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ELECTRONIC DEVICES AND CIRCUITS

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Unit - I

PN Junction Diode

1. a) What do you understand about the depletion region at a PN junction, with the help of necessary diagrams & derive an expression for barrier potential.

Ans: **Depletion Region**: In the region near the junction, there exists a wall of -ve immobile charges on p-side & a wall of +ve immobile charges on n-side. In this region, there are no mobile charge carriers. Such a region is depleted of the free mobile charge carriers & hence called depletion region or depletion layer.

* Depletion region is also called space charge region.

* In equilibrium condition, the depletion region gets widened upto a point where no further electrons or holes can cross the junction. Thus depletion region acts as the barrier.

* The physical distance from one side to other side of the depletion region is called width of the depletion region.

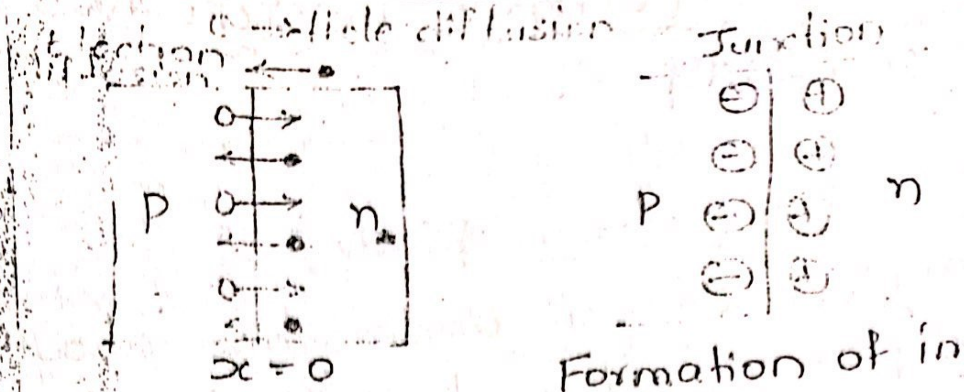


Figure — Formation of immobile ions.

Barrier Potential: The opposite charges existing near the junction creates a potential difference across the junction. The electric field between the charges is responsible to produce potential difference across the junction.

* This potential difference has a fixed polarity & it acts as a barrier to the flow of electrons & holes across the junction.
* Hence this potential is called barrier potential, junction potential or built-in potential barrier of a p-n junction.
* The barrier potential is expressed in volts. Its value is called height of the barrier.
* It is denoted by V_J or V_{bi}.
* The potential barrier is approximately 0.7 V for Si & 0.3 for Ge

at 25°c.

→ The barrier potential of p-n junction mainly depends on the following factors :

1. The type of semiconductor used.
2. The concentration of donor impu-rity on n-side.
3. The concentration of acceptor im-purity on p-side.
4. The intrinsic concentration of basic semiconductor.
5. The temperature.

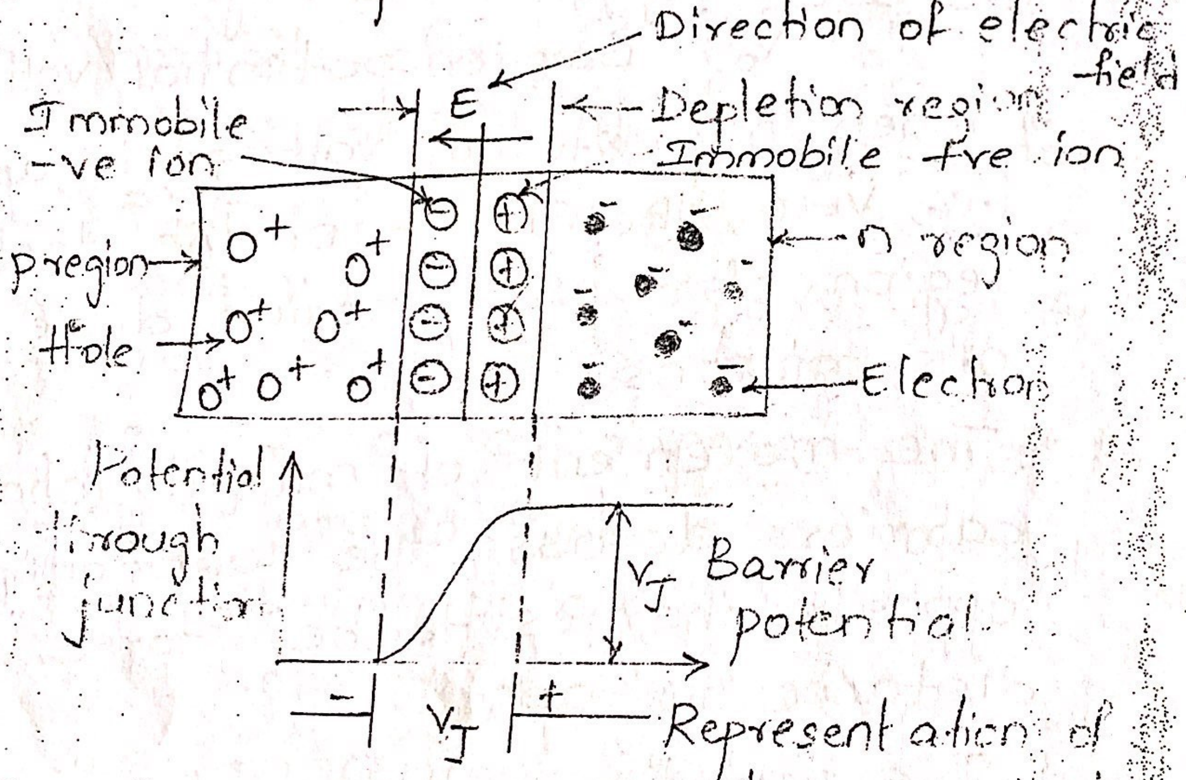


Fig: Open circuited p-n junction.

b) Derive the expression for transition capacitance, C_T of a PN diode ?

Ans: Transition Capacitance: The parallel layers of oppositely charged immobile ions on the two sides of the junc--tion from the transition capacitance (C_T) which is given by $\frac{\varepsilon A}{W}$ i.e., $C_T = \frac{\varepsilon A}{W}$.

where, ε = Permittivity of the material
A = Cross-sectional area of the junction
W = Width of the depletion region over which the ions are uncovered (0.5 µm)

$$W = \left[\frac{2\varepsilon_0 \varepsilon_r (V_0 - V)}{q} \times \frac{N_A + N_D}{N_A N_D}\right]^{1/2}$$

where, V = Applied voltage
V_0 = Barrier potential/voltage

* When no external voltage is applied i.e., V=0, the width of the depletion region of a p-n junction diode is 0.5 microns.
* The movement of majority (charge) carriers across the junction causes opposite charges to be stored at this distance 'W' apart.
* This depletion region acts as a dielectric between two conducting p & n-regions.

* ∴ The region acts as a, parallel plate capacitor whose transition capacitance, C_T is approximately 20 pecofarad with no external bias.
* When forward biased, +v is applied the effective barrier potential $V_B = V_0 - (+V)$ is lowered & hence the width of depletion region 'w' decreases & C_T increases.
* Under reverse-biased condition, the majority carriers moves away from the junction thereby uncovering more immobile charges.

Now the effective barrier potential $V_B = V_0 - (-V)$ is increased & hence 'w' increases with reverse voltage & C_T decreases correspondingly.

* The value of C_T ranges from 5 to 200 pecofarads. The larger values being for the high-power diodes.
* This property of voltage variable capacitance with the reverse bias appears in varacturs, vari-caps or volt-caps.

2. With the help of V-I characteristics, explain the operation of a PN diode

under forward bias & reverse bias?

Ans **Forward V–I characteristics of diode:**

The response of p–n junction can be easily indicated with the help of characteristics called V–I characteristics of p–n junction. It is the graph of voltage applied across the p–n junction & the current flowing through the p–n junction.

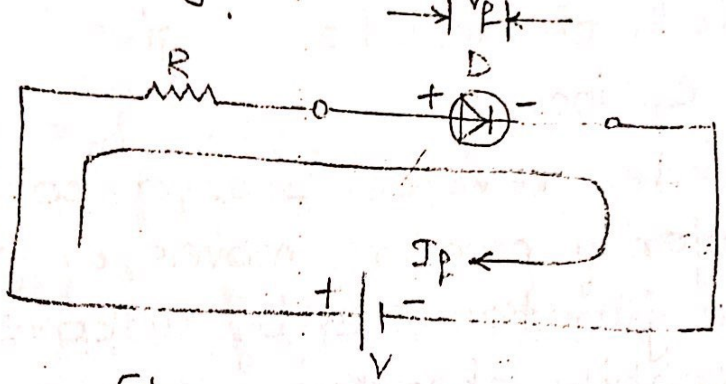


Fig: Forward biased diode

* The applied voltage is V while the voltage across the diode is V_f.
* The current flowing in the circuit is forward current I_f.
* The graph of forward current I_f against the forward voltage V_f across the diode is called forward characteristics of a diode.

→ Basically forward characteristics can be divided into two regions:

1. Region O to P: As long as V_f is less than cut-in voltage (V_γ), the current flowing is very small. Practically this current is assumed to be zero.

2. Region P to Q and onwards: As V_f increases towards V_γ the width of depletion region goes on reducing.

* When V_f exceeds V_γ i.e., cut-in voltage, the depletion region becomes very thin & current I_f increases suddenly.
* This increase in the current is exponential by the region P to Q.
* The point P, after which the forward current starts increasing exponentially is called "knee" of the curve.

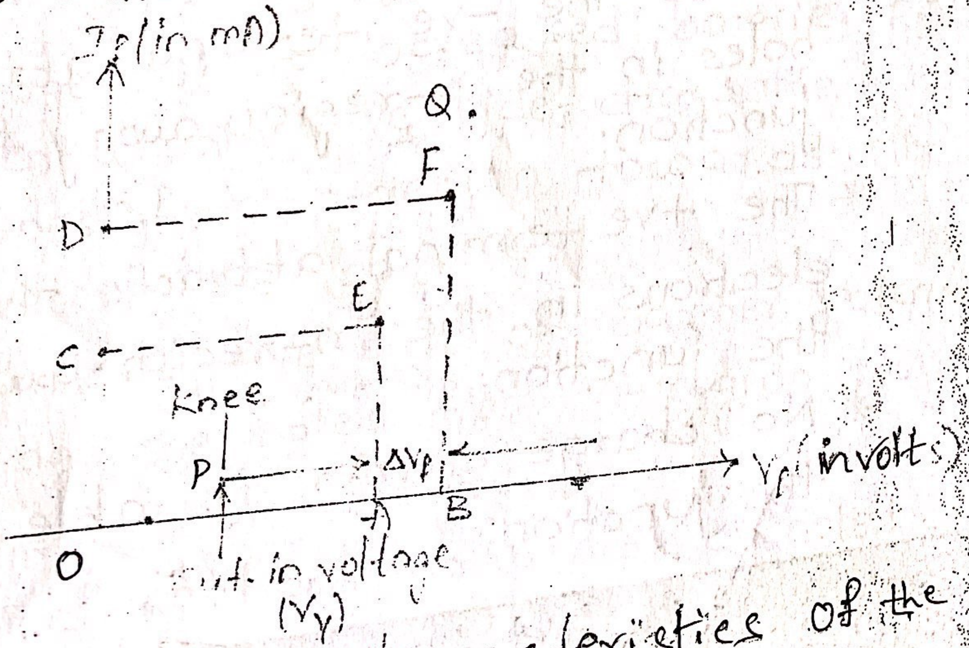


Fig: Forward characteristics of the diode.

* The forward current is the conven-
-tional current, hence it is treated as +ve & the forward voltage V_f is also treated +ve.

Hence the forward characteristics is plotted in the first quadrant.

Operation of Reverse biased diode:

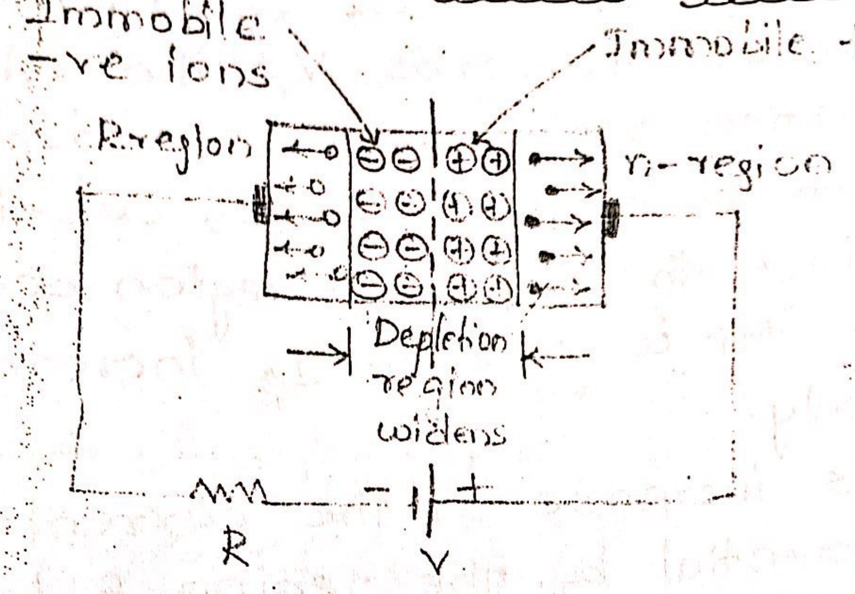


Fig: Depletion region widens in reverse bias.

* When the p-n junction is reverse biased the -ve terminal attracts the holes in the p-region, away from the junction.
* The +ve terminal attracts the free electrons in the n-region away from the junction.
* No charge carrier is able to cross the junction.

* As electrons & holes both move away from the junction, the depletion region widens.
* This creates more +ve ions & hence more +ve charge in the n-region & more -ve ions & hence more -ve charge in the p-region.
* This is because the applied voltage helps the barrier potential.
* As depletion region widens, the barrier potential across the junction also increases. (Cannot continue for long time)
* In the steady state, majority current increases as holes & electrons stop moving away from the junction.
* The polarities of barrier potential are same as that of the applied vol-tage. Due to increased barrier po-tential, the +ve side drags the elec-trons from p-region towards the +ve of the battery.
* Similarly -ve side of barrier potential drags the holes from n-region towards the -ve of battery.
* The electrons on p-side & holes on n-side are minority charge carriers, which constitute the current in reverse

biased condition. Thus reverse conduction takes place.

∴ The reverse current flows due to minority charge carriers which are small in number. Hence reverse current is always very small.

3. a) Explain Avalanche & Zener break down mechanism in semiconductors & compare them.

Ans. **Avalanche and Zener breakdown mechanism:**

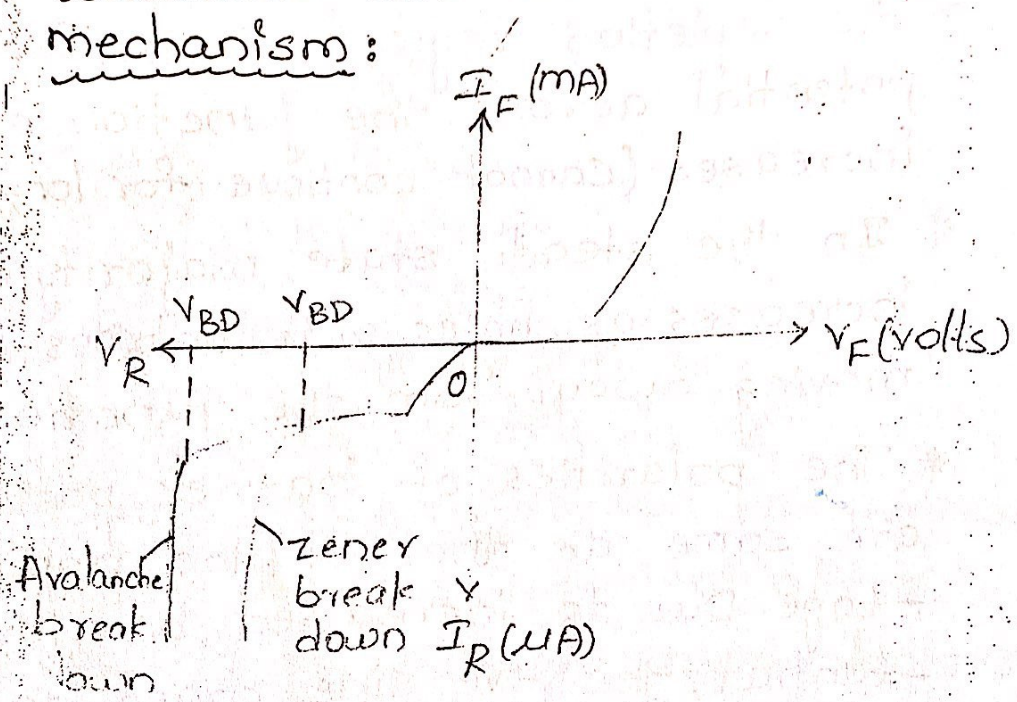


Fig: Breakdown in p-n junction diodes.

The diode equation predicts that under reverse bias condition a small constant current, I_0 flows due to minority carriers which is independent of the magnitude of their I_s (or) I_s/ε

But this prediction is not exactly true in practical diodes. There is a gradual increase of reverse current with increasing bias due to the ohmic leackage currents around the surface of the junction.

* When reverse bias voltage approaches a particular value called breakdown voltage (V_{BD}).
* Once breakdown occurs, the diode is no longer blocking current.
* The diode current can be controlled only by the resistance of external circuit.
* The breakdown occurs due to Avalanche effect in which thermally generated minority carriers cross the depletion region & acquire sufficient kinetic energy from the applied potential to produce new carriers by removing valence electrons from their bonds.
* These new carriers will in turn collide with other atoms & will increase the no. of electrons & holes

available for conduction.

* This multiplication effect of free carriers are represented by

$$M = \frac{1}{1-\left(\frac{V}{V_{BD}}\right)^n}$$

where, M = Carrier multiplication factor which is the ratio of total no. of electrons leaving the depletion region to the no. of entering the region.

V = Applied reverse voltage

V_{BD} = Reverse breakdown voltage

n = Emperical constant (This depends on the lattice material & the carrier type).

* For n-type silicon $n=4$
* For p-type Silicon $n=2$.

As 'V' approaches the breakdown voltage (V_{BD}), the value of M will become infinite & there is a rapid increase in carrier density & a corresponding increase in current

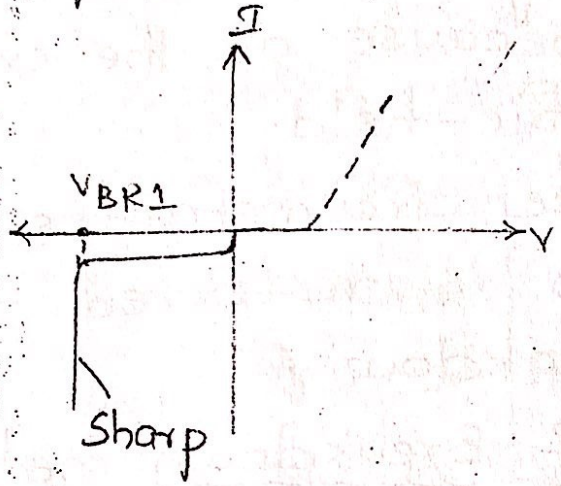
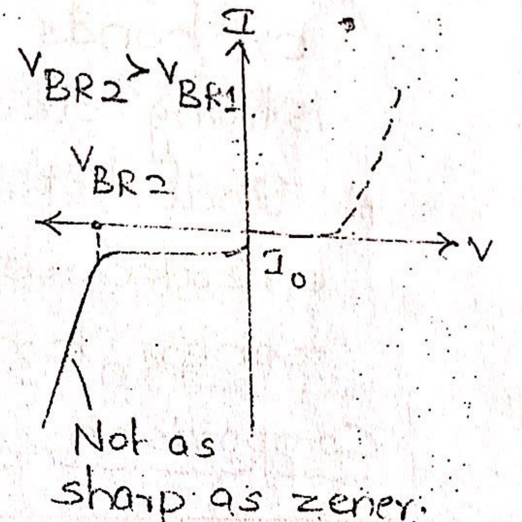
* Because of the cumulative increase

in carrier density, after each colli-
-sion the process is known as Ava-
-lanche breakdown.

* Even if the initially available ca-
-rriers donot gain enough energy
to disrupt the bonds.
* It is possible to initiate break-
down through a direct rupture
of bonds because of the existing
strong electric-field.
* Under these circumstances, the
breakdown is referred to as
zener breakdown.

Comparision of Breakdown mechanisms:

Sl No	Zener Breakdown	Avalanche Breakdown
1.	Breaking of covalent bonds is due to intense electric field across the narrow depletion region. This generates large no. of free electrons to cause breakdown.	Breaking of covalent bonds is due to collision of accelerated charge carriers having large velocity & kinetic energy with adjacent atoms. The process is called carrier multiplication.
2	This occurs for zener diodes with V_{BR} less than 6V.	This occurs for zener diodes with V_{BR} greater than 6V.

3	The temperature co-efficient is −ve.	The temperature co-efficient is +ve.
4	The breakdown voltage decreases as junction temperature increases.	The breakdown voltage increases as the junction temp. increases.
5	The V−I characteristics is very sharp in breakdown region.	The V−I characteristics is not as sharp as zener breakdown in breakdown region.
6	Occurs for heavily doped diodes.	Occurs for lightly doped diodes.
7		

4 a) Define the following terms of p−n diode.

i) Dynamic Resistance ii) Load line

iii) Diffusion capacitance

iv) Reverse saturation current (I_0).

Ans i) Diffusion capacitance ~~Dynamic Resistance~~ : The capacitance that exists in a forward-biased junction is called a diffusion (or) storage capacitance (C_D) whose value is usually much larger than C_T which exist in a reverse bias junction.

This is also defined as the rate of change of injected charge with applied voltage.

$$C_D = \frac{dQ}{dV}.$$

ii) Load line:

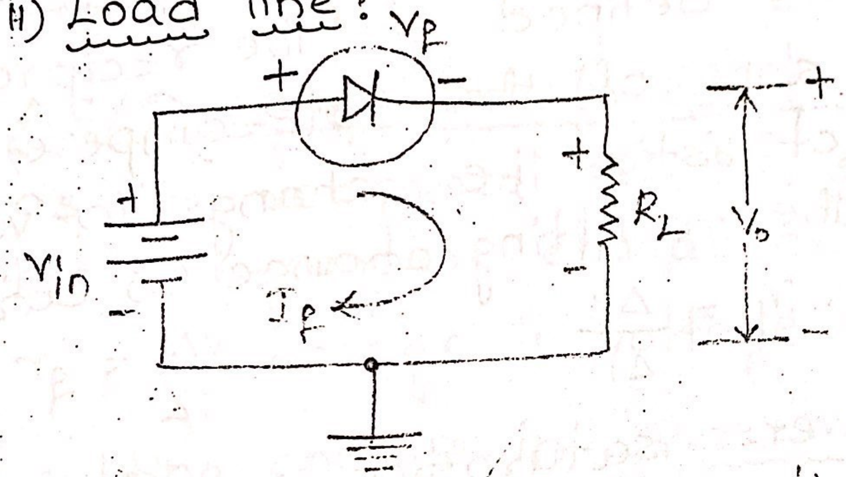


Fig: Simple diode circuit

Consider a simple diode circuit.

* The d.c. voltage V_{in} is applied such that diode is forward biased. The output is the voltage across the load resistance R_L

* The current I_f, which is forward current of diode, flows through the circuit. Now V_f can be obtained by using any one diode approximation.

Applying kirchoff's voltage law to the circuit,

$$-V_f - I_f R_f + V_{in} = 0$$

$$\therefore V_f = V_{in} - I_f R_f \quad \text{—} \ (1)$$

* The eq (1) is a straight line eq, which gives linear eq (1) between V_f & I_f.

This equation is called equation of d.c. load line for the diode.

iii) ~~Diffusion Capacitance~~ Dynamic Resistance:

* It is defined as the reciprocal of the slope of the volt-ampere characteristics i.e., change in voltage to the resulting change in current.

$$r_f = \frac{\Delta V}{\Delta i}$$

iv) Reverse saturation current: The current generated in the reverse bias due to minority charge carriers is called reverse saturation current (I_o).

i.e., In p-type – electrons
n-type – holes.

he

)

e:

b) Differentiate between static and dynamic resistances of a p-n diode.

Ans: Static Resistance / DC : It is denoted by R_F. It is defined as the ratio of the voltage to the current (V/i).

* In the forward-biased, characteristics of the p-n junction diode as static resistance varies rapidly with v & I, It is not a useful parameter.

AC/Dynamic Resistance : It is defined as the reciprocal of the slope of the volt-ampere characteristics i.e., $r_f = \frac{\Delta V}{\Delta i}$ change in voltage to the resulting change in current.

* The AC resistance varies inversely with current i.e., $r_f = \frac{\eta V_T}{I}$ where $V_T = \frac{T}{11600}$, the volt equivalent of temperature 'T' of the diode junction in degree kelvin & η is a constant whose value = 1 for Ge & 2 for Si.

* For si at room temperature,

$V_T = 26mV$

$V_T = 26$ millivolt.

5. a) Explain the effect of temperature on V–I characteristics of a diode.

Ans **Effect of temperature on V–I characteristics of a diode:**

* The rise in temperature increases the generation of electron-hole pairs in semi-conductors & increases their conductivity.
* As a result, the current through the p-n junction diode increases with temperature as given by the diode current equation i.e.,

$$I = I_0 [e^{V/\eta V_T} - 1].$$

* The reverse saturation current (I_0) of the diode increases approximately 7 %/°C for both Ge & Si.

$\therefore (1.07)^{10} = 2$. The I_0 approximately doubles for every 10°C rise in temperature.

Hence, if the temperature is increased at fixed voltage (V), the current (I) increases.

* To bring the current 'I' to its original value, the voltage 'V' has to be reduced.

* It is found that at room temperature for either Ge or Si $\frac{dv}{dt} = -2.5\ mv/°c$, inorder to maintain the current 'I' to a constant value.

* At room temperature i.e., at 300°k, the value of barrier voltage or cut-in voltage is about 0.3 for Ge & 0.7 for Si.

* The barrier-voltage is temperature dependant & it decreases by 2mv/°c for both Ge & Si.

* Mathematically it can be expressed as $I_{02} = I_{01} \times 2^{(T_2-T_1)/10}$

where, I_{01} = Saturation current at temperature T_1.

I_{02} = saturation current at temperature T_2.

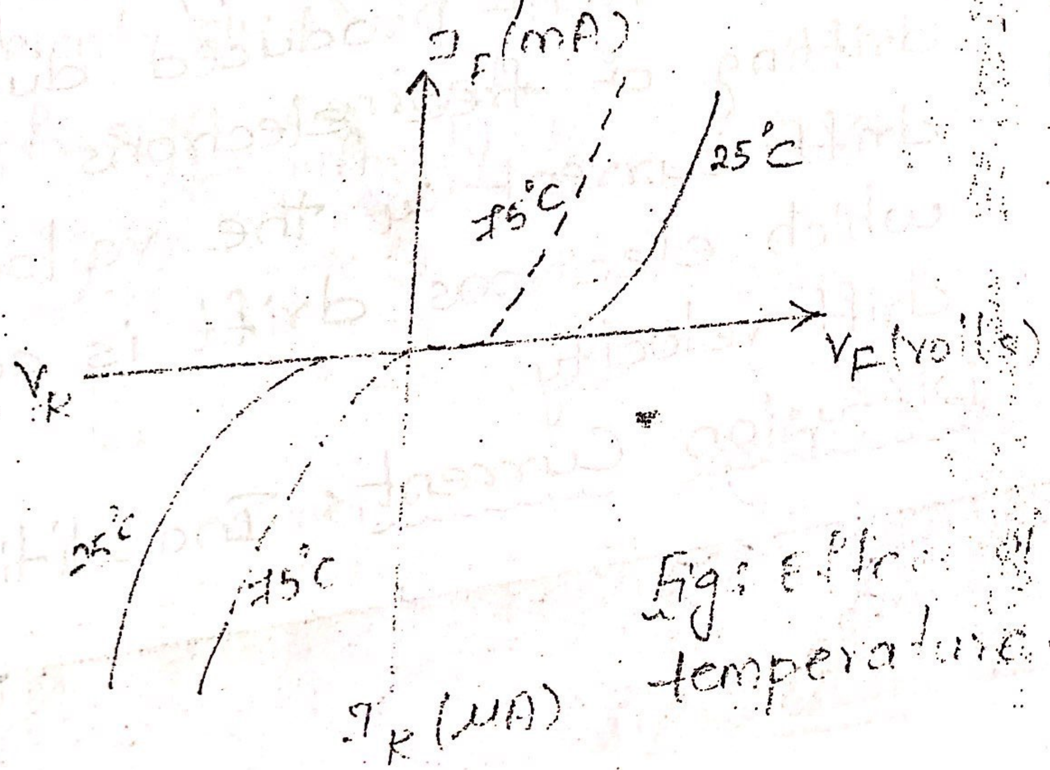


Fig: Effect of temperature.

b) Distinguish between drift & diffusion current in a semiconductor.

Ans **Drift current**: When a voltage is applied to a semiconductor, the free electrons try to move in a straight line towards the +ve terminal of the battery. The electrons, moving towards +ve terminal collide with the atoms of semiconductor & connecting wires, along its way.

* Each time the electron strikes an atom, it rebounds in a random direction.
* But still the applied voltage make the electrons drift towards the +ve terminal.
* This drift causes current to flow in a semiconductor, under the influence of the applied voltage.
* This current produced due to drifting of free electrons is called drift current & the velocity with which electrons drift is called the drift velocity.

Diffusion Current: Inaddition to the drift current, an additional current exists due to the transport of charges in a semiconductor. Such an additional current is due to the phenomenon called diffusion.

* This is the characteristic of semiconductors & cannot be observed in conductors.
* The current due to diffusion is called diffusion current.

(or)

* The movement of charge carriers due to the concentration gradient in a semiconductor is called process of diffusion.

• When charge carriers move, the current is constituted in a bar. This current due to diffusion is called diffusion current.

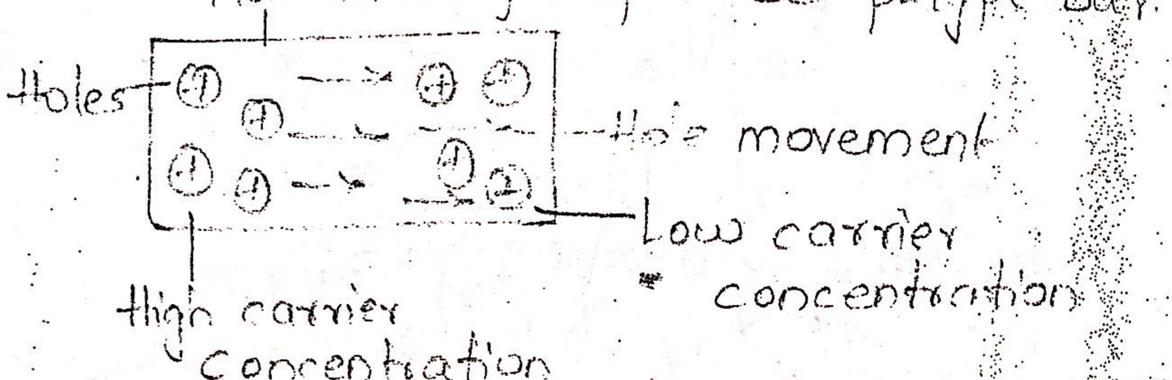


Figure : Diffusion Process

6. a) Explain why p-n junction contact potential cannot be measured by placing a voltmeter across the diode terminal.

Ans When the depletion region is formed, it is completely free from the charge carriers. It consists of immobile ionised particles due to which contact potential exists.

* The overall p-n junction is in equilibrium ∵ no flow of carriers i.e., current can exist in the junction.
* Hence voltmeter cannot (reduce) measure the contact potential ∵ no flow of current is possible.

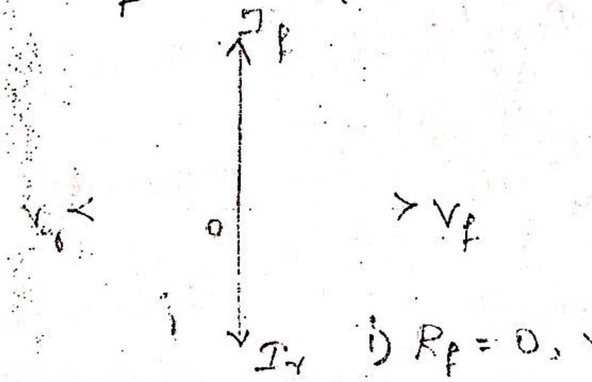
b) Sketch V-I characteristics of sc diode for the following conditions

i) $R_f = 0$, $V_\gamma = 0$, $R_r = \infty$

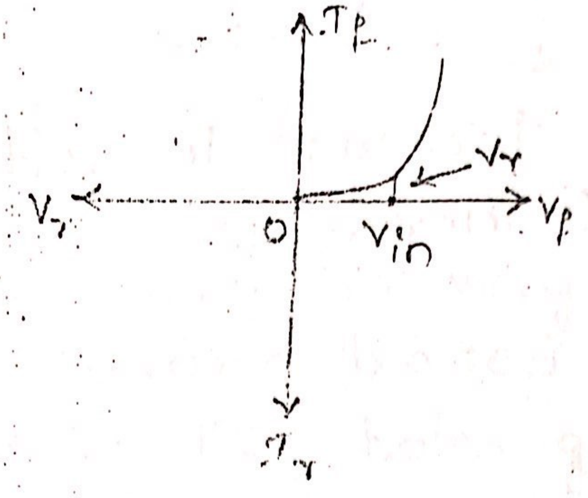
ii) $R_f \neq 0$, $V_\gamma \neq 0$, $R_r = \infty$

iii) $R_f \neq 0$, $V_\gamma = 0$, $R_r = \infty$.

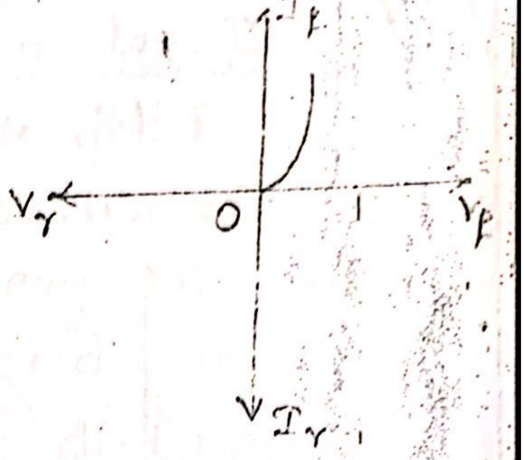
Ans



i) $R_f = 0$, $V_\gamma = 0$, $R_r = \infty$



ii) $R_f \neq 0, V_\gamma \neq 0$



iii) $R_f \neq 0, V_\gamma = 0$

c) Determine the values of forward current in the case of a p-n junction diode, with $I_o = 10$ micro amperes. $V_f = 0.8$ V at T = 300° K. Assume silicon diode.

Ans Given data,

$V_f = 0.8$ V

$I_o = 10\,\mu A$

$T = 300°K$

$V_T = kT = 8.62 \times 10^{-5} \times 300$

$= 0.02586$ V.

$\eta = 2$ for silicon

$I = I_o\,[e^{V/\eta V_T} - 1]$

$= 10 \times 10^{-6}\,(e^{0.8/2\times0.02586} - 1)$

$\therefore I = 52.1945$ A.

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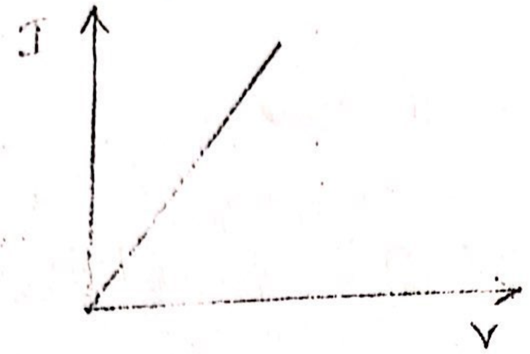
d) Compare ideal diode and practical diode graphically.

Ans **Ideal diode :**

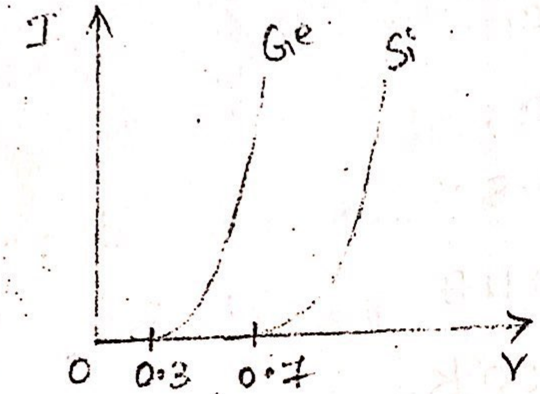
With the increase in voltage, the current increases.



Practical diode :

For Ge it is 0·3

For Si it is 0·7



7. a) Explain about various current components in a forward biased p-n junction diode.

Ans **Current components in a forward biased p-n junction diode :** When a p-n junction is forward biased a large forward current flows, which is mainly due to majority carriers.

* The depletion region near the junction is very very small, under forward biased condition.
* In FBC holes get diffused into n side from p side while electrons get diffused into p-side from n side.
* So on p-side, the current carried by electrons which is diffusion current due to minority carriers, decreases exponentially with respect to distance measured from the junction.
* This current due to electrons, on p-side which are minority carriers is denoted as I_{np}.
* Ily holes from p side diffuse into n side carry current which decreases exponentially with respect to distance measured from the junction.
* This current due to holes on n side, which are minority carriers is denoted as I_{pn}.

If distance is denoted by x.

then,

$I_{np}(x)$ = current due to electrons in p side as a function of x.

$I_{pn}(x)$ = current due to holes in n side as a function of x.

* At the junction i.e., at $x = 0$, electrons crossing from n side to p side constitute a current, $I_{np}(0)$ in the same direction as holes crossing the junction from p side to n side constitute a current, $I_{pn}(0)$.

* Hence the current at the junction is the total conventional current I flowing through the circuit.

$$\therefore I = I_{pn}(0) + I_{np}(0)$$

* Now $I_{pn}(x)$ decreases on n side as we move away from junction on n side.

Similarly $I_{np}(x)$ decreases on p side as we move away from junction on p side.

$I_{pp}(x)$ = Current due to holes in p side.

$I_{nn}(x)$ = Current due to electrons in n side.

On p side, $I = I_{pp}(x) + I_{np}(x)$

On n side, $I = I_{nn}(x) + I_{pn}(x)$.

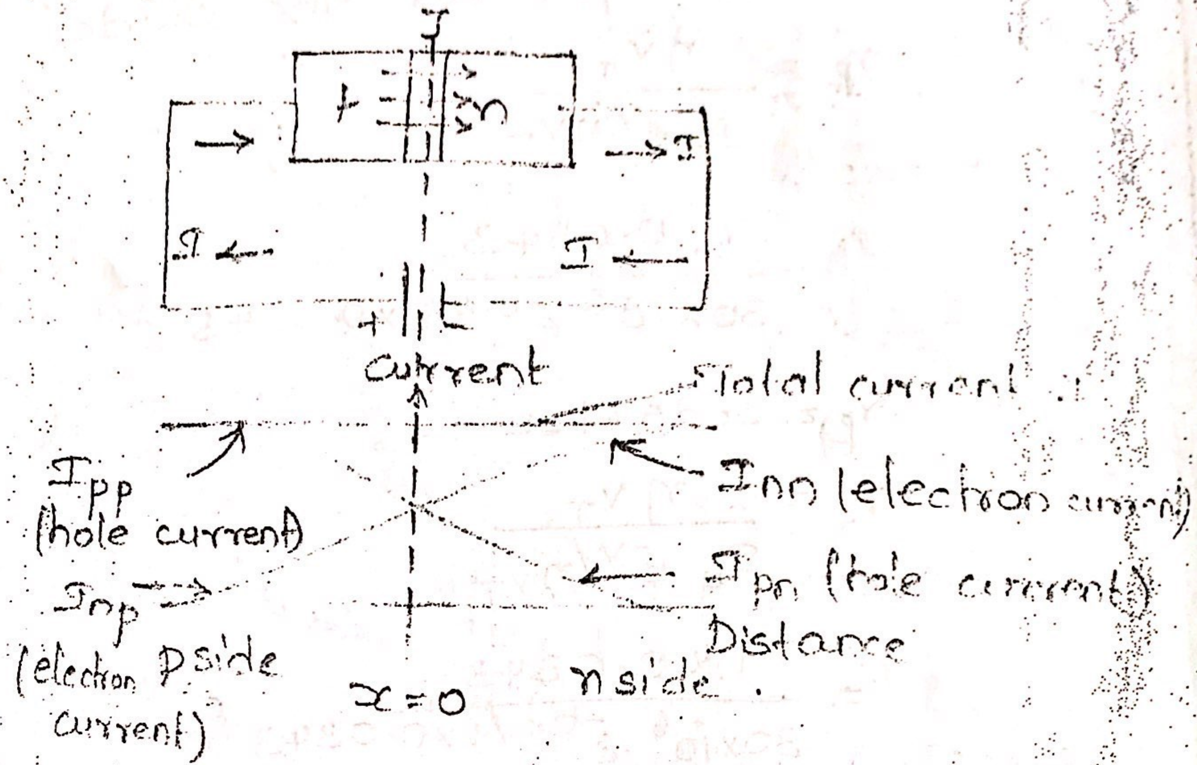


Fig: Current Components

b) A p-n junction diode has a reverse saturation current of 30 μA at a temperature of 125°c. At the same temperature, find the dynamic resistance for 0.2V bias in forward & reverse direction.

Ans Given data:

$I_0 = 30\ \mu A$

$V = 0.2\ V$ in both forward & reverse bias.

$T = 125°C$

$= 125 + 273°K$

$= 398°K$

$V_T = kT$

$= 8.62 \times 10^{-5} \times 398$

$= 0.0343\ V.$

Assume $\eta = 1$ for the diode

$$r_f = \frac{\eta V_T}{I_0 e^{V/\eta V_T}}$$

$$= \frac{1 \times 0.0343}{30 \times 10^{-6} e^{0.2/1 \times 0.0343}}$$

$r_f = 3.3561\ \Omega$

$$r_r = \frac{\eta V_T}{I_0 e^{-V/\eta V_T}}$$

$$= \frac{1 \times 0.0343}{30 \times 10^{-6} e^{-0.2/1 \times 0.0343}}$$

$r_r = 389.495\ k\Omega.$

8. a) What is Fermi-level ? By indicating the position of fermi level in intrinsic ntype & p-type semiconductor, explain its significance in semiconductors?

Ans Fermi-level: The fermi-level is that at which the probability of electron occupation is half at any temperature above 0 kelvin and also it is the highest level of the filled energy states at 0 kelvin.

* With the increase of temperature, the fermi function plot shows deviation.

* The probability F(E) of an electron occupying an energy level 'E' is given by

$$F(E) = \frac{1}{e^{(\alpha + E_i)/K_B T} + 1}$$

$$F(E) = \frac{1}{e^{\frac{(E_i - E_F)}{K_B T}} + 1}.$$

where, E_F = Fermi energy

$F(E)$ = Fermi function.

Fermi level in intrinsic n type:

At 0 kelvin the fermi level lies exactly at the middle of the donor level E_d and the bottom of the conduction band E_c.

$$E_F = \frac{E_d + E_c}{2}.$$

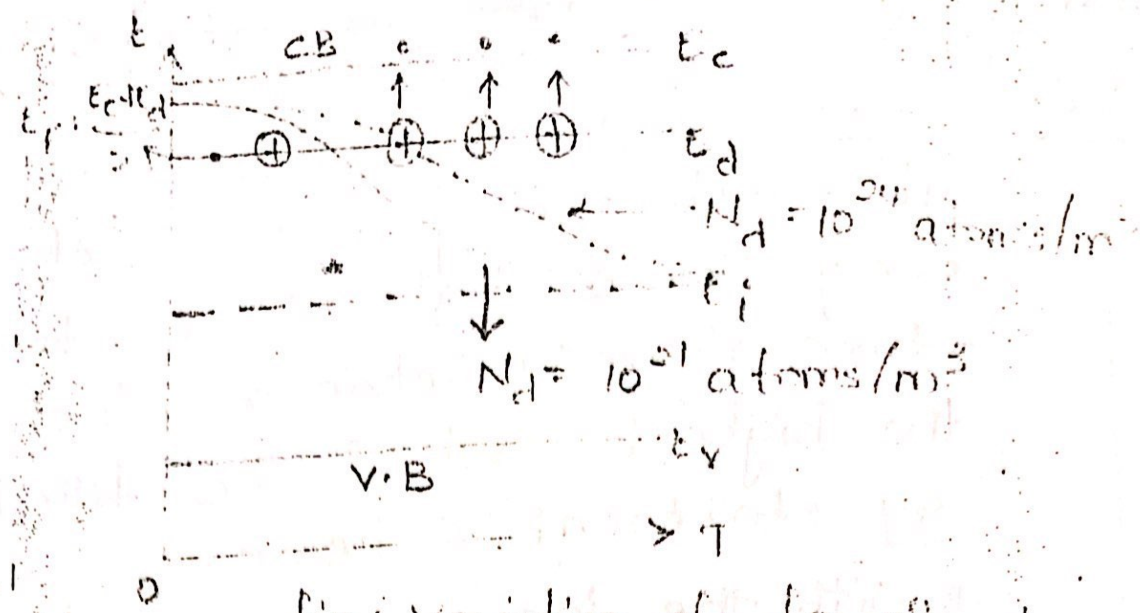


fig: Variation of fermi level with donor concentration.

Fermi level in intrinsic P-type:

At 0 kelvin fermi level lies at the middle of the acceptor level and the top of the valence band.

$$E_F = \frac{E_v + E_a}{2}$$

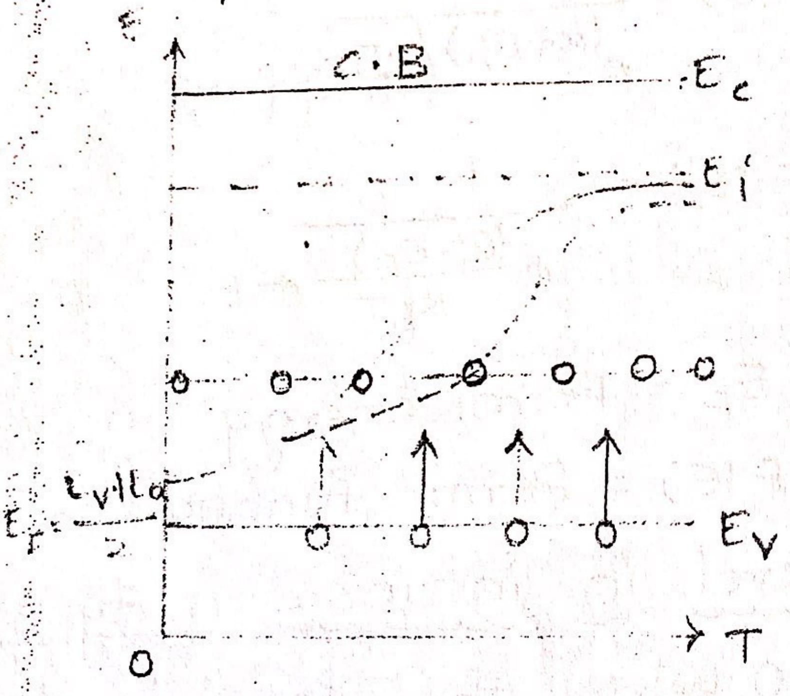


fig: Variation of fermi level with acceptor concentration

Significance :

Fermi-level plays an important role in semi-conductors.

* It gives/shows the energy-level in the semiconductors.
* Based on this, the semiconductors are divided (or) categorised.

b) Calculate the dynamic forward & reverse resistance of p-n junction silicon diode when the applied voltage is 0.25V at T = 300°k with given $I_0 = 2\mu A$.

Ans The dynamic resistance of diode is given by

$$r = \frac{V_T}{I_o\, e^{V/\eta V_T}}$$

$\eta = 2$ for Si, $V_T = 26\,mV$ for $T = 300°k$

For forward resistance use $V = 0.25V$

$$\therefore r_f = \frac{2 \times 26 \times 10^{-3}}{2 \times 10^{-6}\, e^{0.25/2 \times 26 \times 10^{-3}}}$$

$$r_f = 212.337\,\Omega$$

For reverse resistance use $V = -0.25V$,

$$\therefore r_r = \frac{2 \times 26 \times 10^{-3}}{2 \times 10^{-6}\, e^{-0.25/2 \times 26 \times 10^{-3}}}$$

$$r_r = 3.1836\,M\Omega$$

9. a) Explain briefly about practical diode and ideal diode.

Ans Practical diode : In forward biased diode, the total voltage drop across the diode is V_f which consists of drop due to barrier potential which is almost equal to cut-in voltage V_γ & the drop across the internal forward dynamic resistance r_f of the diode.

* While when reverse biased, reverse saturation current is very small & practically neglected.

Hence reverse biased (current) diode is practically assumed to be open circuit.

* Thus the practical diode model consists of a battery equal to cut-in voltage & the forward resistance, in series with an ideal diode, in forward biased condition. fig (a)

* In reverse biased, it is open circuited in fig (b)

* While the fig (c) shows the

corresponding V-I characteristics.

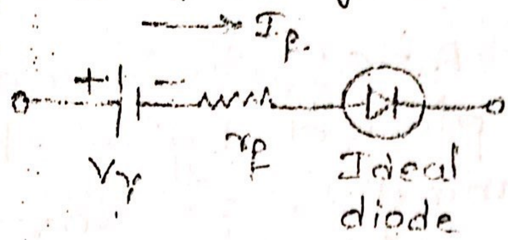


fig (a): Forward biased

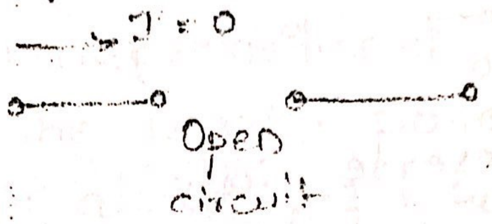


fig (b): Reverse biased

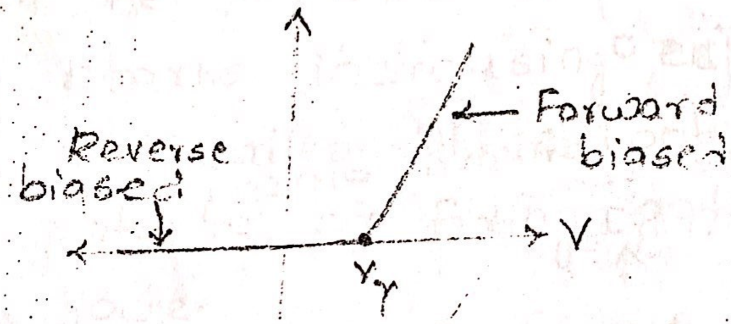


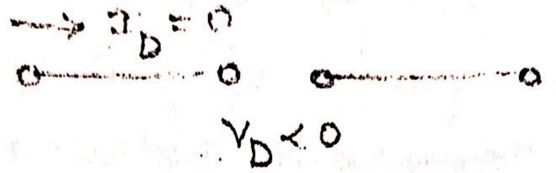
fig (c): V-I characteristics

Ideal diode: In many cases, as the forward resistance of diode is small ~~ie~~ cut-in voltage is also small, the diode is assumed to be an ideal diode.

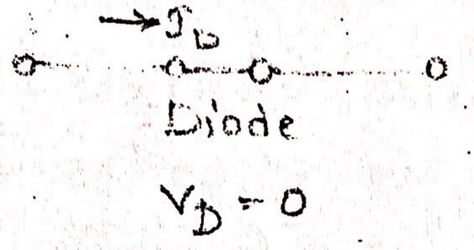
* In case of ideal ideal diode, it is assumed that it starts conducting instantaneously when

applied voltage V_D is just greater than zero & the drop across the conducting diode is zero.

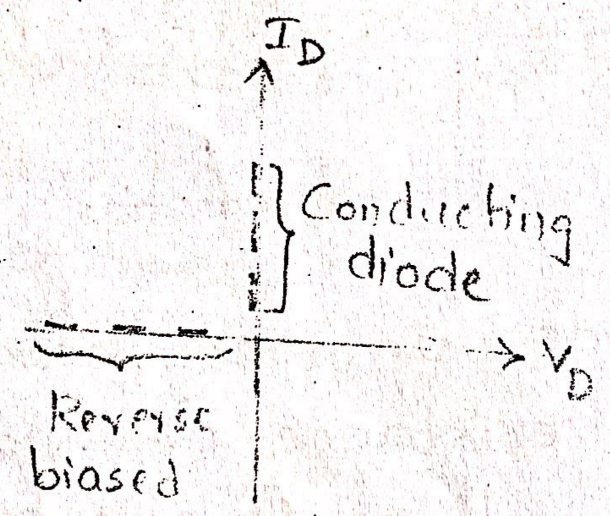
* So conducting diode can be ideally replaced by a short circuit, for the analysis of various diode circuits.



fig(a) : Reverse biased



fig(b) : Forward biased



fig(c) : V-I characteristics

Ideal Diode Model

b) Explain the operation of silicon p-n junction diode & obtain the forward bias & reverse bias volt-ampere characteristics.

Ans: The combined forward & reverse characteristics is called volt-ampere characteristics of a diode.

* The barrier potential for Ge diode is about 0.3 V & for si diode is about 0.7V.

* The potential at which current starts increasing exponentially is also called offset potential, Threshold potential or Firing potential of a diode.

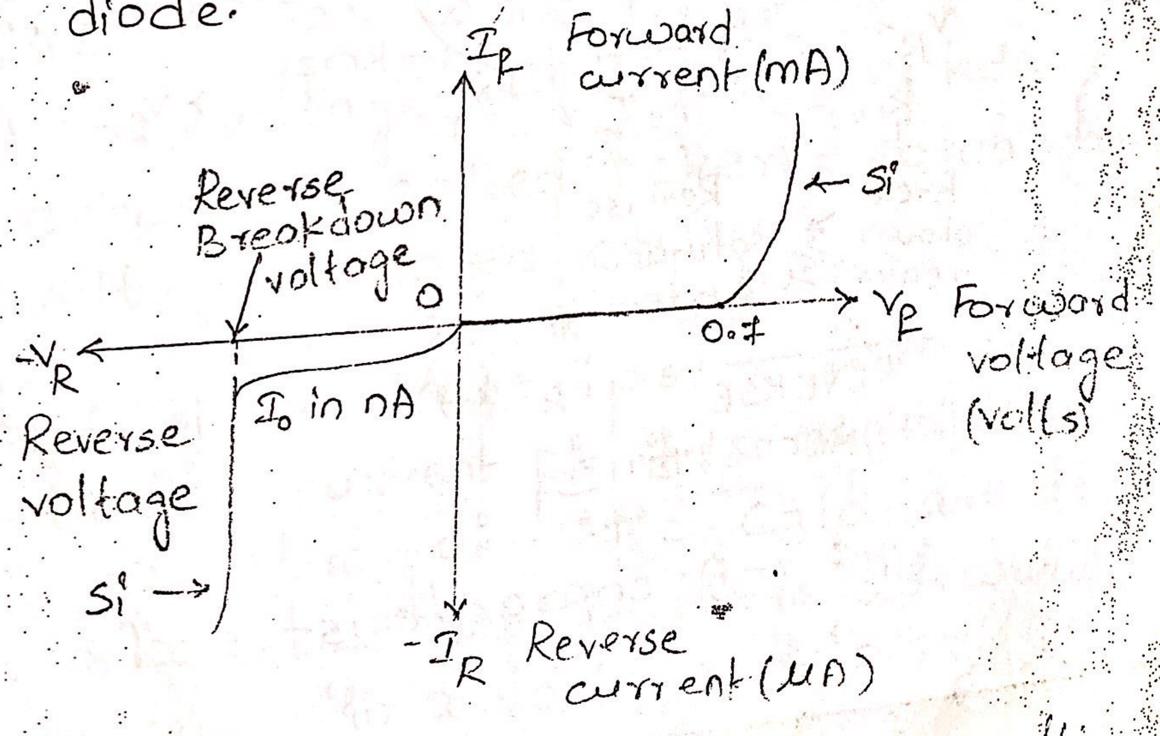


fig: V-A characteristics of a silicon diode.

* The I_0 is of the order of nA for silicon diode.
* Reverse breakdown voltage for Si diode is higher than that of Ge diode of a comparable rating.

10. a) With neat sketches & necessary waveforms explain the volt-ampere characteristics of PN diode.

Ans <u>volt-ampere characteristics of a PN diode</u>: The complete V-A characteristics of a diode is the combination of its (diode) forward as well as reverse characteristics.

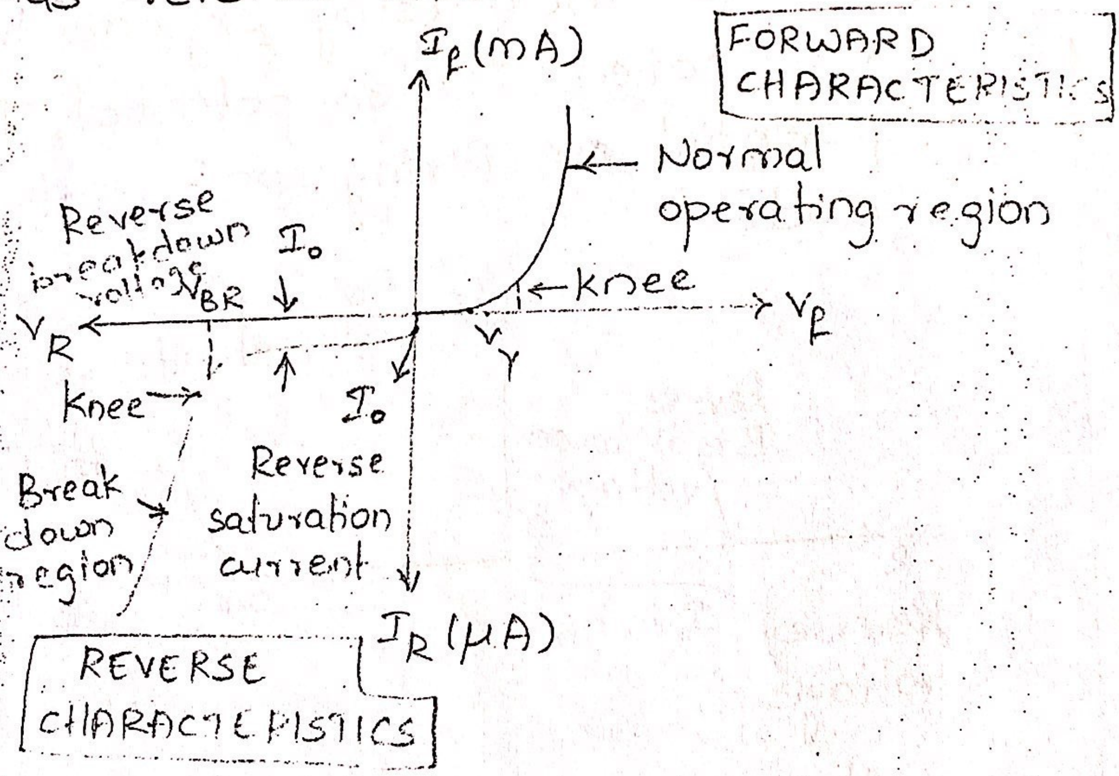


fig: V-A characteristics of a diode.

* In forward characteristics, it is seen that initially forward current is small as long as the bias voltage is less that the barrier potential.
* At a certain voltage close to barrier potential, current increases rapidly.
* The voltage at which diode current starts increasing rapidly is called cut-in voltage.
* It is denoted by V_γ.
* Below this voltage, current is less than 1% of max. rated value of diode current.
* The cut-in voltage for Ge is about 0.2V while for si it is 0.6V.
* The voltage at which breakdown occurs is called reverse breakdown voltage denoted as V_{BR}.

b) A silicon diode has a reverse saturation current of 7.12 nA at room temperature of 27°c. Calculate its forward current if it is forward biased with a voltage of 0.7V.

Ans. Given data,

$$I_0 = 7.12\ nA = 7.12 \times 10^{-9}\ A.$$

$V = +0.7V$

$\eta = 2$ for Si diode

$T = 27°C = 27 + 273$

$= 300° K$

$V_T = kT = 8.62 \times 10^{-5} \times 300$

$= 0.026 V.$

According to diode current equation,

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

$I = 7.12 \times 10^{-9} (e^{0.7/2 \times 0.026} - 1)$

$= 7.12 \times 10^{-9} (701894.59 - 1)$

$= 4.99 \times 10^{-3} A$

$I = 5 mA$

Thus the forward current is 5mA.

28/7/22

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