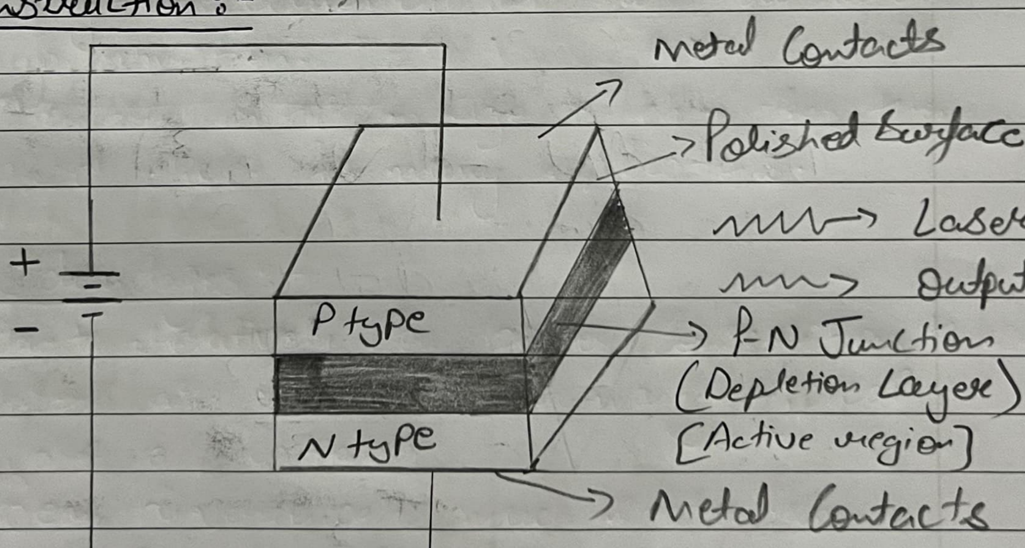
UNIT-4

Semiconductor Laser :-

The Semiconductor laser is very small in size and appearance. It is similar to a transistor and has the operation like LED but the output beam has the characteristics of laser light. It uses P-N junction for producing coherent radiation with the same frequency and phase which is either in the visible or infrared spectrum. It is also called injection laser. Gallium Arsenide is used for the making of Semiconductor laser.

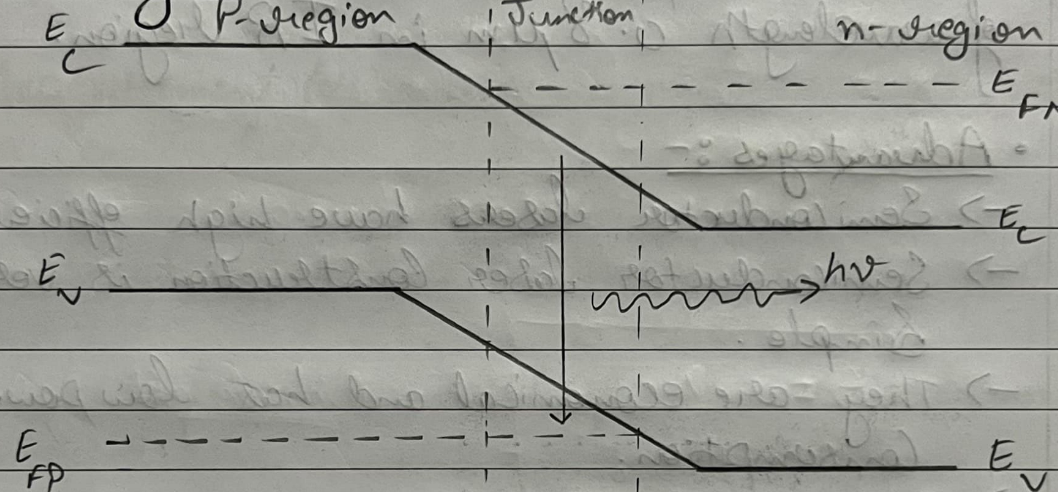
• **Construction :-**



→ GaAs laser diode is a single crystal of GaAs consisting of heavily doped n and p regions. The n region is formed by doping with tellurium and p region is formed by doping with zinc.

-> The doping concentration will be in order of 10^{17} to 10^{19} dopands per cm^3.
-> The top and bottom surfaces are metallized to facilitate forward biasing.
-> The thickness of the active medium (P-N junction) is in the order of 1-100 μm.

• **Working :-**



Due to heavy doping, the Fermi level in n region is pushed into the Conduction band and in p region, it lies within the valence band.

When the diode is forward biased, the electrons from the n region and holes from the p region enter the p-n junction and the recombination takes place which results in spontaneous emission of Photons.

when the Current reaches the threshhold value, large concentration of electrons and holes enter the junction region. At the junction, large no. of electrons present in Conduction band and large no. of holes present in the valence band. This results in the population inversion in the active region.

At this stage, the spontaneously emitted photons triggers the electrons in the conduction band to jump to the vacant sites in valence band. This stimulated electron-hole recombination produces coherent radiations of wavelength 0.8 μm in IR region.

• **Advantages :-**

-> Semiconductor lasers have high efficiency.
-> Semiconductor laser construction is very simple.
-> They are economical and has low power consumption.
-> They are small in size which makes them good choice for many applications.

• **Disadvantages :-**

-> Due to relatively low power consumption, these lasers are not suited to many typical laser applications.
-> Beam divergence is much greater from 125 to 400 milli radians.
-> Semiconductor laser is greatly dependent on temperature. The temperature affects the output of laser.

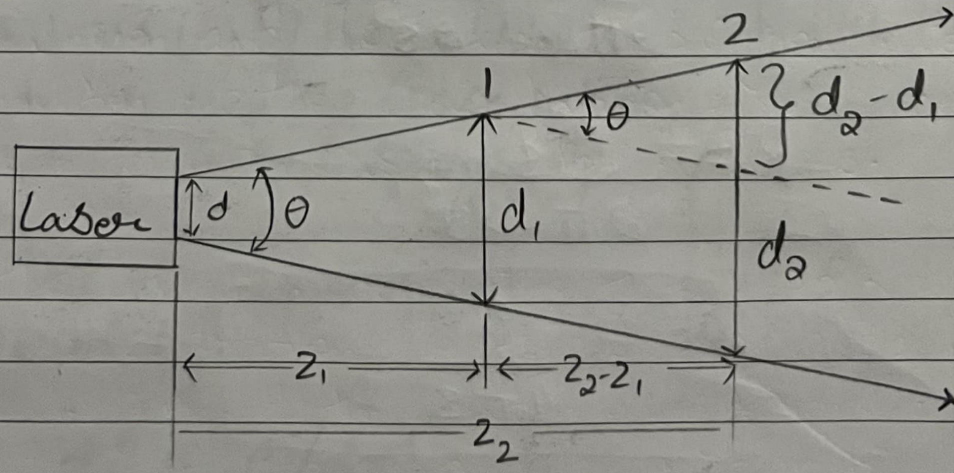
- **Applications :-**

→ They are used in optical fiber communication to provide high frequency waves for modulating the low frequency signal.
→ They are used as a laser pointer.
→ They are used for storing data on CD or DVD.
→ They are used as a pumping source in solid-state laser.

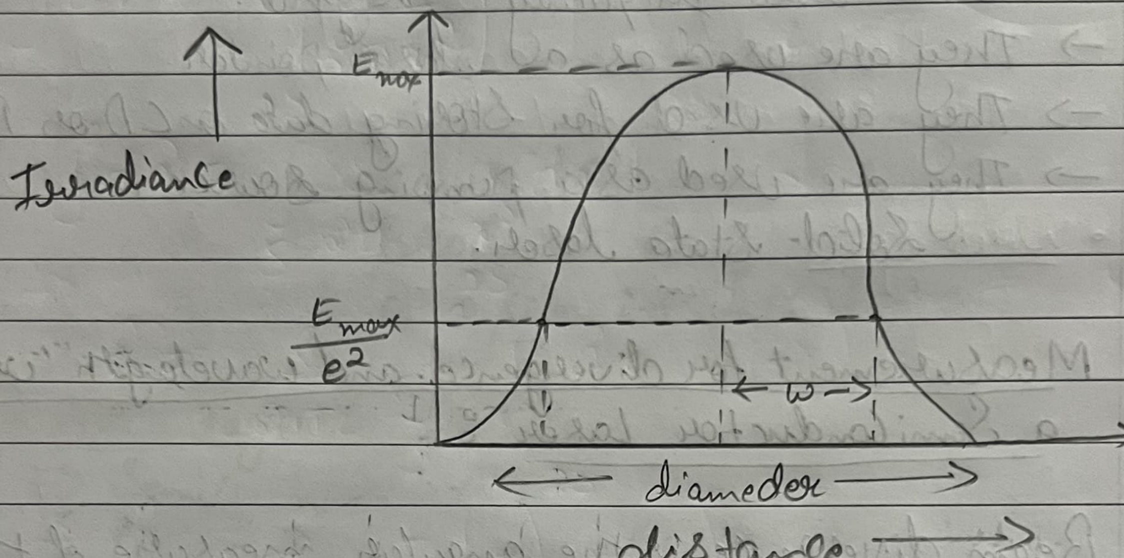
Measurement for divergence and wavelength using a Semiconductor Laser :-

Beam divergence is the angular measure of the increase in the radius or diameter with distance from the optical aperture as the beam emerges.

The divergence of a laser beam can be calculated if the beam diameter d_1 and d_2 at two separate distances are known. Let z_1 and z_2 are the distances along the laser axis, from the end of the laser to points 1 and 2.



$$\boxed{\theta = \frac{d_2 - d_1}{z_2 - z_1}}$$ divergence

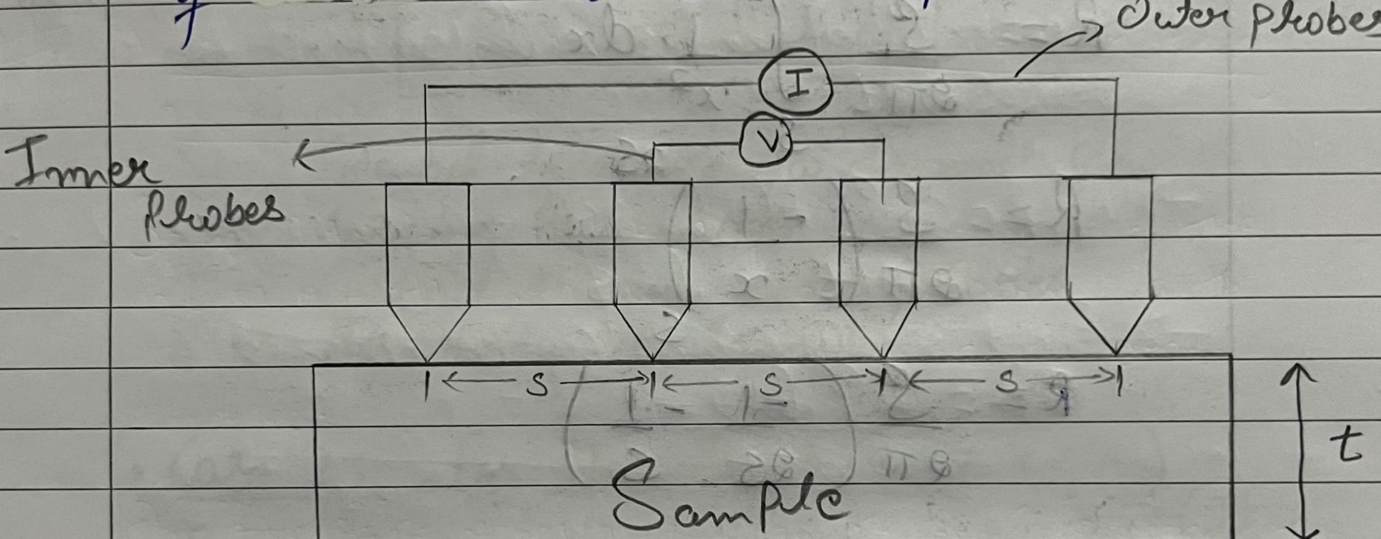


$$\boxed{\theta = \frac{\lambda}{\pi w_0}}$$ wavelength

$\theta \longrightarrow$ divergence
$\lambda \longrightarrow$ wavelength
$w_0 \longrightarrow$ beam waist

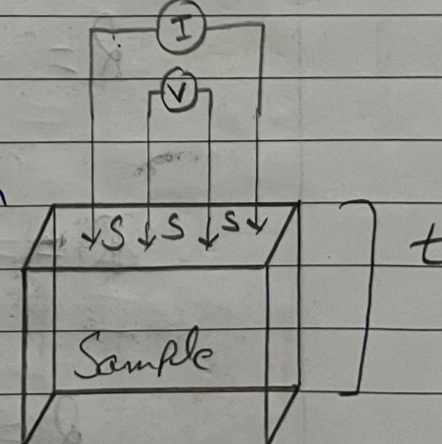
Four Point Probe Method :-

The four point probe contains four thin collinearly placed tungsten wires probes which are made to contact the sample under test. Current I is made to flow b/w the outer probes, Voltage V is measured b/w the two inner probes. It is a simple apparatus for measuring the resistivity of Semiconductor Samples.



• Case 1:- For Bulk Sample:- ($t >> s$)

Consider a bulk material where the thickness (t) of the material is much higher than the space between the probes. Current spheres are formed.



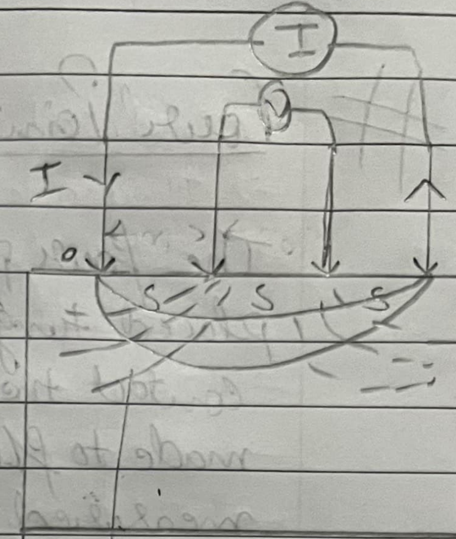
differential resistance can be measured by:-

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

$$dR = \rho \frac{dx}{A}$$

hemisphere

$$\int dR = \int \rho \left(\frac{dx}{2\pi x^2} \right)$$



Current spheres

$$\int dR = \int_{s}^{2s} \frac{\rho}{2\pi} \cdot \frac{1}{x^2} \, dx$$

$$R = \frac{\rho}{2\pi} \int_{s}^{2s} \frac{1}{x^2} \, dx$$

$$R = \frac{\rho}{2\pi} \left(-\frac{1}{x} \right)_{s}^{2s}$$

$$R = \frac{-\rho}{2\pi} \left(\frac{1}{2s} - \frac{1}{s} \right)$$

$$R = \frac{-\rho}{2\pi} \left(\frac{s - 2s}{2s^2} \right)$$

$$R = \frac{\rho \cancel{s}}{2\pi \cdot 2\cancel{s^2}^{1}}$$

$$R = \frac{\rho}{4\pi s}$$

due to Superposition of Current at the outer two probes:-

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

$$\frac{V}{2I} = \frac{\rho}{4\pi s}$$

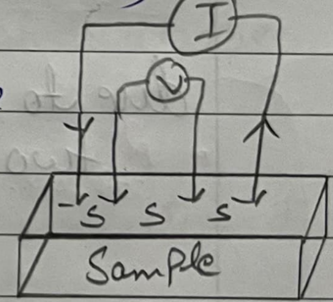
→ Constant

$$\boxed{\rho = 2\pi s \left(\frac{V}{I}\right)}$$

V → Potential difference b/w two inner probes
s → spacing b/w probes
I → Current through outer probes
ρ → Resistivity of sample

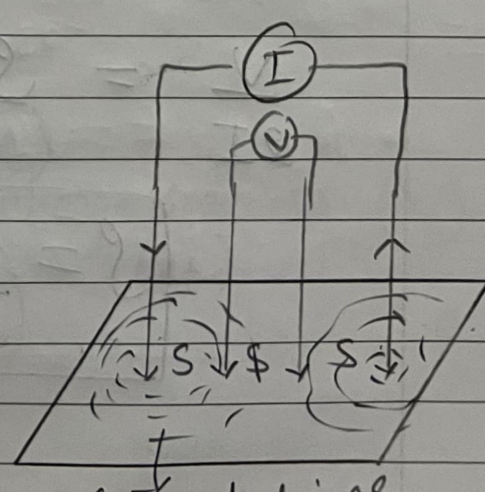
- <u>Case 2:-</u> For Thin Sheet :- $(t \ll s)$

Consider a thin sheet material where the thickness(t) of the material is much smaller than the space b/w the probes. Current rings are formed.



$$dR = \rho \frac{dx}{A}$$

$$\int dR = \int \rho \frac{dx}{2\pi x t}$$



Current rings

$$\int dR = \int_{s}^{2s} \frac{\rho}{2\pi t} \cdot \frac{1}{x} dx$$

$$\int dR = \frac{\rho}{2\pi t} \int_{s}^{2s} \frac{1}{x} dx$$

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

$$R = \frac{\rho}{2\pi t} \left(\ln(2s) - \ln(s) \right)$$

$$R = \frac{\rho}{2\pi t} \left(\ln \frac{2\cancel{s}}{\cancel{s}} \right)$$

$$R = \frac{\rho \ln 2}{2\pi t}$$

due to superposition of current on outer two probes.

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

$$\frac{V}{2I} = \frac{\rho \ln 2}{2\pi t} \rightarrow \text{Constant}$$

$$\boxed{\rho = \frac{\pi t}{\ln 2} \left(\frac{V}{I} \right)} = 4.53 t \left(\frac{V}{I} \right)$$

Van der Pauw Method :-

The Van der Pauw Method is a technique commonly used to measure the resistivity and Hall Coefficient of a Sample.

This method involves applying current and measuring voltage using four small contact on the circumference of a flat, arbitrarily Shaped Sample of uniform thickness. Four very Small contacts should be made on the periphery of the Sample Surface.

- **Conditions :-**

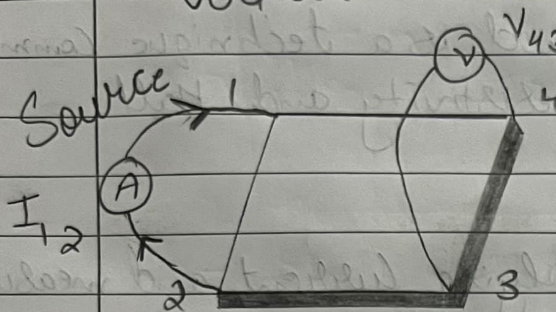
-> The Sample must have a flat shape of uniform thickness.
-> The Sample must not have any isolated hole.
-> All four Contacts must be located at the edges of the Sample.
-> Sample must be homogenous.
-> Sample thickness must be much less than the width and legth of the Sample.

- **Calculations :-**

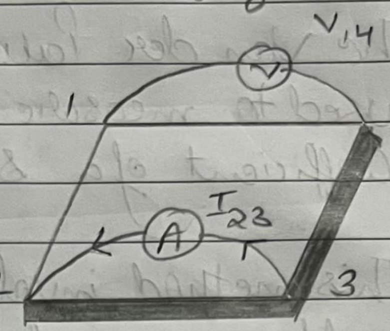
-> Resistivity (ρ)
-> Doping type (n or p type)
-> Carrier density of majority charge carriers (n_e)
-> Mobility of charge carriers. (μ)

- **Methodalogy :-**

Vertical



Horizontal



-> The Contacts are named Counter Clockwise.
-> Same bath of wire should be used for all leads.

-> Apply current I_{12} and measure voltage V_{43}.

-> Eight measurements can be obtained! -

Horizontal

- $R_{12,43} = \dfrac{V_{43}}{I_{12}}$
- $R_{34,21} = \dfrac{V_{21}}{I_{34}}$
- $R_{32,41} = \dfrac{V_{41}}{I_{32}}$
- $R_{41,32} = \dfrac{V_{32}}{I_{41}}$
- $R_{23,14} = \dfrac{V_{14}}{I_{23}}$
- $R_{14,23} = \dfrac{V_{23}}{I_{14}}$
- $R_{43,12} = \dfrac{V_{12}}{I_{43}}$
- $R_{21,34} = \dfrac{V_{34}}{I_{21}}$

Vertical

$$R_{vertical}\ (R_v) = \frac{R_{12,43} + R_{34,21} + R_{21,34} + R_{43,12}}{4}$$

$$R_{Horizontal}\ (R_H) = \frac{R_{23,14} + R_{41,32} + R_{32,41} + R_{14,23}}{4}$$

$$R_V = R_H = R$$

<u>Van der Pauw formula :-</u> $R_S \rightarrow$ Sheet Resistance

$$e^{\frac{-\pi R_V}{R_S}} + e^{\frac{-\pi R_H}{R_S}} = 1$$

$$e^{\frac{-\pi R}{R_S}} + e^{\frac{-\pi R}{R_S}} = 1$$

$$2e^{\frac{-\pi R}{R_S}} = 1$$

$$e^{\frac{-\pi R}{R_S}} = \frac{1}{2}$$

taking $\log_e$ on both sides

$$\log_e\left(e^{\frac{-\pi R}{R_S}}\right) = \log_e\left(\frac{1}{2}\right)$$

$$\frac{-\pi R}{R_S} = \log 1 - \log 2$$

$$\frac{\pi R}{R_S} = \log 2$$

$$\boxed{R_S = \frac{\pi R}{\log 2}} = 4.53\left(\frac{V}{I}\right)$$

_/_/_

$$R = \rho \frac{l}{A} = \rho \frac{l}{wt}$$

$A \rightarrow$ area of cross section
$w \rightarrow$ width
$t \rightarrow$ thickness
$R_s \rightarrow$ Sheet Resistance
$\rho \rightarrow$ Resistivity

$$R = \left(\frac{\rho}{t}\right)\left(\frac{l}{w}\right)$$

$$R = R_s \cdot \left(\frac{l}{w}\right)$$

$$\boxed{R_s = \frac{\rho}{t}} \Rightarrow \boxed{\rho = R_s \cdot t}$$

Sheet Resistance
↓
resistivity of a material divided by its thickness

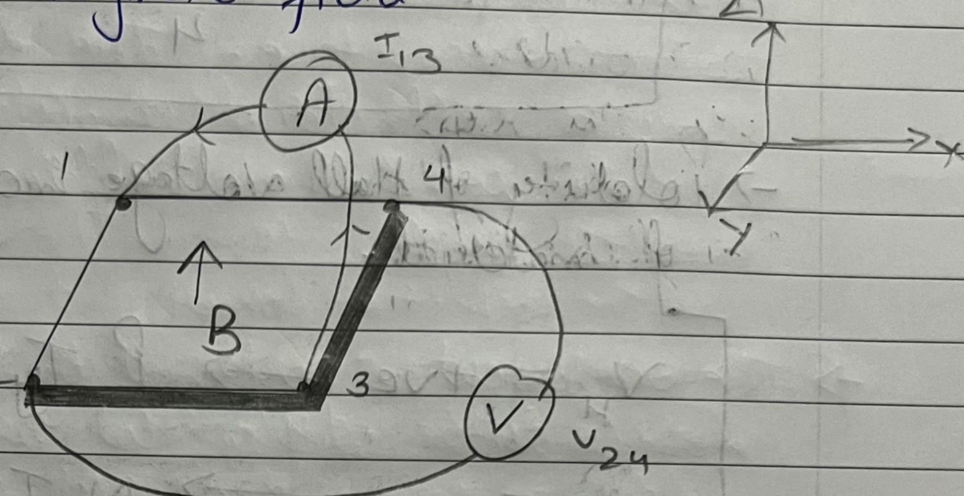
Now, $\rho = R_s \cdot t$

$$\rho = 4.53\left(\frac{V}{I}\right) \cdot t$$

$$\boxed{\rho = 4.53\, t\left(\frac{V}{I}\right)}$$ Resistivity

• **Hall Measurements :-** • **Doping Type :-**

-> Hall measurements are carried out in the presence of magnetic field.



I_{13} = DC current injected into contact 1 and taken out from contact 3

Similarly we can measure I_{31}, I_{24}, I_{42}

$V_{24}P$ = Hall voltage measured between contacts 2 and 4 with +ve magnetic field for I_{13}.

Positive

Similarly we have $V_{42}P$, $V_{13}P$, $V_{31}P$ and $V_{24}N$, $V_{42}N$, $V_{13}N$, $V_{31}N$ for negative magnetic field.

reverse direction of magnetic field

for Hall voltage

$V_{13} = V_{13P} - V_{13N}$

$V_{24} = V_{24P} - V_{24N}$

$V_{31} = V_{31P} - V_{31N}$

$V_{42} = V_{42P} - V_{42N}$

Overall Hall voltage (V_H) :-

$$\boxed{V_H = \frac{V_{13} + V_{31} + V_{24} + V_{42}}{4}}$$

→ Polarity of Hall voltage indicates the type of material.

$V_H = +ve \longrightarrow$ P Type

$V_H = -ve \longrightarrow$ N Type

- Sheet density :- (n_s)

no. of charge carriers in a certain volume multiplied by thickness.

$$n_s = \underbrace{n}_{\text{no. density}} \times \underbrace{t}_{\text{thickness}}$$

$$\boxed{n_s = \frac{IB}{q V_H}}$$

$I \rightarrow$ Current
$B \rightarrow$ Magnetic field
$q \rightarrow$ Charge of e^-
$V_H \rightarrow$ Hall voltage

• **Hall Mobility :-** Mobility of charge carriers

$\sigma = nq\mu \Rightarrow \mu = \frac{\sigma}{nq} = \frac{1}{\rho nq}$

charge of e^-

no. density

$\therefore \mu = \frac{1}{R_s \cdot t \cdot nq}$

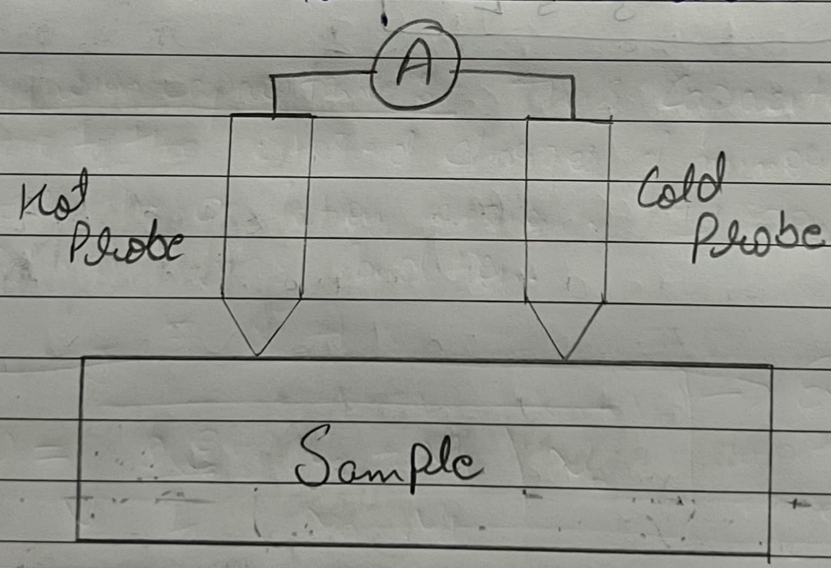
$[n \cdot t = n_s]$

$$\boxed{\mu = \frac{1}{R_s n_s q}}$$

Hot Probe Method :-

A Hot probe method is a method of quickly determining whether a Semiconductor Sample is n type or p type. The Sample is probed using a voltmeter or ammeter and a Heat Source, Such as Soldering iron, is placed on one of the leads.

-> The experiment is performed by contacting a Semiconductor with a Hot probe such as heated Soldering iron and a Cold probe. Both probes are wired to a Sensitive Current meter.

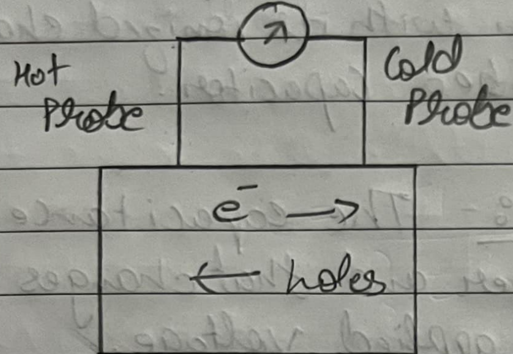


-> The heat Source will cause charge carriers (e^- in n type, holes in p type) to move away from the lead.

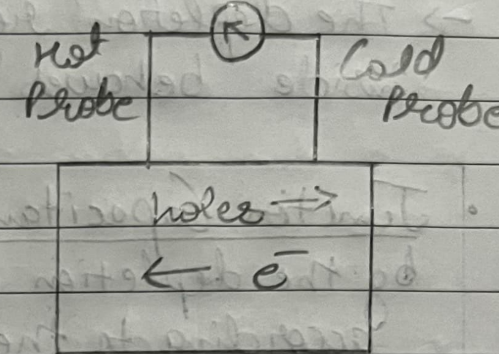
-> The heat from the probe creates an increased number of higher energy carriers which then diffuse away from the Contact point.

-> This diffusion of charge carriers causes a Current flow.

→ If the carriers are negative (electrons), the current flow will be in same direction and if the carriers are positive (holes), the current will be in opposite direction.



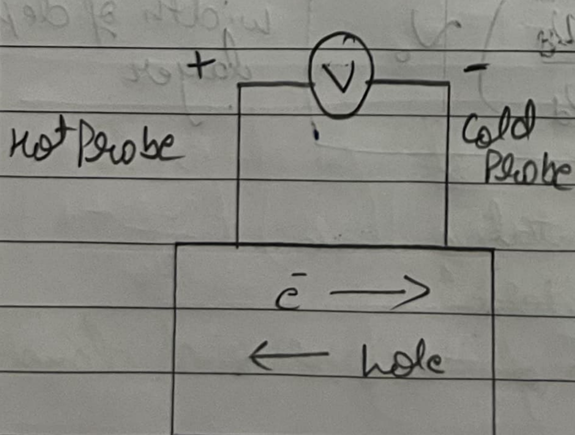
N-Type



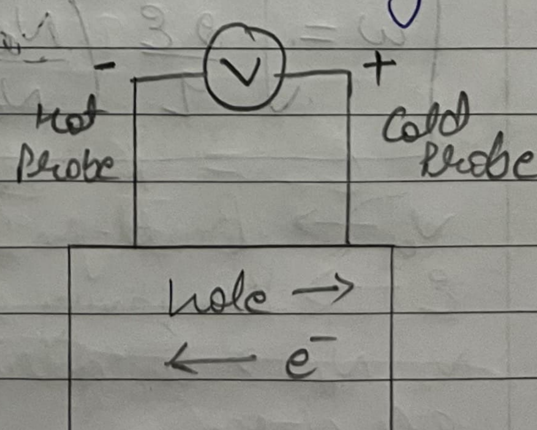
P-Type

→ If the hot side is positive w.r.t cold side, the sample is N type as the majority carriers i.e electrons have moved to cold side leaving the hot side positive.

→ If the hot side is negative, the sample is P type as the majority carriers i.e holes have moved to cold side, leaving the hot side negative.



N-type



P-type

Capacitance - Voltage Measurement :-

→ It is a method for measurement of junction capacitance of semiconductor junctions.
→ The depletion region with its ionized charges inside behaves like a capacitor.

- **Junction Capacitance :-** The capacitance formed by the depletion layer and that changes according to the applied voltage.
  It is also called Depletion layer capacitance or Transition capacitance. This dominates in Reverse bias condition.

- **Diffusion Capacitance :-** This capacitance occurs due to the stored charges of minority carriers near the depletion region. It dominates in forward bias condition.

$$\boxed{w = \sqrt{\frac{2\varepsilon}{q}\left(\frac{N_a + N_d}{N_a \cdot N_d}\right) V_0}}$$

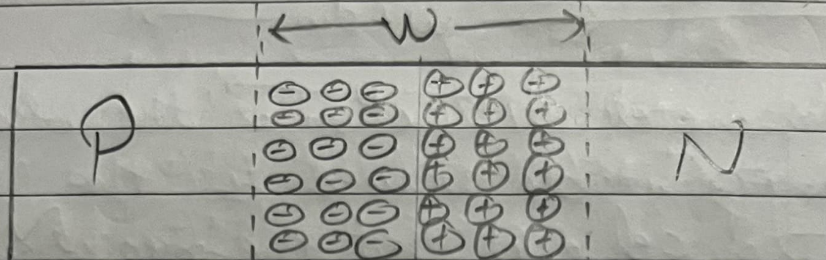
→ Expression for width of depletion layer

V_0 → Built-in potential
ε → Permitivity of material
N_a, N_d → Concentration of acceptor and donor
q → charge
w → width

→ no external voltage

- Case 1 :- At Equilibrium

→ width of depletion layer



Junction Capacitance at equilibrium $C_{J_0} = \dfrac{\varepsilon A}{W}$

$A \rightarrow$ area
$W \rightarrow$ width
$\varepsilon \rightarrow$ Permitivity

we know,

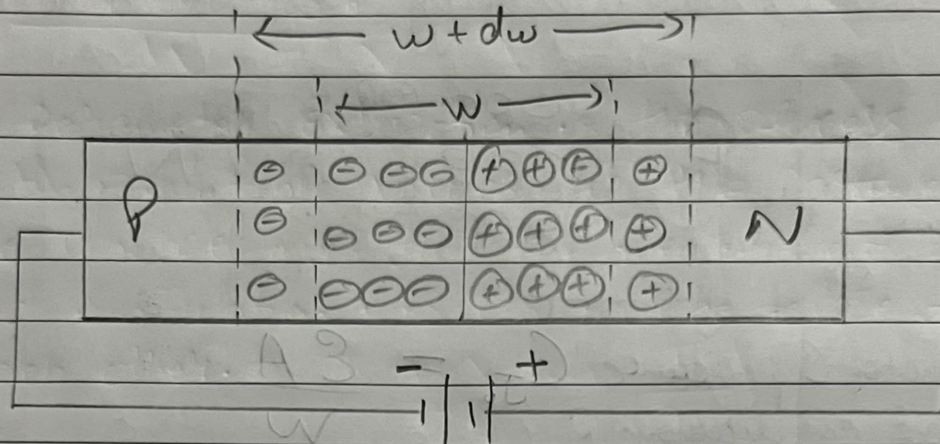
$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{N_a + N_d}{N_a \cdot N_d}\right) V_0}$$

$$C_{J_0} = \frac{\varepsilon A}{\sqrt{\frac{2\varepsilon}{q}\left(\frac{N_a + N_d}{N_a \cdot N_d}\right) V_0}}$$

$$\boxed{C_{J_0} = \frac{A}{2}\sqrt{2q\,\varepsilon\left(\frac{N_a \cdot N_d}{N_a + N_d}\right)\left(\frac{1}{V_0}\right)}} \quad — (1)$$

Junction Capacitance at zero bias Condition

• Case 2 :- Reverse bias



for reverse bias,

$$w = \sqrt{\frac{2\varepsilon}{q}\left(\frac{N_a + N_d}{N_a \cdot N_d}\right)(V_R + V_0)}$$

$V_R \rightarrow$ reverse Voltage

$$C_J = \frac{\varepsilon A}{w}$$

$$C_J = \frac{\varepsilon A}{\sqrt{\frac{2\varepsilon}{q}\left(\frac{N_a + N_d}{N_a \cdot N_d}\right)(V_R + V_0)}}$$

$$\boxed{C_J = \frac{A}{2}\sqrt{2q\varepsilon\left(\frac{N_a \cdot N_d}{N_a + N_d}\right)\left(\frac{1}{V_0}\right)\left(\frac{1}{\frac{V_R}{V_0}+1}\right)}}$$

$$\boxed{C_J = \frac{C_{J0}}{\sqrt{\frac{V_R}{V_0}+1}}}$$

If applied voltage (V_R) is very high as compared to built in voltage (V_0)

$\therefore V_R >> V_0$

we can neglect V_0

$$C_J = \frac{A}{2}\sqrt{2q\,\varepsilon\left(\frac{N_a \cdot N_d}{N_a + N_d}\right)\left(\frac{1}{V_R}\right)}$$

Assuming $\frac{A}{2}\sqrt{2q\,\varepsilon\left(\frac{N_a \cdot N_d}{N_a + N_d}\right)}$ to be constant (K)

$$\Rightarrow C_J = K\left(\frac{1}{\sqrt{V_R}}\right)$$

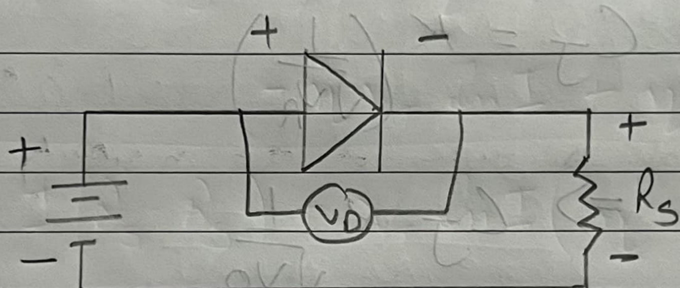
$$\Rightarrow C_J \propto \frac{1}{\sqrt{V_R}}$$

i.e. Junction capacitance decreases with the increase in reverse voltage.

Parameter Extraction from diode I-V Characteristics :-

The parameter extraction is the process of finding suitable values for the parameters of the model such that the measurement results and simulation results will be close to each other.

Let us consider a simple forward bias PN junction diode



By KVL,

$$V - V_D - IR_S = 0$$

$$\therefore \quad V_D = V - IR_S$$

The I-V characteristics can be described by the equation:-

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

$I_0 \rightarrow$ Saturation Current

$V_T \rightarrow$ Thermal voltage $= \frac{K_B T}{q}$

$\eta \rightarrow$ Ideality factor

$V - IR_S = V_D$ → diode voltage

Ideality factor describes how slope of real diode differ from ideal diode

The factor $e^{\left(\frac{V-IR_s}{\eta V_T}\right)}$ is very large as Compared to 1.

$$\therefore\ I = I_o\, e^{\left(\frac{V-IR_s}{\eta V_T}\right)}$$

$$\Rightarrow \frac{I}{I_o} = e^{\left(\frac{V-IR_s}{\eta V_T}\right)}$$

taking log on both sides

$$\ln\left(\frac{I}{I_o}\right) = \ln e^{\left(\frac{V-IR_s}{\eta V_T}\right)}$$

$$\ln\left(\frac{I}{I_o}\right) = \frac{V-IR_s}{\eta V_T}$$

$$V - IR_s = \eta V_T \ln\left(\frac{I}{I_o}\right)$$

$$\Rightarrow \boxed{V = IR_s + \eta V_T \ln\left(\frac{I}{I_o}\right)} \quad -\ 1$$

A similar equation as eq 1 can be written as:-

$$V' = IR_s' + \eta' V_T \ln\left(\frac{I}{I_o'}\right) \quad -\ 2$$

where V', I_o', R_s' and η' are arbitary values assumed from eq (1) and (2), we have

$$\Delta V = V' - V$$

$$\therefore \Delta V = \left[I R_s' + \eta' V_T \ln\left(\frac{I}{I_0'}\right) \right] - \left[I R_s + \eta V_T \ln\left(\frac{I}{I_0}\right) \right]$$

$$\Delta V = I(R_s' - R_s) + \eta' V_T \ln I - \eta' V_T \ln I_0' - \eta V_T \ln I + \eta V_T \ln I_0$$

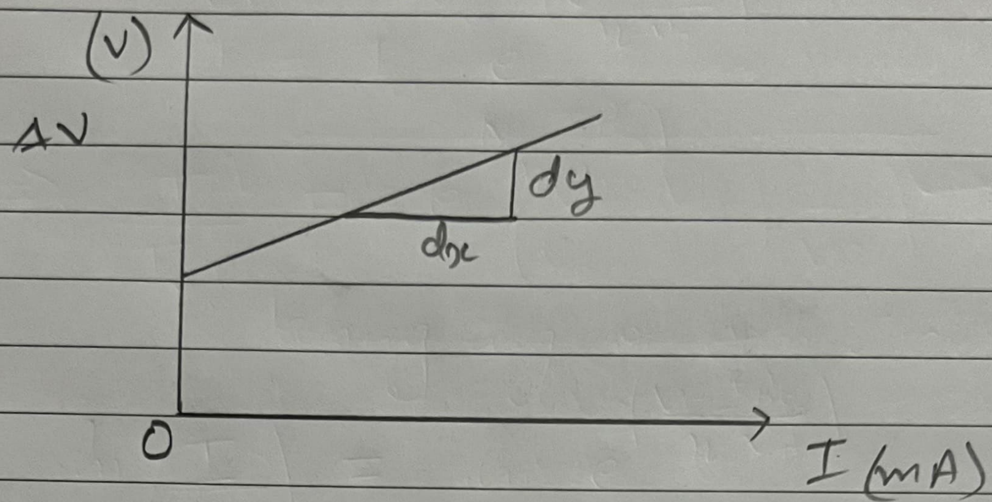
$$\boxed{\Delta V = I(R_s' - R_s) + V_T \ln I (\eta' - \eta) + V_T (\eta \ln I_0 - \eta' \ln I_0')} \quad (3)$$

where $\eta = \eta'$ in the above eq, the curve $\Delta V = f(I)$ becomes a straight line

i.e. $\Delta V = I(R_s' - R_s) + \eta V_T (\ln I_0 - \ln I_0')$

$$\boxed{\Delta V = I(R_s' - R_s) + \eta V_T \ln\left(\frac{I_0}{I_0'}\right)} \quad (4)$$

The eq (4) is the standard equation of straight line. $y = mx + c$



→ Slope can be determined from the graph as $\frac{dy}{dx}$

Let $a = \frac{dy}{dx}$ (Slope)

So, $R_s' - R_s = a$

$$\boxed{R_s = R_s' - a} \quad — (5)$$

→ We can obtain zero ordinate at $y = f(0)$ $(I = 0)$

Let zero ordinate $= b$

$\therefore \quad b = \eta V_T \ln\left(\frac{I_o}{I_o'}\right)$

$$\boxed{\therefore I_o = I_o' e^{\frac{b}{\eta V_T}}} \quad — (6)$$