^0. When $R_L = R_B$, the conduction angle = 180^0, and the current is continuous. So just as we have determined the critical inductance L_C, when $R_L = R_B$, the Bleeder Resistance, I_{DC} = the negative peak of the second harmonic term.

$$\therefore \qquad I_{DC} = \frac{2V_m}{\pi R_B}$$

$$I'\text{ peak} = \frac{4V_m}{3\pi}.\frac{1}{XL}$$

$$\therefore \qquad \frac{2V_m}{\pi R_B} = \frac{4V_m}{3\pi}.\frac{1}{X_L}$$

$$R_B = \frac{3.X_L}{2}; \qquad R_B \text{ is Bleeder Resistance.}$$

I_{DC} should be equal to or greater than 'I' peak, since, 'X_L' determines the peak value of the ripple component. If 'X_L' is large 'I' peak can be $\leq I_{DC}$ and so the ripple is negligible or pure D.C. is obtained, where $X_L = 2\omega L$ corresponding to the second harmonic. Therefore, R should be at least equal to this value of R_B, the Bleeder Resistor.

1.21.3 SWINGING CHOKE

The value of the inductance in the LC circuits should be > L_C the minimum value so that conduction angle of the diodes is 180^0 and ripple is reduced. But if the current I_{DC} is large, then the inductance for air cored inductors as $L = N\phi/I$ (flux linkages per ampere of current), as 'I' increases, 'L' decreases and may become below the critical inductance value L_C. Therefore, Iron cored inductors or chokes are chosen for filters such that the value of L varies within certain limits and when 'I' is large, the core saturates, and the inductance value will not be < L_C. Such chokes, whose inductance varies with current within permissible limits, are called ***Swinging Chokes***. (In general for inductors ϕ/I remains constant so that L is constant for any value of current I) This can be avoided by choosing very large value of L so that, even if current is large, Inductance is large enough > L_C But this increases the cost of the choke. Therefore, swinging choke are used.

$L_C \geq R_L / 3\omega$
R_L = Load Resistance
L_C = Critical Inductance
$\omega = 2\pi f$

At no load $R_L = \infty$. Therefore, L should be ∞ which is not possible. Therefore, Bleeder Resistance of value = $3X_L / 2$ is connected in parallel with R_L, so that even when R_L is ∞, the conduction angle is 180^0 for each diode.

The inductance of an iron - cored inductor depends up on the D.C. current flowing through it, L is high at low currents and low at high currents. Thus its L varies or swings within certain limits. This is known as ***Swinging Choke***.

Typical values are

L = 30 Henrys at I = 20 mA and
L = 4 Henrys at I = 100 mA.

Problem 1.22

Design a full wave rectifier with an LC filter (single section) to provide 9V DC at 100mA with a maximum ripple of 2%. Line frequency f = 60 HZ.

Solution

$$\text{Ripple factor } \gamma = \frac{\sqrt{3}}{2} \times \frac{1}{2\omega C} \times \frac{1}{2\omega L} = \frac{0.83}{LC}\,\mu$$

$$\therefore \quad 0.02 = \frac{0.83}{LC} \quad \text{or} \quad LC = \frac{0.83}{0.02} = 42.\mu$$

$$R_L = \frac{V_{DC}}{I_{DC}} = \frac{9V}{0.1} = 90\Omega$$

$$LC \geq \frac{R_L}{3\omega} \geq \frac{R_L}{1130}$$

But LC should be 25% larger. ∴ for f = 60 Hz,the value of LC should be $\geq \frac{R_L}{900}$.

$$LC \geq \frac{R_L}{900}. \geq \frac{90}{900} = 0.1 \text{ Henry.}$$

If L = 0.1H, then $C = \frac{42}{0.1} = 420\mu f$. This is high value

If L = 1H, then $C = 42\ \mu f$.

If the series resistance of L is assumed to be 50 Ω, the drop across L is

$$I_{DC} \times R = 0.1 \times 50 = 5V.$$

Transformer Rating :

$$V_{DC} = 9V + 5V = 14V$$

$$\therefore \quad V_m = \frac{\pi}{2}(9 + 5) = 22V$$

$$\therefore \quad \text{rms value is } \frac{22}{\sqrt{2}} = 15.5V$$

Therefore, a 15.5 – 0 –15.5 V, 100mA transformer is required. PIV of the diodes is $2V_m$ Because it is FWR Circuit.

$$\therefore \quad PIV = 44V$$

So, diodes with 44V, 100mA ratings are required.

Problem 1.23

In a FWR with C filter circuit, V_rp-p = 0.8v and the maximum voltage is 8.8 volts (Fig. 1.30). $R_L = 100\Omega$ and C = 1050 μf. Power line frequency = 60 Hz. Determine the Ripple Factor and DC output voltage from the graph and compare with calculated values.

Solution

$$V_r' \text{ p-p} = 0.8V.$$

$$\therefore \quad V_{rms}' = \frac{0.8}{2\sqrt{3}} = 0.231V$$

$$V_{DC} = Vm - \frac{V_r'p-p}{2} = 8.8 - \frac{0.8}{2} = 8.4V.$$

$$\therefore \quad \gamma = \frac{V'rms}{V_{DC}} = \frac{0.2}{8.4} = 0.0238 \text{ or } 2.38\%$$

$$\text{Theoretical values, } \gamma = \frac{1}{4\sqrt{3fR_L \, . C}}$$

$$= \frac{1}{4\sqrt{3 \times 60 \times 100 \times 1050 \mu f}}$$

$$= 0.057 \text{ or } 5.75\%$$

$$V_{DC} = \frac{4fR_L C}{1 + 4fR_L C} \times V_m = 8.46V$$

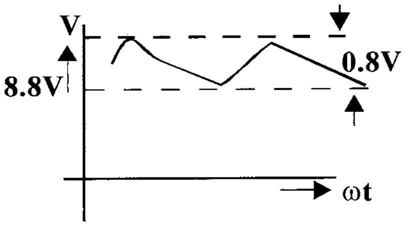


Fig 1.30 For problem 23

1.22 π-SECTION FILTER

In the LC filter or L section filter, there is some voltage drop across L. If this cannot be tolerated and more D.C. output voltage V_0 is desired, pi or π filter or CLC filter is to be used. The ripple factor will be the same as that of L section filter, but the regulation will be poor. It can be regarded as a L section filter with L_1 and C_1, before which there is a capacitor C, i.e. the capacitor filter. The input to the L section filter is the output of the capacitor filter C. The output of capacitor filter will be a triangular wave superimposed over D.C.

Now the output V_0 is the voltage across the input capacitor C less by the drop across L_1. The ripple contained in the output of 'C' filter is reduced by the L section filter L_1C_1.

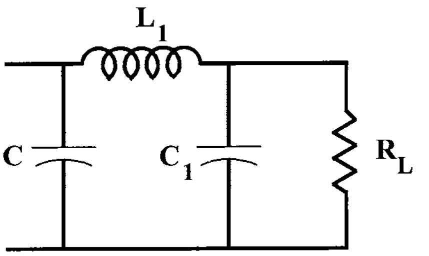


Fig 1.31 CLC or π section filter

1.22.1 π-SECTION FILTER WITH A RESISTOR REPLACING THE INDUCTOR

Consider the circuit shown here. It is a π filter with L replaced by R. If the resistor R is chosen equal to the reactance of L (the impedance in Ω should be the same), the ripple remains unchanged.

V_{DC} for a single capacitor filter = ($V_m - I_{DC}/4fC$) If you consider C_1 and R, the output across C_1 is ($V_m - I_{DC}/4fC$). There is some drop across R. Therefore, the net output is

$$V_m - \frac{I_{DC}}{4fC} - I_{DC} \times R$$

The Ripple Factor for π sector is

$$\gamma = \frac{\sqrt{2} X_c X_{c_1}}{R_L . X_{L_1}} \qquad \text{.......... (1.34)}$$

So by this, saving in the cost, weight and space of the choke are made . But this is practical only for low current power supplies.

Suppose a FWR output current is 100 mA and a 20 H choke is being used in π section filter. If this curve is to be replaced by a resistor, $X_L = R$. Taking the ripple frequency as 2f = 100 Hz,

$$X_L = \omega L = 2\pi(2f).L = 4\pi fL$$
$$= 4 \times 3.14 \times 50 \times 20 = 12560\Omega$$
$$\simeq 12\ K\Omega$$

Voltage drop across R = 12,000 × 0.1 = 1200V, which is very large.

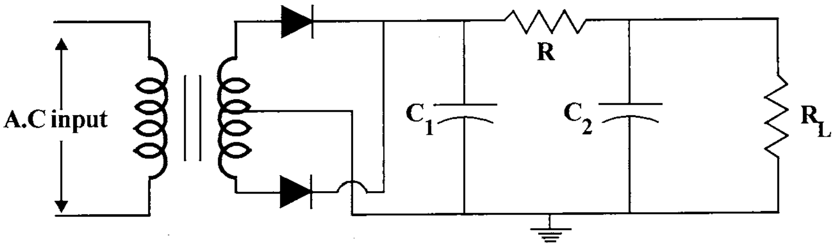


Fig 1.32 **FWR circuit π section / CRC filter.**

1.22.2 EXPRESSION FOR RIPPLE FACTOR OF π-SECTION FILTER

The output of the capacitor in the case of a capacitor filter is a Triangular wave. So assuming the output V_0 across C to be a Triangular wave, it can be represented by Fourier series as

$$V = V_{DC} - \frac{V'P-P}{\pi}\left(\text{Sin } 2\omega t - \frac{\sin 4\omega t}{2} + \frac{\sin 6\omega t}{3} \ldots\right)$$

But the ripple voltage peak to peak V' p-p = $\frac{I_{DC}}{2fc}$ · (for Δ wave)

Neglecting 4th and higher harmonic, the rms voltage of the Second Harmonic Ripple is

$$\frac{v'p-p}{\pi\sqrt{2}} = \frac{I_{DC}}{2\sqrt{2}\pi fc} = \frac{I_{DC} \times 2}{4\sqrt{2}\pi fc} = \frac{\sqrt{2}I_{DC}}{4\pi fc}$$

$$\frac{1}{4\pi fc} = x_c$$

It is the capacitive reactance corresponding to the second harmonic.

$$V'_{rms} = \sqrt{2}I_{DC}X_C \qquad \text{(across 'C' filter only)}$$

The output of C filter is the input for the L section filter of L_1C_1 . Therefore, as we have done in the case of L section filter,

Current through the inductor (harmonic component) = $\frac{\sqrt{2}I_{DC}X_C}{X_{L_1}}$

Output Voltage = Current (X_C) ($V_0 = I.X_C$)

$$V'_{rms} = \frac{\sqrt{2}I_{DC}X_C}{X_{L_1}}.X_{C_1} \qquad \text{(after L section)}$$

Ripple factor, $$\gamma = \frac{v'_{rms}}{V_{DC}} = \frac{\left(\sqrt{2}.I_{DC}.X_C\right)}{V_{DC}}\frac{X_{C_1}}{X_{L_1}}$$

$$V_{DC} = I_{DC}.R_L$$

$$\therefore \quad \gamma = \frac{\left(\sqrt{2}.X_C\right)}{R_L}\left(\frac{X_{C_1}}{X_{L_1}}\right)$$

where all reactances are calculated at the 2nd harmonic frequency $\omega = 2\pi f$.

DC output voltage = (The DC voltage for a capacitor filter) – (The drop across L_1).

Problem 1.24

Design a power supply using a π-filter to give DC output of 25V at 100 mA with a ripple factor not to exceed 0.01%. Design of the circuit means, we have to determine L,C, diodes and transformers.

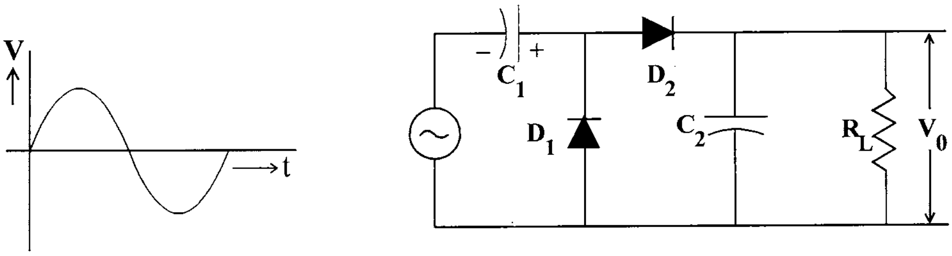


Fig 1.33 Peak to peak detector.

Solution

Design of the circuit means, we have to determine L, C, Diodes and Transformer

$$R_L = \frac{V_{DC}}{I_{DC}} = \frac{25V}{I_{DC}} = \frac{25V}{100\text{ mA}} = 250\Omega$$

Ripple factor $$\gamma = \sqrt{2}.\frac{X_c}{R_L}.\frac{X_{C1}}{X_{L1}}$$

X_C can be chosen to be = Xc_1

$$\therefore \quad \gamma = \sqrt{2}.\frac{X_C^2}{R_L.X_{L1}}$$

This gives a relation between C and L.

$$C^2 L = y$$

There is no unique solution to this.

Assume a reasonable value of L which is commercially available and determine the corresponding value of capacitor. Suppose L is chosen as 20 H at 100 mA with a D.C. Resistance of 375Ω (of Inductor).

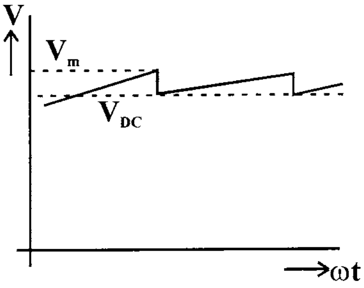


Fig 1.34 For problem 1.7.

$$\therefore \quad c^2 = \frac{y}{L}$$

$$\text{or} \quad c = \sqrt{\frac{y}{L}}$$

$$V_{DC} = Vm - \frac{V_\gamma}{2}$$

$$V_\gamma = \frac{I_{DC}}{2fc}$$

Now the transformer voltage ratings are to be chosen.

The voltage drop across the choke = choke resistance × $I_{DC} = 375 \times 100 \times 10^{-3} = 37.5V$.

$$V_{DC} = 25V.$$

Therefore, voltage across the first capacitor C in the π-filter is

$$V_c = 25 + 37.5 = 62.5V.$$

The peak transformer voltage, to centre tap is

$$V_m = (V_C) + \frac{V_\gamma}{2} \text{ (for C filter)}$$

$$V_\gamma = \frac{I_{DC}}{2fc}$$

$$\therefore \quad V_m = 62.5 \text{ V} + \frac{0.1}{4 \times 50 \times c}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}} \cong 60v$$

Therefore, a transformer with 60-0-60V is chosen . The ratings of the diode should be, current of 125 mA and voltage = PIV = $2V_m = 2 \times 84.6V = 169.2V$.

Problem 1.25

A full wave rectifier with LC filter is to supply 250 V at 100 mA. D.C. Determine the ratings of the needed diodes and transformer, the value of the bleeder resistor and the ripple, if R_C of the choke = 400Ω. L = 10H and C = 20 μF.

Solution

$$R_L = \frac{V_{DC}}{I_{DC}}$$

$$R_L = \frac{250v}{0.1} = 2{,}500\Omega.$$

For the choke input resistor,

$$E_{DC} = \frac{2E_m}{\pi(1+\frac{R_C}{R_L})}$$

and $\quad I_{rms} \cong I_{DC}$

$$E_m = \frac{\pi E_{DC}}{2}(1+\frac{R_C}{R_L}) = \frac{\pi\times 250}{2}(1+\frac{400}{2500}) = 455V$$

$$\therefore \quad E_{rms} = \frac{455}{\sqrt{2}} = 322V$$

Therefore, the transformer should supply 322V rms on each side of the centre tap. This includes no allowance for transformer impedance, so that the transformer should be rated at about 340 volts 100 mA, D.C

The Bleeder Resistance $R_B = \frac{3X_L}{2}$

$L = 10000\Omega.$

$$I_B = \frac{2E_m}{3\pi\omega L} = \frac{2\times 455}{3\pi\times 377\times 10} = 0.0256A$$

Ripple factor $\quad \gamma = \frac{0.47}{4\omega^2 LC - 1} = \frac{0.47}{4\times 377^2 \times 20\times 10^{-6}}$

The current ratings of each diode = 0.00413. Should be 50mA.

1.23 USE OF ZENER DIODE AS REGULATOR

Voltage Regulator Circuits are electronic circuits which give constant DC output voltage, irrespective of variations in *Input Voltage V_i, current drawn by the load I_L* from output terminals, and *Temperature T.* Voltage Regulator circuits are available in discrete form using BJTs, Diodes etc and in IC (Integrated Circuit) form. The term voltage regulator is used when the output delivered is DC voltage. The input can be DC which is not constant and fluctuating. If the input is AC, it is converted to DC by Rectifier and Filter Circuits and given to I.C. Voltage Regulator circuit, to get constant DC output voltage. If the input is A.C 230 V from mains, and the output desired is constant DC, a stepdown transformer is used and then Rectifier and filter circuits are used, before the electronic regulator circuit. The block diagrams are shown in Fig. 1.35 and 1.36.

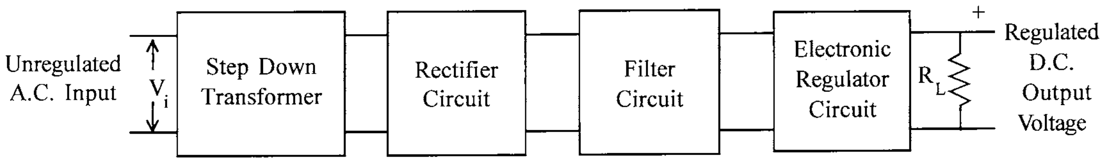


Fig. 1.35 Block diagram of voltage regulator with A.C input.

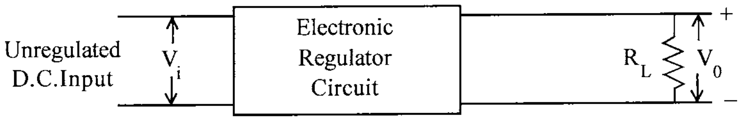


Fig. 1.36 Block diagram of voltage regulator with D.C input.

The term *Voltage Stabilizer* is used, if the output voltage is AC and not DC. The circuits used for voltage stabilizers are different. The voltage regulator circuits are available in IC form also. Some of the commonly used ICs are, µA 723, LM 309, LM 105, CA 3085 A.

7805, 7806, 7808, 7812, 7815 : Three terminal positive Voltage Regulators.

7905, 7906, 7908, 7912, 7915 : Three terminal negative Voltage Regulators.

The Voltage Regulator Circuits are used for electronic systems, electronic circuits, IC circuits, etc.

The specifications and Ideal Values of Voltage Regulators are :

	Specifications		**Ideal Values**
1.	Regulation (S_V)	:	0 %
2.	Input Resistance (R_i)	:	∞ ohms
3.	Output Resistance (R_0)	:	0 ohms
4.	Temperature Coefficient (S_T)	:	0 mv/oc.
5.	Output Voltage V_0	:	-
6.	Output current range (I_L)	:	-
7.	Ripple Rejection	:	0 %

Different types of Voltage Regulators are

1. Zener regulator
2. Shunt regulator
3. Series regulator
4. Negative voltage regulator
5. Voltage regulator with foldback current limiting
6. Switching regulators
7. High Current regulator

1.23.1 ZENER VOLTAGE REGULATOR CIRCUIT

A simple circuit without using any transistor is with a zener diode Voltage Regulator Circuit. In the reverse characteristic voltage remains constant irrespective of the current that is flowing through Zener diode. The voltage in the break down region remains constant (Fig. 1.37).

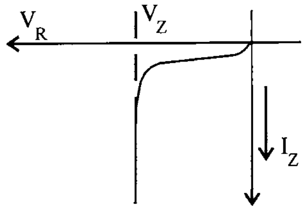


Fig. 1.37 Zener diode reverse characteristic.

Therefore in this region the zener diode can be used as a voltage regulator. If the output voltage is taken across the zener, even if the input voltage increases, the output voltage remains constant. The circuit as shown in Fig. 1.38.

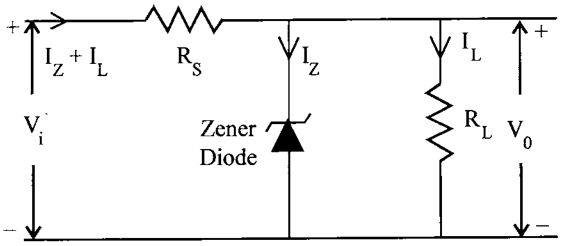


Fig. 1.38 Zener regulator circuit.

The input V_i is DC. Zener diode is reverse biased.

If the input voltage V_i increases, the current through R_s increases. This extra current flows, through the zener diode and not through R_L. Therefore zener diode resistance is much smaller than R_L when it is conducting. Therefore I_L remains constant and so V_0 remains constant.

The limitations of this circuits are

1. The output voltage remains constant only when the input voltage is sufficiently large so that the voltage across the zener is V_Z.
2. There is limit to the maximum current that we can pass through the zener. If V_i is increased enormously, I_Z increases and hence breakdown will occur.
3. Voltage regulation is maintained only between these limits, the minimum current and the maximum permissible current through the zener diode. Typical values are from 10 mA to 1 ampere.

1.23.2 SHUNT REGULATOR

The shunt regulator uses a transistor to amplify the zener diode current and thus extending the Zener's current range by a factor equal to transistor h_{FE}. (Fig. 1.39)

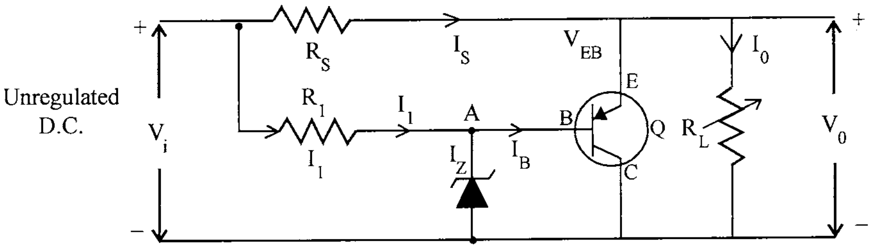


Fig. 1.39 Shunt regulator circuit

Zener current, passes through R_1

Nominal output voltage

$$= V_Z + V_{EB}$$

The current that gets branched as I_B is amplified by the transistor. Therefore the total current $I_0 = (\beta + 1)\, I_B$, flows through the load resistance R_L. Therefore for a small current through the zener, large current flows through R_L and voltage remains constant. In otherwords, for large current through R_L, V_0 remains constant. Voltage V_0 does not change with current.

Problem 1.26

For the shunt regulator shown, determine

1. The nominal voltage
2. Value of R_1,
3. Load current range
4. Maximum transistor power dissipation.
5. The value of R_S and its power dissipation.

V_i = Constant. Zener diode 6.3V, 200mW, requires 5mA minimum current.

Transistor Specifications :

$$V_{EB} = 0.2\text{V},\ h_{FE} = 49,\ I_{CBO} = 0.$$

1. The nominal output voltage is the sum of the transistor V_{EB} and zener voltage.

$$V_0 = 0.2 + 6.3 = 6.5\text{V} = V_{Eb} + V_Z$$

2. R_1 must supply 5mA to the zener diode :

$$\therefore \qquad R_1 = \frac{8\text{V} - 6.3}{5 \times 10^{-3}} = \frac{1.7}{5 \times 10^{-3}} = 340\ \Omega$$

3. The maximum allowable zener current is

$$\frac{\text{Power rating}}{\text{Voltage rating}} = \frac{0.2}{6.3} = 31.8\ \text{mA}$$

The load current range is the difference between minimum and maximum current through the shunt path provided by the transistor. At junction A, we can write,

$$I_B = I_Z - I_1$$

I_1 is constant at 5 mA

$$\therefore \qquad I_B = I_Z - I_1$$

I_l is constant at 5 mA

$$\therefore \quad I_B = 5 \times 10^{-3} - 5 \times 10^{-3} = 0$$

$$I_B\ (\text{min}) = I_{Z\ \text{Max}} - I_2$$

$$= 31.8 \times 10^{-3} - 5 \times 10^{-3} = 26.8 \text{ mA}$$

The transistor emitter current $I_E = I_B + I_C$

$$I_C = \beta\, I_B = h_{FE}\, I_B$$

$$\therefore \quad I_E = (\beta + 1)\, I_B = (h_{FE} + 1)\, I_B$$

I_B ranges from a minimum of 0 to maximum of 26.8 mA

$\therefore$ Total load current range is $(h_{FE} + 1)\, I_B$

$$= 50\ (26.8 \times 10^{-3}) = \mathbf{1.34\ A}$$

4. The maximum transistor power dissipation occurs when the current is maximum $I_E \simeq I_C$

$$P_D = V_o\, I_E = 6.5\ (1.34) = \mathbf{8.7\ W}$$

5. R_S must pass 1.34 A to supply current to the transistor and R_L.

$$R_S = \frac{V_i - V_0}{1.34} = \frac{8 - 6.5}{1.34} = 1.12\ \Omega$$

The power dissipated by R_S,

$$= I_S^2\, R_S$$

$$= (1.34)^2 . (1.12) = 3\text{W}$$

REGULATED POWER SUPPLY

An unregulated power supply consists of a transformer, a rectifier, and a filter. For such a circuit regulation will be very poor i.e. as the load varies (*load means load current*) [*No load means no load current or 0 current. Full load means full load current or short circuit*], we want the output voltage to remain constant. But this will not be so for unregulated power supply. The short comings of the circuits are :

1. Poor regulation
2. DC output voltage varies directly as the a.c. input voltage varies
3. In simple rectifiers and filter circuits, the d.c. output voltage varies with temperature also, if semiconductors devices are used.

An electronic feedback control circuit is used in conjuction with an unregulated power supply to overcome the above three short comings. Such a system is called a "*regulated power supply*".

Stabilization

The output voltage depends upon the following factors in a power supply.

1. Input voltage V_i
2. Load current I_L
3. Temperature

$\therefore$ Change in the output voltage ΔV_0 can be expressed as

$$\Delta V_0 = \frac{\partial V_0}{\partial V_i}.\Delta V_i + \frac{\partial V_0}{\partial I_L}.\Delta I_L + \frac{\partial V_0}{\partial T}.\Delta T$$

$$\Delta V_0 = S_I\ \Delta V_i + R_0\ \Delta I_L + S_T\ \Delta T$$

Where the three coefficients are defined as,

(i) Stability factors.

$$S_V = \frac{\Delta V_0}{\Delta V_i}\bigg|_{\Delta I_L=0,\ \Delta_T=0}$$

This should be as small as possible. Ideally 0 since V_0 should not change even if V_i changes.

(ii) *Output Resistance*

$$R_0 = \frac{\Delta V_0}{\Delta I_L}\bigg|_{\Delta V_i=0,\ \Delta_T=0}$$

(iii) *Temperature Coefficient*

$$S_T = \frac{\Delta V_0}{\Delta_T}\bigg|_{\Delta V_i=0,\ \Delta I_L=0}$$

The smaller the values of the three coefficients, the better the circuit.

SUMMARY

- Energy possessed by an electron rotating in an orbit with radius r;

$$E = -\frac{e^2}{8\pi \in_0 r}$$

- Expression for the radius of orbit, $r = \frac{n^2 h^2 \in_0}{\pi m e^2}$
- Expression for wavelength of emitted radiation, $\lambda = \frac{12{,}400}{(E_2 - E_1)}$
- Types of Electronic Emissions from the surface.
  1. Thermionic Emission
  2. Secondary Emission
  3. Photo electric Emission
  4. High Field Emission
- Expression for Threshold Frequency f_T in photoelectric emission,

$$f_T = \frac{e\phi}{h}$$

- Fermi Level lies close to E_C in *n-type* semiconductor
- Fermi Level lies close to E_V in *p-type* semiconductor
- $\sigma = ne\mu_n + pe\mu_p$
- Hall Voltage, $V_H = \frac{BI}{\rho\omega}$
- Expression for current through a *p-n junction.*

$$\text{Diode is } I = I_O \left(e^{\frac{V}{\eta V_T}} - 1 \right)$$

- The three types of breakdown mechanisms in semiconductor diodes are
  1. Avalanche Breakdown
  2. Zener Breakdown
  3. Thermal Breakdown.
- Rectifier circuit converts AC to Unidirectional Flow.
- Filter Circuit converts Unidirectional flow to DC. It minimises Ripple.
- The different types of filter circuits are
  1. Capacitor Filter
  2. Inductor Filter
  3. L-Section (LC) Filter.
  4. π-Section Filter
  5. CRC and CLC Filters

- Ripple Factor = $\frac{I'_{rms}}{I_{DC}}$. For Half Wave Rectifier, $\gamma = 1.21$, for Full Wave Rectifier $\gamma = 0.482$
- Expression for Ripple Factor for C Filter,

$$\gamma = \frac{1}{4\sqrt{3}fCR_L}$$

- Expression for Ripple Factor for L Filter,

$$\gamma = \frac{R_L}{4\sqrt{3}\omega L}$$

- Expression for Ripple Factor for LC Filter,

$$\gamma = \frac{\sqrt{2}}{3} \times \frac{1}{2\omega C} \times \frac{1}{2\omega L}$$

- Expression for Ripple Factor for π Filter,

$$\gamma = \frac{\sqrt{2}X_C}{R_L}\left(\frac{X_{C_1}}{X_{L_1}}\right)$$

- Critical Inductance $L_C \geq \frac{R_L}{3\omega}$
- Bleeder Resistance $R_B = \frac{3X_L}{2}$

OBJECTIVE TYPE QUESTIONS

1. Free electron concentration in semiconductors is of the order of ....
2. Insulators will have resistivity of the order of ....
3. Expression for J in the case of a semiconductor with concentrations n and p is ....
4. According to Law of Mass Action in semiconductors, ...
5. Intrinsic concentration depends on temperature T as ....
6. Depletion region width varies with reverse bias voltages as ....
7. In *p-type* semiconductor, Fermi Level lies close to ....
8. In *n-type* semiconductor, Fermi Level lies close to ....
9. The rate at with I_o changes with temperature in Silicon diode is ....
10. Value of Volt equivalent of Temperature at 25^oC is ....
11. Einstein's relationship in semiconductors is ....
12. A very poor conductor of electricity is called ....

13. When donor impurities are added allowable energy levels are introduced a little .... the .... band.
14. Under thermal equilibrium, the product of the free negative and positive concentration is a constant independent of the amount of .... doping and this relationship, called the mass action low and is given by np = ...
15. The unneutralized ions in the neighbourhood of the junction are referred to as .... charges and this region depleted of mobile charges is called .... charge region.
16. General expression for E_0, the contact difference of potential in an open circuited *p-n junction* in terms of N_C, N_A and n_i is ....
17. Typical value of E_0 = ...eV
18. The equation governing the law of the junction is ....
19. The expression for the current in a forward biased diode is ....
20. The value of cut in voltage in the case of Germanium diode .... and Silicon Diode .... at room temperature.
21. Expression for V_B the barrier potential in terms of depletion region width W is V_B = ...
22. Expression for I_0 in terms of temperature T and V_T is ....
23. Zener breakdown mechanism needs relatively .... electric field compared to Avalanche Breakdown.
24. Rectifier Converts .... to ....
25. Filter Circuit Converts .... to ....
26. Ripple Factor in the case of Full Wave Rectifier Circuit is ....
27. The characteristics of a swinging choke is ....
28. In the case of LC Filter Circuits, Bleeder Resistance ensures
    (1) ....
    (2) ....

ESSAY TYPE QUESTIONS

1. Explain the concept of 'hole'. How *n-type* and *p-type* semiconductors are formed? Explain.
2. Derive the expression for E_G in the case of intrinsic semiconductor.
3. Derive the expression for E_G in the case of of *p-type* and *n-type* semiconductors.
4. With the help of necessary equations, Explain the terms Drift Current and Diffusion Current.
5. Explain about Hall Effect. Derive the expression for Hall Voltage. What are the applications of Hall Effect?
6. Distinguish between Thermistors and Sensistors.

7. Derive the expression for contact difference of potential V_o in an open circuited p-n junction.
8. Draw the forward and reverse characteristics of a p-n junction diode and explain them qualitatively.
9. Derive the expression for Transistor Capacitance C_T in the case of an abrupt p-n junction.
10. Compare Avalanche, Zener and Thermal Breakdown Mechanisms.
11. Derive the expression for E_0 in the case of open circuited *p-n junction* diode.
12. Qualitatively explain the forward and reverse characteristic of *p-n junction* diode.
13. How junction capacitances come into existance in *p-n junction* diode.
14. Distinguish between Avalanche, Zener and Thermal Breakdown Mechanisms
15. Obtain the expression for ripple factor in the case of Full Wave Rectifier Circuit with Capacitor Filter.
16. Explain the terms Swinging Choke and Bleeder Resistor.
17. Compare C, L, L-Section, π-Section (CLC and CRC) Filters in all respects.

MULTIPLE CHOICE QUESTIONS

1. The force of electron 'F' between nucleus and electron with charge 'e' and radius 'r' is, proportional to, F α

(a) $\frac{e^2}{r^2}$ (b) $\frac{r^2}{e^2}$ (c) $e^2 r^2$ (d) $\frac{e}{r}$

2. The energy possesed by the electron, W orbitting round the nucleus is,

(a) $\frac{-e}{8\pi \varepsilon_0 r}$ (b) $\frac{-e^2}{8\pi \varepsilon_0 r}$ (c) $\frac{-e.r}{8\pi \varepsilon_0}$ (d) $\frac{-e^2}{8\pi \varepsilon_0 r^2}$

3. The expression for the Kinetic Energy E of free electron in terms of momentum of the electron 'p' and mass of the electron m is,

(a) $\frac{p}{2m}$ (b) $\frac{p}{2m^2}$ (c) $\frac{p^2}{2m^2}$ (d) $\frac{p^2}{2m}$

4. The expression for radius of stable state 'e' r, is

(a) $\frac{n^2h^2\varepsilon_o}{\pi me^2}$ (b) $\frac{n h \varepsilon_o}{\pi^2 m^2 e^2}$ (c) $\frac{n^2 h \varepsilon_o{}^2}{\pi m e^2}$ (d) $\frac{n^2 h^2 \varepsilon_o{}^2}{\pi m e^2}$

5. The value of the radius of the lowest state or ground state is, given, h = 6.626 × 10^{-34} J - Secs ε_o = $10^{-9}/36\pi$

(a) 0.28 A^0 (b) 0.98 A^0 (c) 0.18 A^0 (d) 0.58 A^0

6. The energy required to detach an electron from its parent atom is called,

(a) Ionization potential (b) Eletric potential

(c) Kinetic energy (d) Threshold potential

7. **Electron collision without transfer of energy in collision is called,**
(a) Null collision (b) Impact collision
(c) Elastic collision (d) Stiff collision

8. **Wave mechanics in electron theory is also known as**
(a) Eienstein theory (b) Quantum mechanics
(c) Bohr mechanics (d) Classical theory

9. **The expression for threshold frequency f_T to cause photoelectric emission is, with usual notation is,**
(a) $\frac{e\phi^2}{h}$ (b) $\frac{e\phi}{h}$ (c) $\frac{eh}{\phi}$ (d) $\frac{e^2\phi^2}{h^2}$

10. **The conductivity of a good conductor is typically**
(a) 10^{-3} Ω/cm (b) 10^3 Ω/cm (c) 10^3 ℧/cm (d) 10 ℧/m

11. **The free electron concentration of a good conductor is of the order of**
(a) 10^{10} electrons/m3 (b) 10^{28} electron/m^3
(c) 10^2 electrons/cm^3 (d) 10^{10} electrons/m^3

12. **Fermi level in Intrinsic semiconductor lies**
(a) close to conduction band (b) close to valence band
(c) In the middle (d) None of the these

13. **The potential which exists in a p-n junction to cause drift of charge carriers is called**
(a) contact potential (b) diffusion potential
(c) ionisation potential (d) threshold potential

14. **The rate of increase of reverse saturation current for Germanium diode is,**
(a) 5% (b) 4% (c) 1% (d) 7%

15. **Special types of diodes in which transition time and storage time are made small are called ...**
(a) Snap diodes (b) Rectifier diodes (c) Storage diodes (d) Memory diodes

16. **The Circuit which converts undirectional flow to D.C. is called**
(a) Rectifier circuit (b) Converter circuit
(c) filter circuit (d) Eliminator

17. **For ideal Rectifier and filter circuits, % regulations must be ...**
(a) 1% (b) 0.1 % (c) 5% (d) 0%

18. **The value of current that flows through R_L in a 'π' section filter circuit at no load is**
(a) ∞ (b) 0.1 mA (c) 0 (d) few mA

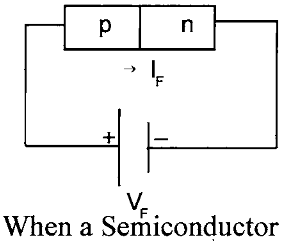
CONCEPTUAL QUESTIONS (Interview Questions)

1. When it is said that an electron moves from valence band to conduction band, will there be physical movement of the electron ?

Ans : No, The energy band diagram represents the energy levels of the electrons. When an electron "moves" from valence band to conduction band, it only means that the energy possessed by the electron has increased from Ev electron volts to Ec+ electron volts. The energy diagram is only Pictorial representation of the energy possessed by the electrons. The energy levels of different electrons will be different.

2. What does the arrow in the symbol of a P-n junction diode (—▷|—) indicate?

Ans : The arrow mark $\underset{(p)}{\overset{A}{-}}\triangleright|\underset{(n)}{\overset{K}{-}}$ indicates the direction of current flow when the P - n juction is forward biased.



Direction of I_F is the same as that of the direction of arrow.

3. When a Semiconductor device 'breaks down'; what does it mean?

Ans : It does not mean physical breakdown. The shape of the device remains the same. But the device looses its Semiconductor properties. The device may become a short or open circuited.

4. What is the difference between Avalanche and zener breakdown mechanisms?

Ans : In Zener breakdown mechanism, due to sudden increase in the electric field strength ε, when it reaches a critical value, covalent bonds break and due to this there will be sudden increase in the number of free electrons and hence, the reverse current which was small till that time increases suddenly. But in Avalanche breakdown the field strength is not that high. A free electron with lot of energy collides with another electron, transfers its energy and makes it a free electron. This in turn generates some more free electrons. Thus there is multiplication of carriers. This will occur usually in a forward biased device. Avalanche breakdown precedes Zener breakdown, for comparision, though both cannot occur in the same device at a time.

5. How for a low voltage like 6.8 V, in the case of Fz 6.8 Zener doide zener breakdown occurs, which requires high electric field strength?

Ans : Electric field strength $\varepsilon = \frac{V}{d}$. Even if V is small, if 'd' is very small, ε can be very high. This is what happens in a Zener diode. Due to heavy doping depletion, region width near the junction becomes very small. So, when the voltage V_Z reaches the required value, electric field 'ε' reaches the critical value, covalent bonds will be broken and Zener breakdown occurs.

Specifications for Silicon Diode

Sl.No.	Parameter	Symbol	Typical Value	Units
1.	Reverse breakdown voltage	V_{br}	75	V
2.	Static Reverse Current	I_R	5	µA
3.	Static Forward voltage (for silicon)	V_F	0.5	V
4.	Total Capacitance	C_T	2	pf
5.	Reverse Recovery Time	t_{rr}	4	ns
6.	Continuous Power Dissipation	P	500	mw
7.	Max. For Ward Current	I_F	50	mA

Some type numbers of Diodes

1. 0A79 : 0 → Semiconductor Device.
A → Denotes Germanium device.
2. BY127 : B → Denotes Silicon Device.
Y → Rectifying Diode.
Number 127 is owing a type no and has significance.
3. 1N4153 : N → Bipolar Device.
1 → Single Polar function.
4. BY100:800V, 1 A Silicon Diode.

Specifications of a junction diode

Sl.No.	Parameter	Symbol	Typical Value	Units
1.	Working Inverse voltage	WIV	80	V
2.	Average Rectifield current	I_U	100	A
3.	Continious forward current	I_F	300	mA
4.	Peak repetetive forward current	i_f	400	mA
5.	Forward Voltage	V_f	0.6	V
6.	Reverse current	I_R	500	nA
7.	Breakdown voltage	BV	100	V

Specifications of a Germanium Tunnel Diode IN 2939

Sl.No.	Parameter	Symbol	Typical Value	Units
1.	Forward current	I_F	5	mA
2.	Reverse current	I_R	10	mA
3.	Peak current	I_p	1	mA
4.	Valley current	I_v	0.1	mA
5.	Peak voltage	V_P	50	V
6.	Valley voltage	V_V	30	V
7.	Ratio of I_p to I_V	I_P/I_V	10	-