UNIT-IV

CONCEPT OF ELECTRICAL MEASUREMENTS —

Electrical measurements— These are the methods, devices and calculations used to measure electrical quantities. This can be done to measure electrical parameters of a system. This is the branch of science of metrology.

This measurement can reveal information that completely characterizes the electrical properties of the material. Conductivity measurements gives the information on the conductivity (resistivity) of the material and indirectly the mobility of charge carriers. Resistivity is one of the most sensitive measure of electrical transport of Materials.

In case of semiconductors, we can find the same parameters with some different values as compared to metals. Fermi level can be calculated with the help of e^- and hole concentration. With respect to hall effect, resistivity, mobility & carrier density can be calculated.

1

⇒ Significance of resistivity -

Resistivity or electrical resistivity is an intrinsic property which quantifies how strongly a given material opposes the flow of electrical current, that can be measured by several methods depending on magnitude of resistance involved in materials.

According to Ohm's law, we have

R in ohm.

$$V = IR$$

& the constant of proportianality R, is called the resistance of the material.

<u>Resistivity</u> - At a given constant temperature, ~~resis~~ resistance R of the conductor (i) proportional to length (L) and (ii) inversely proportional to its area of cross-section (A) ie

$$\rho = \frac{RA}{L} \quad \text{or} \quad R \propto L/A \quad \left(R = \rho \frac{l}{A}\right)$$

It is defined as the resistance offered by a wire of material of unit length and unit cross-sectional area. <u>Unit</u> - ohm-meter.

It is the key to measure electrical resistance. It helps to compare the conductivity of various materials, depending on its length, area of cross-section and temperature of the conductor.

⟹ Significance of hall mobility – Mobility inferred from the Hall-Effect ~~ma~~ measurement. (2)

It is the measure of the mobility of the e^- and holes in a semiconductor. It is the product of conductivity and hall constant for a conductor or a semiconductor.

Equationally :–

N-type – $\sigma_n = ne\mu_e$ or $\mu_e = \frac{\sigma_n}{ne} = -\sigma_n \cdot R_H$

P-type : $\mu_n = \frac{\sigma_p}{pe} = \sigma_p \cdot R_H$. So, by measuring σ & R_H, μ can be calculated.

This is very important parameter for semiconductor materials. Higher mobility leads to better device performance, with other things equal.

Depending on drift velocity $v_d = \mu E$

where v_d = drift velocity, E = Electric field

& μ = carrier mobility (hall mobility)

With the help of this, we can find

(i) Whether, the conductivity is due to holes or e^-

(ii) to determine magnetic flux density.

(iii) ~~To cal~~ Hall voltage, hall current, hall coefficient & hall angle etc.

⇒ Significance of carrier density — Also ~~call~~ called as carrier concentration denoting the no. of charge carrier per volume.

$$N = \int_V n(r)\,dV.$$

(No. of charge carriers) — over a volume V:–

where $n(r)$ = position-dependent charge carrier density.

This is important for semiconductors, for the process of chemical doping.

for N-type — $n_e = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_C}{kT}\right)$ —(1)

for P-type — $p_e = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right)$ —(2)

It is helpful to find the hall coefficient, location of fermi level (either for n or for p-type), even in intrinsic semiconductor also, we can get the location of fermi level and conductivity of intrinsic semiconductors.

In case of metals, we have the free electrons as the carrier density calculated from the drude model. We can infer conductivity of metals, current density

Semiconductors

Hall Coeff. $R_H = -1/ne$ or $1/pe$ (N & p-type respectively)

Fermilevel

Intrinsic Semiconductor – $E_F = \frac{E_C + E_V}{2}$

N-type – $E_C - kT \ln \frac{N_c}{N_d}$

P-type – $E_V + kT \ln \frac{N_v}{N_a}$

Two-Point Probe Technique -

This is one of the standard and most commonly used method for the resistivity measurement of very high resistivity samples - near insulators.

let us consider a long thin wire of length L, and uniform cross-section A, or the materials with long parallelopiped shaped with uniform cross-section as shown in fig below -

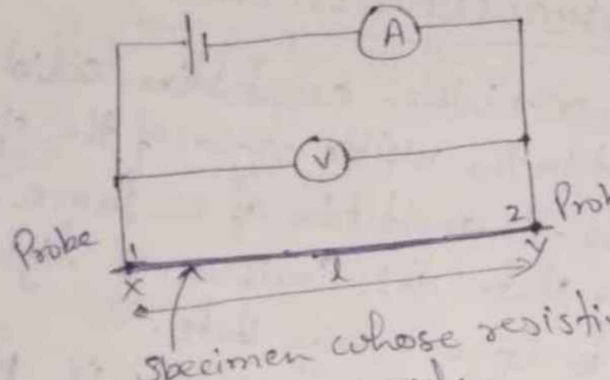


fig:- Schematic of two-probe setup

Resistivity can be measured by measuring voltage drop across the wire due to passage of known current supplied by the battery E through the probes 1 and 2.

Voltmeter - measures the potential difference between two contacts at the wire ends

$$\rho = \left(\frac{V}{I}\right)\left(A/l\right)$$

Two probe method is a simple and advantageous method for measuring resistance above 1Ω directly.

2

<u>Problems</u>: Two probe method suffers few issues as stated below -

(i) Error due to contact resistance of the measuring leads

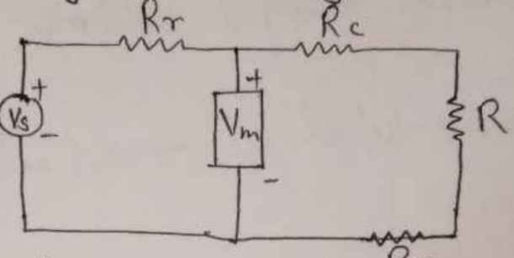
(ii) Materials having random shapes,

(iii) Soldering of the test leads on some materials could be difficult.

(iv) Heating of the ~~lea~~ leads, during soldering may inject additional impurities in materials

→ Eliminated by pressure contacts.

* Two point probe (contd.) — A more realistic view of a two point measurement using an ohmmeter is shown in fig (2). A voltage source and a variable range resistor (R_r) supply the current, where (R_r) is adjustable to give convenient voltage across the voltmeter.



Fig(2) – Two-point ohmmeter measurement circuit.

R_c – Series resistance from the wire to sample contact resistance

Resistance is calculated as

$$R = \frac{(R_r V_m / V_s)}{(1 - V_m / V_s)} - 2R_c .$$

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FOUR-PROBE METHOD – This method is an electrical impedance measuring technique which uses separate pairs of current-carrying and voltage sensing electrodes to make more accurate measurements than the simpler & more usual two-terminal (2T) sensing.

This is also known as 'Kelvin Sensing'

Principle – When current is supplied via a pair of source, it generates a voltage drop across the impedance to be measured as per Ohm's law.

Note:- Since almost no current flows to the measuring instrument, the voltage drops seems to be negligible.

TECHNIQUES –

(i) Four point Collinear-method and (ii) Vander Pauw method.

(I) COLLINEAR METHOD – Most common way of measuring resistivity of material that involves four equally spaced probes.

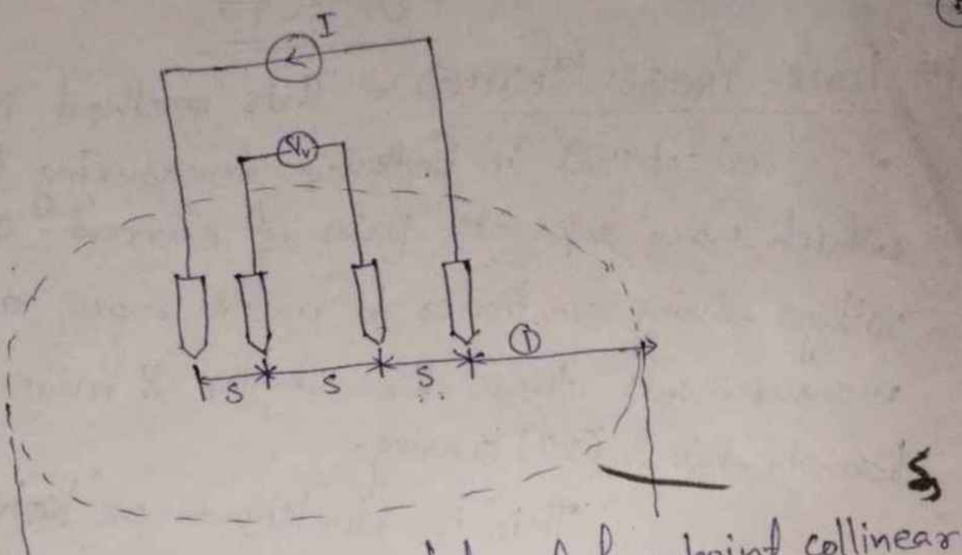
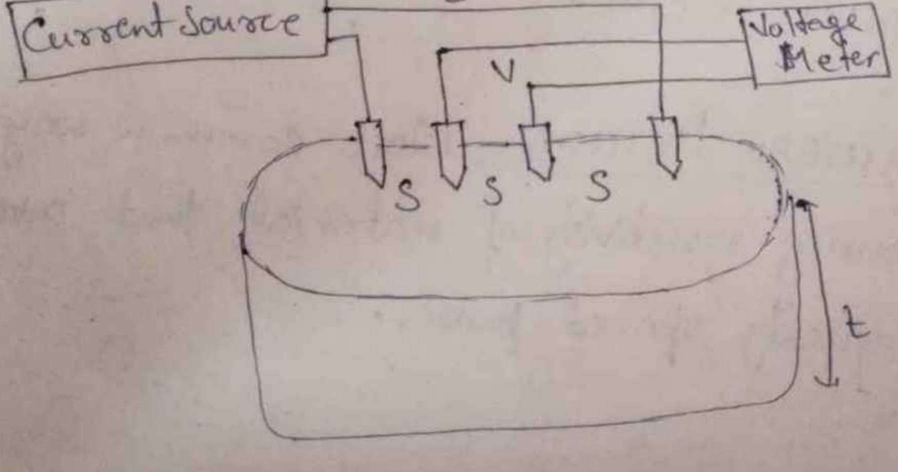


fig- Schematic representation of four-point collinear probe method.

This is applicable for bulk and thin films.

→ For Bulk:- Consider a bulk material with thickness (t) of the material is such higher than the space between probe(s). The differential resistance due to spherical protrusion of current emanating from the outer probe is

$$\Delta R = \rho \left(\frac{dx}{A}\right)$$



On carrying out the integration we get.

$$R = \int_{v_1}^{v_2} \rho \frac{dx}{2\pi x^2} = \int_{s}^{2s} \rho \frac{dx}{2\pi x^2}$$

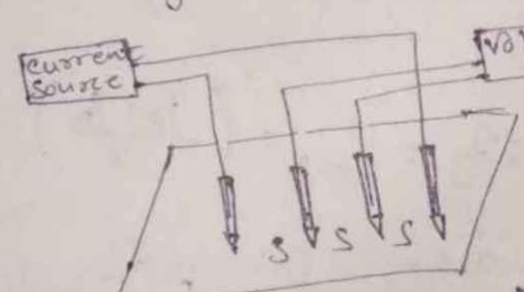
$$R = \frac{\rho}{2\pi}\left(-\frac{1}{x}\right)\Big|_{s}^{2s} = \frac{\rho}{2\pi}\frac{1}{2s}$$ where probe spacing is uniform.

Due to superposition of current at outer tips

$$R = \frac{V}{2I}$$

$$\text{or } \rho = \frac{V}{I}(2\pi s)$$

→ <u>for thin sheet</u> – for thin sheet where t << space between probes (s), ~~we~~ we can get current rings instead of spheres. So $A = 2\pi x.t$.



Four-point collinear method for thin sheet

$$R = \int_{v_1}^{v_2} \rho \frac{dx}{2\pi x t} = \int_{s}^{2s} \frac{\rho}{2\pi t}\frac{dx}{x}$$

$$R = \frac{\rho}{2\pi t} \ln(x)\Big|_{s}^{2s} = \frac{\rho}{2\pi t}\ln 2.$$

$\therefore R = V/2I$; $\rho = \left(\frac{V}{I}\right)\left(\frac{\pi t}{\ln 2}\right)$ (independent of probe spacing)

VAN-DER PAUW METHOD

In this current and measuring voltage is applied using four small contact on the circumference of a flat, arbitarily shaped sample of uniform thickness.

$$\rho_A = \left(\frac{\pi}{\ln 2}\right) f_A \, t_s \left[\frac{(V_1 - V_2 + V_3 - V_4)}{4I}\right] \quad \text{--- (1)}$$

$$\rho_B = \left(\frac{\pi}{\ln 2}\right) f_B \, t_s \left[\frac{(V_5 - V_6 + V_7 - V_8)}{4I}\right] \quad \text{--- (2)}$$

where ρ_A and ρ_B are volume resistivity in Ω cm.

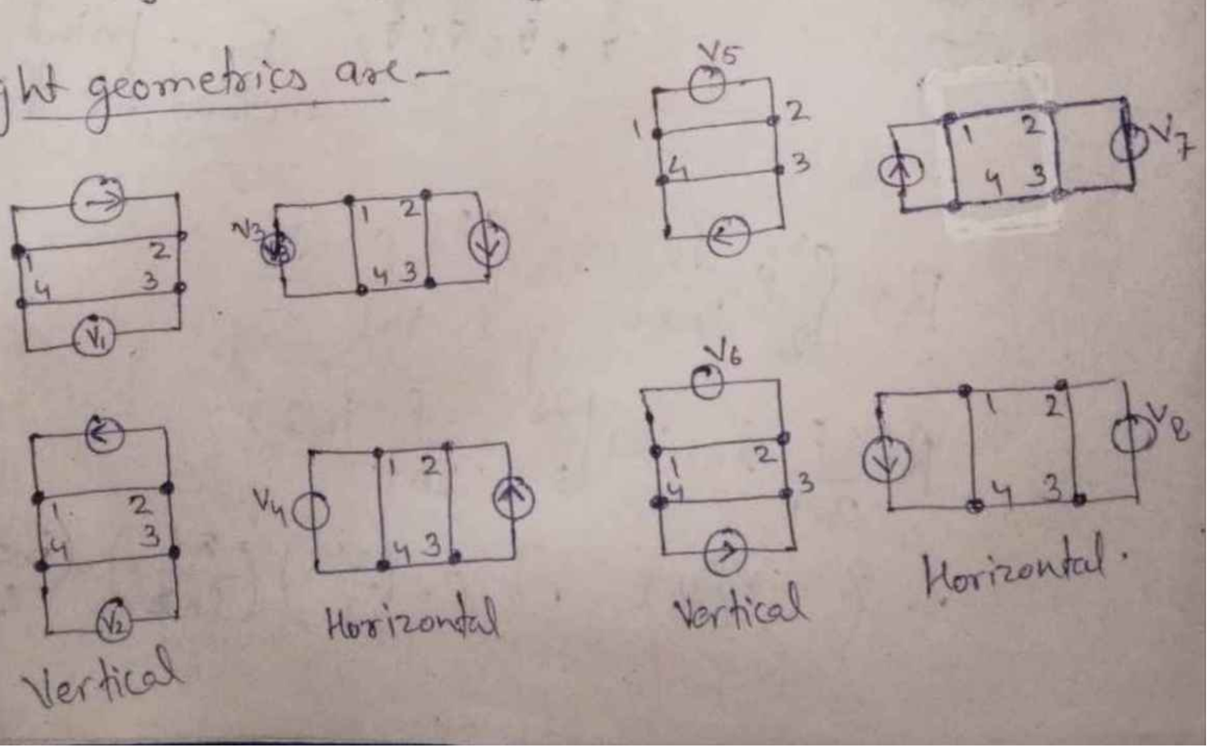
t_s = sample thickness (cm)

V_1 to V_8 represent voltages measured by the voltmeter under eight geometrics respectively. I is the current through the sample in amperes. For a perfect symmetry system

$$f_A = f_B \approx 1$$

$$\text{Avg. resistivity} = \rho_{avg} = \left(\frac{\rho_A + \rho_B}{2}\right)$$

Eight geometrics are –



Vertical Horizontal Vertical Horizontal

HOT-POINT PROBE METHOD – This is a simple method to determine whether a semiconductor is N or P-type.

Principle – – Two probes touches the wafer, one is warmer than the other.

– Voltmeter reads the potential between the probes.

– for N-type → warmer probe is more positive than the colder probe.

– for P-type – Warmer probe is more ~~positive~~ negative than the colder probe.

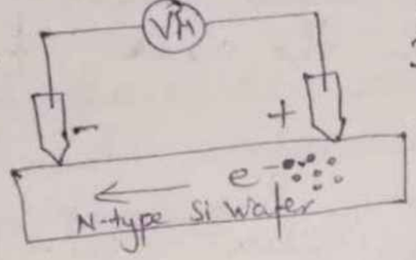
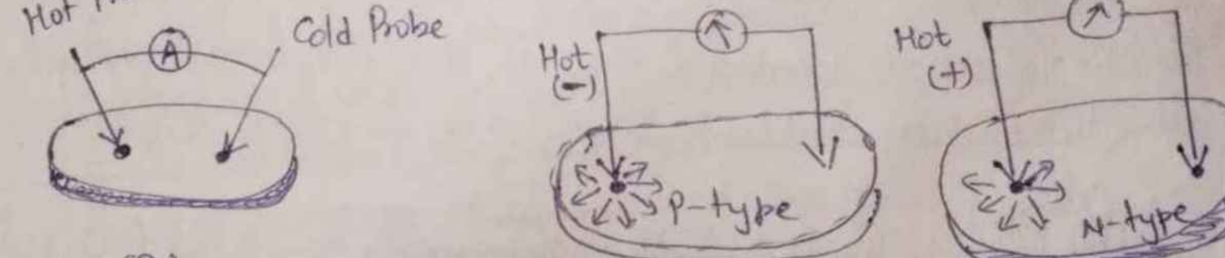


fig – Basic principle of the hot probe, illustrated for N-type sample, for determining N/P type behavior in semiconductor



(a)

Energetic holes diffuses away

Energetic electrons diffuses away.

Note → Net Effect :–

i) Deficient of holes – (net –ve charge for P-type)

ii) Deficient of e⁻ (net +ve charge for n-type) of Van-der Pauw Method

From this measurement made, following features can be calculated – ⑤

① Resistivity of the material.

② Doping type. ③ Sheet carrier density of the majority carrier ④ Mobility of majority carrier..

Conditions – ① Sample must have a flat shape of uniform thickness.

② Sample must not have any isolated holes.

③ Sample must be homogeneous & isotropic

④ All four contacts must be located at the edge of the sample.

⑤ Area of contact of any individual contact should be at least an order of magnitude smaller than the area of the entire sample.

Explanation of Hot point probe Method – Principle – Seebeck Effect – When heat is applied to one of the two conductors or semiconductors, heated electrons flow towards the cooler conductor or semiconductor. If the pair is connected through an electrical circuit, direct current (DC) flows through that circuit.

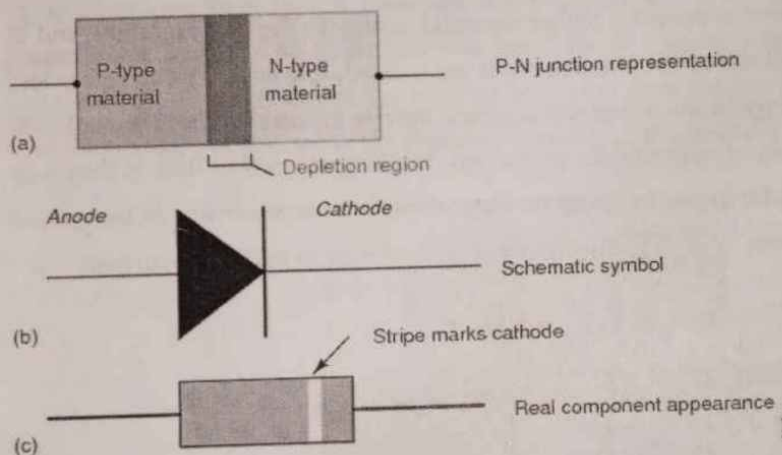
(N-type)
Hot Probe is heated, & the thermally generated (-ve) charge carriers are there that moves towards the cold probe by thermal diffusion process (moves from hot probe to cold probe) making hot probe to be positive which is shown in the voltmeter.

I-V characteristics of a Diode:

A **current–voltage characteristic** or **I–V curve** (current–voltage curve) is a relationship, typically represented as a chart or graph, between the electric current through a circuit, device, or material, and the corresponding voltage, or potential difference across it.

There are three possible biasing conditions and two operating regions for the typical PN-Junction Diode, they are: zero bias, forward bias and reverse bias.

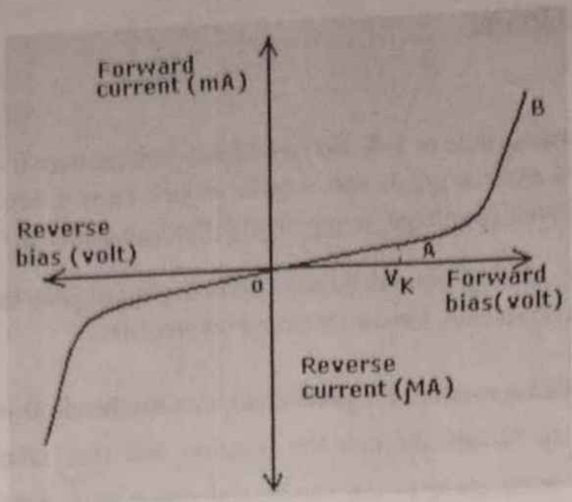
When no voltage is applied across the PN junction diode then the electrons will diffuse to P-side and holes will diffuse to N-side through the junction and they combine with each other. Therefore, the acceptor atom close to the P-type and donor atom near to the N-side are left unutilized. An electronic field is generated by these charge carriers. This opposes further diffusion of charge carriers. Thus, no movement of the region is known as depletion region or space charge.



PN Junction Diode

If we apply forward bias to the PN-junction diode, that means negative terminal is connected to the N-type material and the positive terminal is connected to the P-type material across the diode which has the effect of decreasing the width of the PN junction diode.

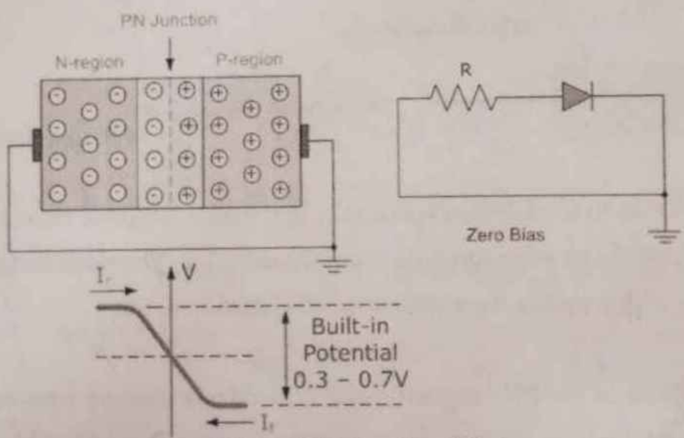
If we apply reverse bias to the PN-junction diode, that means positive terminal is connected to the N-type material and the negative terminal is connected to the P-type material across the diode which has the effect of increasing the width of the PN junction diode and no charge can flow across the junction.



VI Characteristics of PN Junction Diode

Zero Biased PN Junction Diode

In the zero bias junction, potential provides higher potential energy to the holes on the P and N side terminals. When the terminals of the junction diode are shorted, few majority charge carriers in the P-side with plenty energy to overcome the potential barrier to travel across the depletion region. Therefore, with the help of majority charge carriers, the current starts to flow in the diode and it is denoted to as forward current. In the same way, minority charge carriers in the N-side move across the depletion region in reverse direction and it is referred to as reverse current.



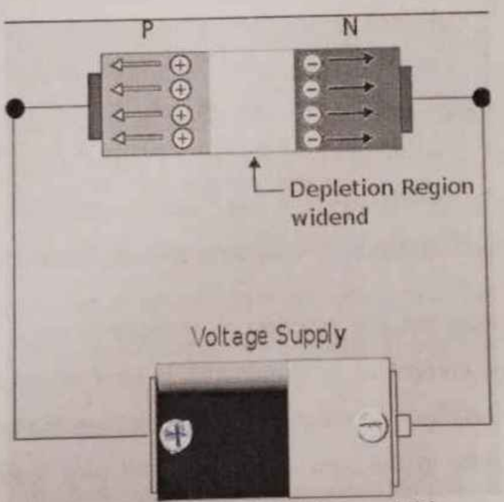
Zero Biased PN Junction Diode

Potential barrier opposes the movement of electrons & holes across the junction and permits the minority charge carriers to drift across the PN junction. However, the potential barrier helps minority charge carriers in P-type and N-type to drift across the PN-junction, then an equilibrium will be established when the majority charge carriers are equal and both moving in reverse directions, so that the net result is zero current flowing in the circuit. This junction is said to be in a state of dynamic equilibrium.

When the temperature of the semiconductor is increased, minority charge carriers have been endlessly generated and thus leakage current starts to rise. But, electric current cannot flow since no external source has been connected to the PN-junction.

PN Junction Diode in Forward Bias

When a PN-junction diode is connected in a forward bias by giving a negative voltage to the N-type and a positive voltage to the P-type material. If the external voltage becomes more than the value of the potential barrier (estimate 0.7 V for Si and 0.3V for Ge) the opposition of the potential barriers will be overcome and the flow of current will start.Because, the negative voltage repels electrons near to the junction by giving them the energy to combine and cross over with the holes being pushed in the opposite direction to the junction by the positive voltage.

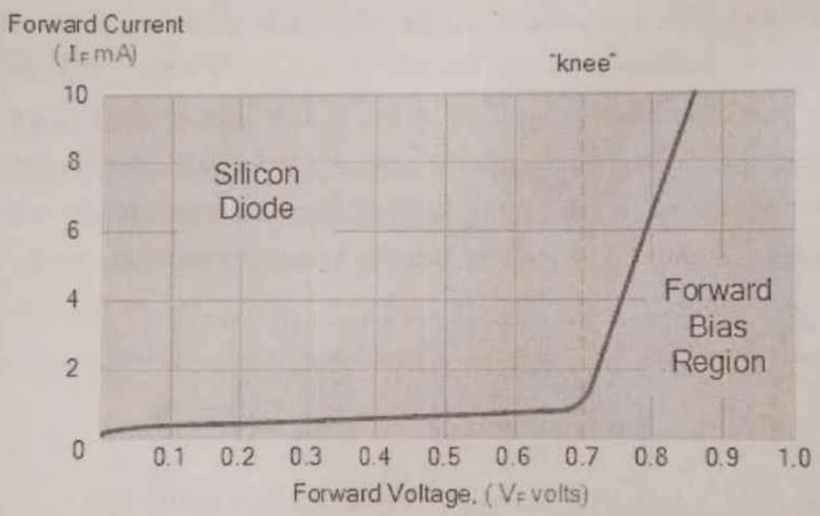


PN Junction Diode in Forward Bias

The result of this in a characteristic curve of zero current flowing up to built in potential is called as "knee current" on the static curves & then a high current flow through the diode with a slight increase in the external voltage as shown below.

VI Characteristics of PN Junction Diode in Forward Bias

The VI characteristics of PN junction diode in forward bias are non linear, that is, not a straight line. This nonlinear characteristic illustrates that during the operation of the N junction, the resistance is not constant. The slope of the PN junction diode in forward bias shows the resistance is very low. When forward bias is applied to the diode then it causes a low impedance path and permits to conduct a large amount of current which is known as infinite current. This current starts to flow above the knee point with a small amount of external potential.



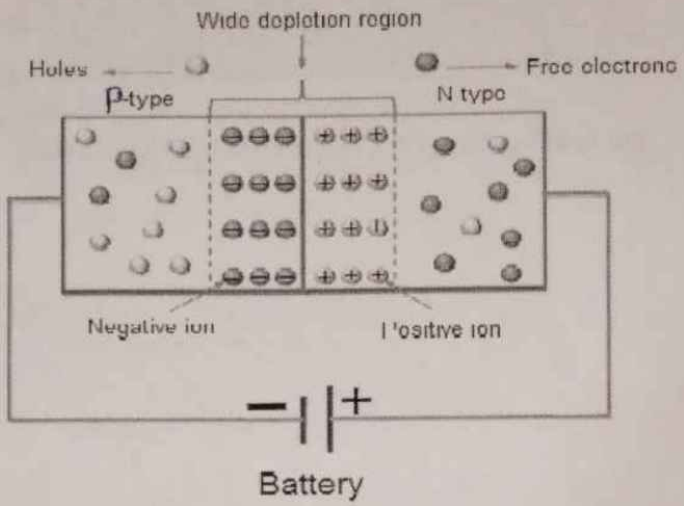
PN Junction Diode VI Characteristics in Forward Bias

The potential difference across the PN junction is maintained constant by the depletion layer action. The max amount of current to be conducted is kept incomplete by the load resistor, because when the PN junction diode conducts more current than the normal specifications of the diode, the extra current results in the heat dissipation and also leads to serve damage to the device.

PN Junction Diode in Reverse Bias

When a PN junction diode is connected in a Reverse Bias condition, a positive (+ Ve) voltage is connected to the N type material & a negative (-Ve) voltage is connected to the P-type material.

When the +Ve voltage is applied to the N-type material, then it attracts the electrons near the positive electrode and goes away from the junction, whereas the holes in the P-type end are also attracted away from the junction near the negative electrode.

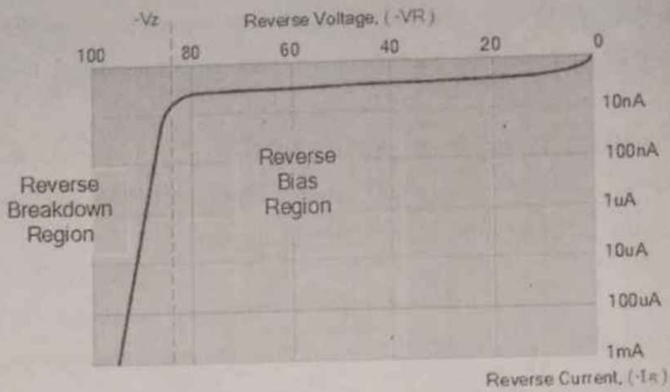


PN Junction Diode in Reverse Bias

In this type of biasing, current flow through the PN junction diode is zero. Though, the current leakage due to minority charge carriers flows in the diode that can be measured in a uA (micro amperes). As the potential of the reverse bias to the PN junction diode ultimately increases and leads to PN junction reverse voltage breakdown and the current of the PN junction diode is controlled by an external circuit. Reverse breakdown depends on the doping levels of the P & N regions. Further, with the increase in reverse bias the diode will become short circuited due to overheat in the circuit and max circuit current flows in the PN junction diode.

VI Characteristics of PN Junction Diode in Reverse Bias

In this type of biasing, the characteristic curve of diode is shown in the fourth quadrant of the below figure. The current in this biasing is low till breakdown is reached and hence the diode looks like as open circuit. When the input voltage of the reverse bias has reached the breakdown voltage, reverse current increases enormously.

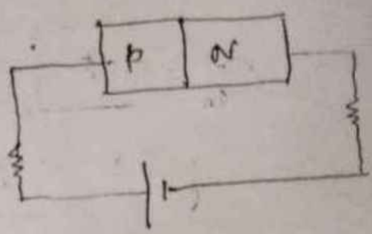


PN Junction Diode VI Characteristics in Reverse Bias

Case I Forward Bias Condition

(i) V = positive value
= Small in magnitude

(ii) $e^{\frac{V}{nV_T}} \gg 1$



$\therefore e^{\frac{V}{nV_T}} - 1 \simeq e^{V/nV_T}$

So equation ① reduces to

$$\boxed{I = I_0\, e^{\frac{V}{nV_T}}} \quad \dashrightarrow ②$$

Case II Reverse Bias Condition

(i) V = Negative value
= Small in magnitude

(ii) $e^{\frac{V}{nV_T}} \lll 1$

$\therefore e^{\frac{V}{nV_T}} - 1 \simeq -1$

So equation ② reduces to

$$\boxed{I = -I_0} \quad \dashrightarrow ③$$

So based on Case I & Case II, the VI Characteristics of P-N Junction diode was drawn.

Extraction of parameters.

P-N Junction Diode

The P-N junction itself forms the most basic semiconductor device called semiconductor di-ode. The meaning of the terms DIODE is the device having two electrodes (di-ode).

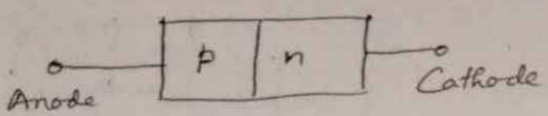


Fig (a) A p-n junction diode forms semiconductor diode

Symbol

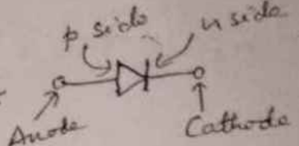


Fig (b) Circuit symbol of a diode

~~Biasing of a P-N Junction diode~~

V-I Characteristics of P-N Junction diode

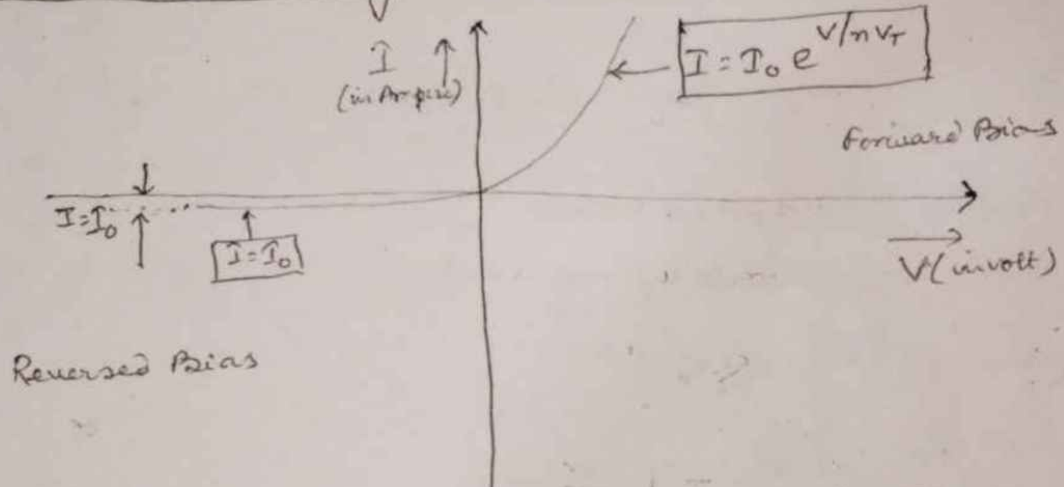


Fig (c) - VI Characteristics of PN Junction Diode

As. Diode Equation from VI characteristics shows that

$$\boxed{I = I_0\left(e^{V/nV_T} - 1\right)} \longrightarrow (1)$$

$$= I_{FB} + I_{RB}$$

Where I_0 = Reverse saturation current

η = Constant value

= 1 for Ge element

= 2 for Si element

V_T = Voltage equivalent to Temperature (T)

$= \dfrac{T}{11600}$ volt.

Reverse saturation Current (I_0)

→ It is the current flowing through the PN Junction in the reverse biased condition.

→ Its depends upon the minority charge carrier concentration and its magnitude is very small in the order of μA

→ This current is independent of the Reverse biased applied so long as the magnitude of this reverse bias is large

→ This current is temperature dependent and is Doubled for every 10° rise in temperature

$$\boxed{I_0' = 2 I_0 \; 2^{(T'-T)/10}}$$

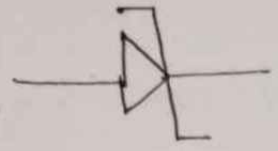
I_0 = Reverse saturation current at temperature T

I_0' = Reverse Saturation current at temperature T'

ZENER DIODE

- → PN Junction diode with heavy doping
- → Always operated in Reverse Biased condition
- → Operation depends upon
  - (a) Zener Breakdown
  - (b) Avalance Breakdown

Symbol



Zener Diode Phenomenon

(a) It is a PN Junction diode with very heavy doping

(b) The magnitude of Reverse Bias applied is relatively low in the order of 6V

doping ↑	→ d ↓
RB ↑	→ d ↑

(c) The junction width (d) and therefore the depletion width (d) is always narrow (i.e in the range of Å)

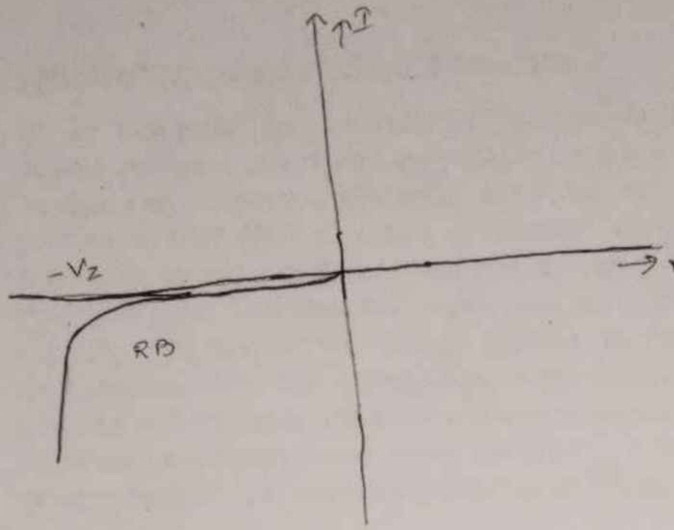
(d) The applied electric field near the junction is very large; is of the order of 10^7 V/m

$$\boxed{E = \frac{V}{d}}$$

(e) At a given RB voltage, the electric field is sufficiently high so that there is directly rupture of covalent bonds near the junction.

(f) A large number of carrier is generated. At each region, conductivity increases and hence the current increases maintaining a constant potential across the junction

VI Characteristics



V_Z = Zener Voltage [... Breakdown Voltage]

Case I $\quad |V| < V_Z$; $\quad I \approx 0$; ... Zener diode work as open circuited

Hence $\boxed{r_z \to \infty}$

Case II $\quad |V| > V_Z$; $\quad I \uparrow\uparrow$

i.e Zener Diode act as a voltage Regulator

$\boxed{r_z \to 0}$