UNIT – 4 (Measurements)

4.1   Introduction:

- ✓ Semiconductor electronics plays vital role in every aspect of life. Semiconductor materials is basis of modern electronic inducstry and it plays important role in the foundation of electronic circuitry with componants such as integrated circuits, diodes, solar cells and transistors.

- ✓ Therefore, precious measurement of electrical and optical properties of given semiconductor is an important step for fabrication of semiconductor device.

- ✓ The efficiency of an opto-electronic device depands on how charge carriers moves inside semiconducting material.

- ✓ The semiconductor electrical properties such as electrical resistivity, mobility, the charge carrier concentration, etc. allows us to characterize electrical properties of semiconductor.

- ✓ The electrical characterization of semiconductor is helpful to improve functionality of device.

- ✓ In this chapter we will also give brief overview about UV-Visible spectroscopy, which give information about transmission, absorption and energy band gap of given semiconductor.

4.2   Four – Probe Method

- ✓ Any type of material will have some amount of resistance (R), and by using the equation of ohm's law we can measure the resistance of any materials.

- ✓ There are few techniques to measure the value of resistance for any type of materials.
    1) Two Probe Method
    2) Four Probe Method

❖ **Two Probe Method:**
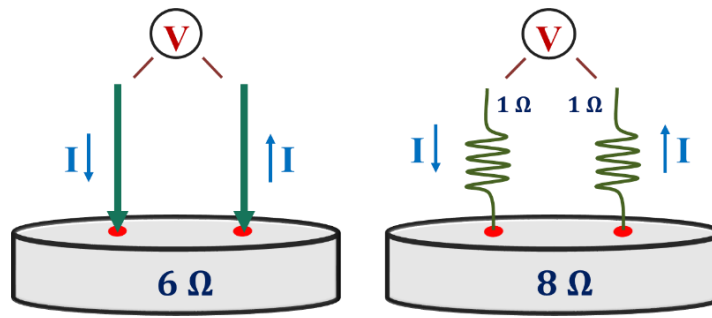
✓ The major problem in such method is error due to contact resistance of measuring leads.

✓ The above method cannot be used for materials having random shapes.

✓ For some type of materials soldering the test leads would be difficult.

✓ In case of semiconductors, the heating of samples due to soldering results in injection of impurities into the materials thereby affecting intrinsic electrical resistivity.

✓ In case of semiconductors, contacts between metallic probes and semiconducting sample are not Ohmic in nature (rather they are of Schottky nature) works as barrier.

❖ **Four – Probe Method:**

✓ Four-probe method, also known as four terminal sensing (4T sensing) or 4-wire sensing is an electrical impedance measuring technique, that uses separate pairs of current carrying and voltage sensing electrodes to make more accurate measurements.

✓ It is used to measure the sheet resistance of either a bulk or a thin film specimen.

✓ It uses a set of four probes, distance between each probe is 's'.

✓ A current source is connected between the outer two probes and a voltmeter is connected between the inner two probes.

✓ To measure the resistivity of the sample, a constant current I goes through the two outer probes and voltage drop between the inner two probes is measured.

✓ A very high impedance voltmeter is used, so current does not flow through the voltmeter, hence the contact resistance are eliminated.

- ✓ Differential resistance can be measure as:

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

- ✓ dR is the resistance between two points with the distance dx.

- ✓ A is the area that current goes through.

- ✓ ρ is the resistivity of the sample.

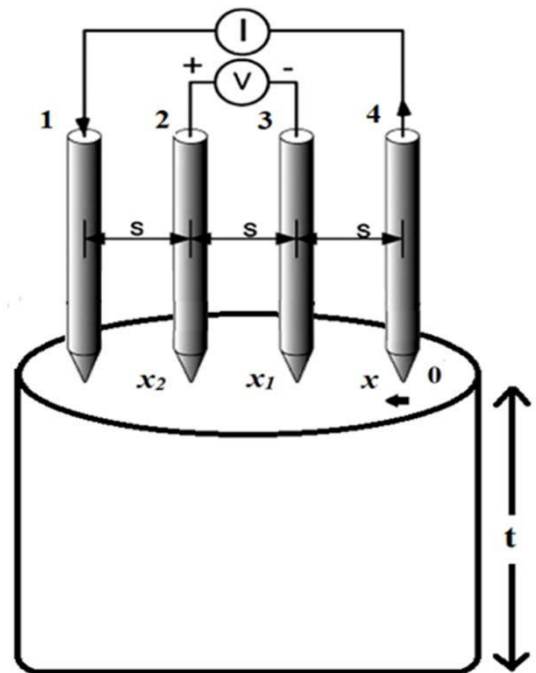- ❖ **Case: 1 Bulk material (when s << t):**

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

- ✓ Integrating both the sides,

$$= \int_{x_1}^{x_2} \rho \left(\frac{dx}{A} R \right)$$

$$R = \int_{x_1}^{x_2} \rho \left(\frac{dx}{2 \pi x^2} \right)$$

- ✓ Area of half hemispherical shell = $2 \pi x^2$.

Explanation:

- ✓ Current is injected through the outer probes it travels outward from the point of contact through bulk area.

$$\therefore R = \frac{\rho}{2\pi} \int_{x_1}^{x_2} \frac{1}{x^2} dx$$

$$\therefore R = \frac{\rho}{2\pi} \left[-\frac{1}{x} \right]_{s}^{2s}$$

$$\therefore R = \frac{\rho}{2\pi} \left[-\frac{1}{2s} + \frac{1}{s} \right]$$

$$\therefore R = \frac{\rho}{2\pi} \left[\frac{1}{2s} \right]$$

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

✓ Due to super position of current, at the outer two probes, we have

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

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

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

✓ Where, V = potential difference between inner probes

✓ I = current through outer probes

✓ S = spacing between probes

✓ ρ = Resistivity of sample

❖ **Case: 2 For thin sheet (when t << s):**

✓ For a very thin sample, we get current rings instead of hemispheres. i.e., current travels in short cylindrical shell of equipotential.

✓ So the area will be the area of the cylinder i.e., A = 2πxt.

$$dR = \rho \left(\frac{dx}{A} \right) = \rho \left(\frac{dx}{2\pi xt} \right)$$
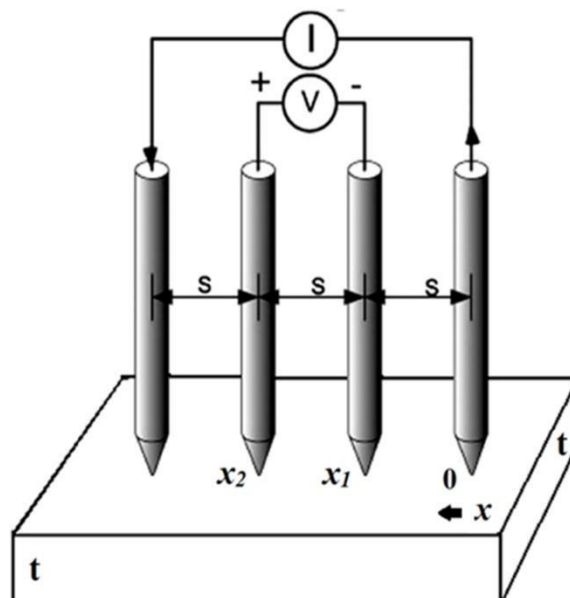
✓ Integrating both sides,

$$R = \int_{x_1}^{x_2} \rho \left(\frac{dx}{2\pi xt} \right)$$

$$R = \int_{x_1}^{x_2} \rho \left(\frac{dx}{2\pi xt} \right)$$

$$\therefore R = \frac{\rho}{2\pi t} \int_{x_1}^{x_2} \frac{1}{x} dx$$

$$\therefore R = \frac{\rho}{2\pi t} [\ln(x)]^{2s} [\ln 2]$$

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

✓ Due to super position of current, at the outer two probes, we have

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

✓ By Comparing above two equation we get,

$$\frac{V}{2I} = \frac{\rho}{2\pi t} [\ln 2] \frac{V}{}$$

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

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

✓ Above expression gives the value of resistivity for thin film.

4.3   Vander Pauw measurement

✓ The van der Pauw method involves applying a current and measuring voltage using four small contacts on the circumference of a flat, arbitrarily shaped sample of uniform thickness.

✓ This method is particularly useful for measuring very small samples because geometric spacing of the contacts is unimportant. Effects due to a sample's size, which is the approximate probe spacing, are irrelevant.

Irregular   Bridge   Square
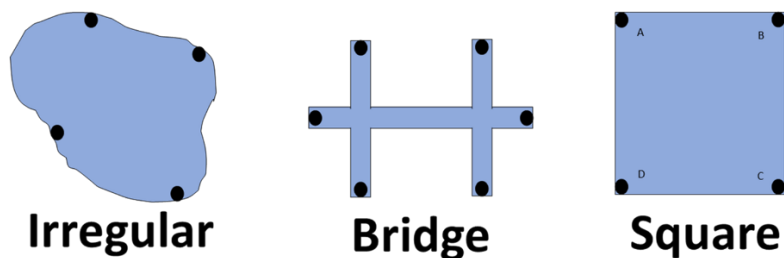
✓ From the measurement made, the following properties of a material can be calculated.

1) Resistivity of the material

2) Doping type

3) Carrier density of majority charge carriers

4) Mobility of charges carriers.

✓ The basic requirements of the method are as under:

1. All the contacts should be at the periphery of the sample.
2. Size of the contacts should be negligibly small as compared to that of the sample.
3. All the contacts should be Ohmic.
4. Sample should be very thin as compared to its area.
5. Surface of the sample should be singly connected i.e. the sample should be free from steps and discontinuities.
6. Sample should be flat so that the sample surface and contacts lie in the sample plane.
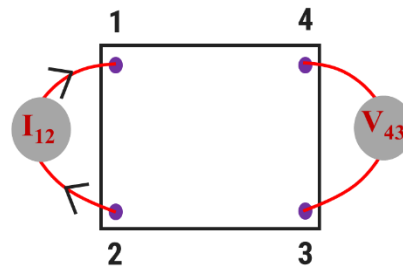
Resistance Measurement:

(1)

$$R_{1243} = \frac{V_{43}}{I_{12}}$$

$$R_{2134} = \frac{V_{34}}{I_{21}}$$

$$R_{4312} = \frac{V_{12}}{I_{43}}$$

$$R_{3421} = \frac{V_{21}}{I_{34}}$$

Vertical Resistance Measurement

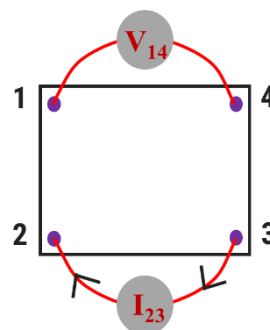$$R_{vertical} = \frac{R_{1243} + R_{2134} + R_{4312} + R_{3421}}{4}$$

(2)

$$R_{2314} = \frac{V_{14}}{I_{23}}$$

$$R_{3241} = \frac{V_{41}}{I_{32}}$$

$$R_{1423} = \frac{V_{23}}{I_{14}}$$

$$R_{4132} = \frac{V_{32}}{I_{41}}$$

Horizontal Resistance Measurement

$$R_{horizontal} = \frac{R_{2314} + R_{3241} + R_{1423} + R_{4132}}{4}$$

✓ The Vander Pauw formula becomes:

$$e^{\frac{-\pi R_{vertical}}{R_s}} + e^{\frac{-\pi R_{horizontal}}{R_s}} = 1$$

$$R_{vertical} = R_{horizontal} = R$$

$$e^{\frac{-\pi R}{R_s}} + e^{\frac{-\pi R}{R_s}} = 1$$
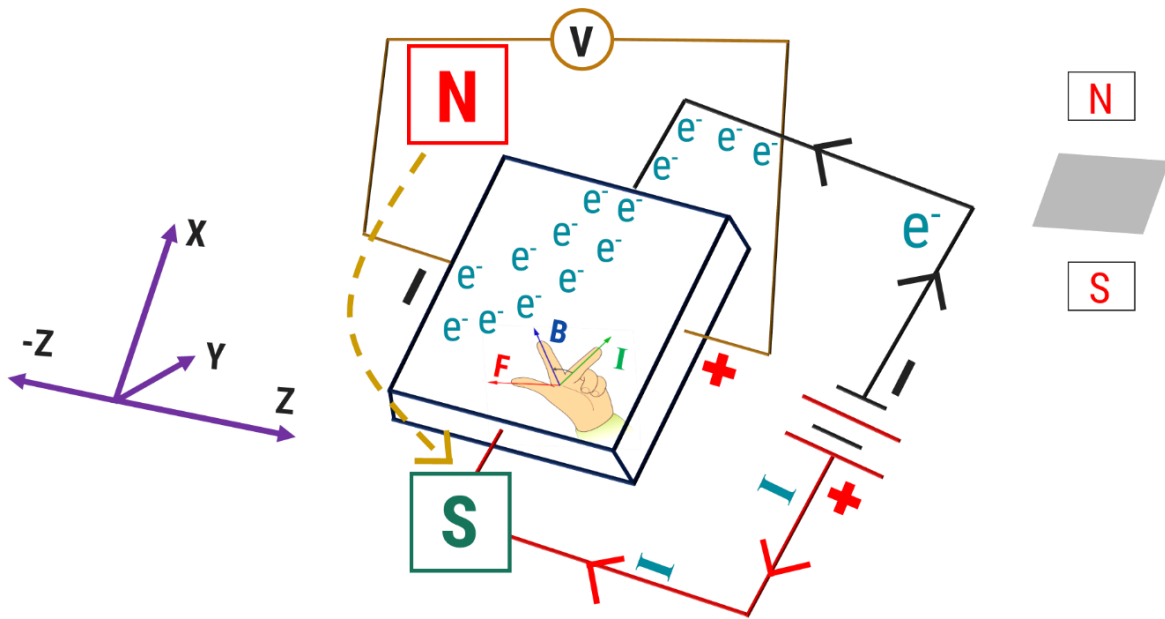
$$2\, e^{\frac{-\pi R}{R_s}} = 1$$

$$\frac{\pi R}{R_s} = \ln 2$$

$$\pi R = \frac{\ln 2\, R_s =}{}$$

$$\rho = R_s\, d$$

4.4 Hall effect:

- **Hall Effect:** If a sample of conductor or semiconductor carrying current I is placed in a transverse magnetic field B, an electric field E induced in a direction perpendicular to both current and magnetic field. This phenomena is known as Hall effect and generated voltage is known as Hall voltage V_H.

- In order to derive the equation of Hall mobility first we will derive the equation of Hall coefficient.

- Magnetic field vector 'B' is applied on this sample along y-axis. Now if a current 'I' is passed through the sample in the direction of x-axis, charge carriers (in this case we assume electrons) will drift with drift velocity 'v_d' in the opposite direction '-z'. Magnetic force 'F_B' acts on each drifting electron, pushing it toward the left edge of the sample.

$$F_B = - e\,(v \times B) = - B\,e\,v\,\sin(90°) = - B\,e\,v \quad F_B = - B\,e\,v \;\dots\dots\dots (1)$$

- The Lorentz force is exerted on electrons in the negative –Z direction and causes a negative charge to accumulate at the left edge of the sample. Moreover, the right edge of the sample becomes positively charged due to loss of electrons. Therefore, a potential difference causes a field E_H in negative –Z direction.

- In the equilibrium condition,

$E_H = B \, v \ldots \ldots \ldots (2)$

- ✓ The current density is given by,

$J = n \, e \, v \ldots \ldots \ldots (3)$

- ✓ Where n is number of carrier concentration, comparing equation (2) & (3),

$$E_H = \frac{B \, J_x}{ne} \ldots \ldots \ldots (4)$$

- ✓ Hall effect is explained by Hall coefficient,

$E_H = R_H \, B \, J_x \ldots \ldots \ldots (5)$

$\text{where,} \ R_H = \dfrac{1}{ne}$

- ✓ As the electric field in n-type semiconductor is established in negative –z direction value of Hall coefficient becomes.

$$R_H = -\frac{E}{B \, J_x} = -\frac{1}{n \, e} \ldots \ldots (6)$$

- ✓ Value of Hall coefficient (R_H) is negative for n-type semiconductor.

- ✓ In case of p-type semiconductor current is due to majority charge carriers holes, in that case,

$$R_H = \frac{E}{B \, J_x} = \frac{1}{p \, e} \ldots \ldots (7)$$

- ✓ In case of p – type semiconductor value of Hall coefficient (R_H) is positive.

❖ **Determination of value of Hall coefficient:**

- ✓ Hall voltage generates Hall electric field (E_H),

$$E_H = \frac{V_H}{t}$$

$V_H = E_H \, t \ldots \ldots \ldots (8)$

- ✓ Substituting value of E_H from equation (5)

$V_H = R_H \, B \, J_x \, t$

- ✓ If w is the width of the semiconductor, then its cross-section area (A) will be wt and the current density,

$$J_x = \frac{I}{wt}$$

$$V_H = \frac{R_H \, B \, t \, I}{wt}$$

$$V_H = \frac{R_H \, B \, I}{w}$$

Therefore, $R_H = \dfrac{V_H \, w}{B \, I}$ ... ... (9)

- ✓ The value of hall voltage is opposite for n-type and p-type semiconductor.

- ❖ **Determination of Hall mobility:**

- ✓ In case of n-type semiconductor value of conductivity is given by,

$$\sigma_e = n_e \, e \, \mu_e$$

Therefore, $\mu_e = \dfrac{\sigma_e \, n_e}{e}$

- ✓ We know for the n-type semiconductor,

$$R_H = - \frac{1}{n \, e}$$

Hence, $\mu_e = - \sigma_e \, R_H$ ... ... (10)

- ✓ Similarly, for p-type semiconductor

$$R_H = \frac{1}{n \, e}$$

$\mu_h = \sigma_h \, R_H$ ... ... (11)

- ✓ The Hall mobility μ_h is defined as the product of Hall coefficient (R_H) and conductivity (σ).

Q.1 A n-type semiconductor material has Hall coefficient and the conductivity 1.15×10^{-3} m³/C and 115 $(\Omega \cdot m)^{-1}$ respectively. Calculate charge carrier density and electron mobility.

Ans. $R_H = 1.15 \times 10^{-3}$ m³/C

$\sigma_e = 115 \, (\Omega \cdot m)^{-1}$

$n_e = ?$

$\mu_e = ?$

$\mu_e = \sigma_e \times R_H$

$\mu_e = 115 \times 1.15 \times 10^{-3}$

$\mu_e = 0.13 \, m^2/V \cdot sec$

$= \dfrac{\sigma_e \, \mu_e}{n_e \, e}$

$= \dfrac{\sigma_e \, n_e}{\mu_e \, e}$

$n_e = \dfrac{115}{0.13 \times 1.6 \times 10^{-19}}$

$\mu_e = 5.53 \times 10^{21}$

Q.2 A semiconductor having the Hall coefficient 3.75×10^{-4} m³/C. The resistivity of the sample is 7.21×10^{-3} $\Omega \cdot m$. Calculate the mobility and density of charge carriers.

Ans. $R_H = 3.75 \times 10^{-4}$ m³/C

$\rho = 7.21 \times 10^{-4}$ $\Omega \cdot m$

$n = ?$

$\mu = ?$

$R_H = \dfrac{1}{n e}$

$$n = \frac{1}{R_H\, e}$$

$$n = \frac{1}{3.75 \times 10^{-4} \times \ 1.6 \times 10^{-19}}$$

$$n = 3.75 \times 10^{22} \text{ charge carrier/m}^3$$

Mobility of charge carrier

$$\mu = \sigma\, R_H$$

$$\mu = \frac{R_H}{\rho}$$

$$\mu = \frac{5.75 \times 10^{-4}}{7.21 \times 10^{-3}}$$

$$\mu = 0.0520 \ \text{m}^2\text{V}^{-2}\text{s}^{-1}$$

4.5 Deep level Transient Spectroscopy (DLTS):

- ✓ 'Deep level', here is used to denote the crystal defects or traps in mainly p-n junction and Schottky diodes. 'Transient Spectroscopy' means a powerful set of techniques, used to identify electrons and structural properties of short-lived excited states.

- ✓ Deep Level Transient Spectroscopy 'DLTS' was initially introduced by D. V. Lang in the year 1974.

- ✓ It is an efficient method to observe and identify deep level impurities in the semiconductors.

- ✓ It is a capacitance transient thermal scanning technique which uses the capacitance of P-N junction to monitor and find out the defects.

- ✓ DLTS helps to distinguish between the majority and minority carrier traps.
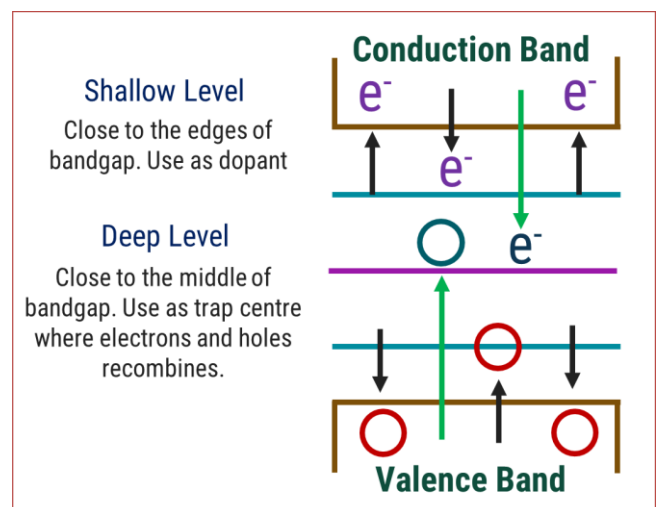
- ✓ It also gives the concentrations, energy and capture rates of both types of traps.

- ✓ When the voltage across a p-n junction is charged, there is a corresponding change in the depletion layer width. This change in width causes a change in no. of free charge carriers on both sides, resulting in the change in junction capacitance.

- ✓ Consider a p-n junction with the deep level (i.e. defects) present, having its energy as E_T.

- ✓ In steady state, there is no net flow of charge carriers across the trap.

- ✓ The total density of deep level state N_T can be given by,

$$N_T = \frac{e_p\, n_T}{e_n + e_p}$$
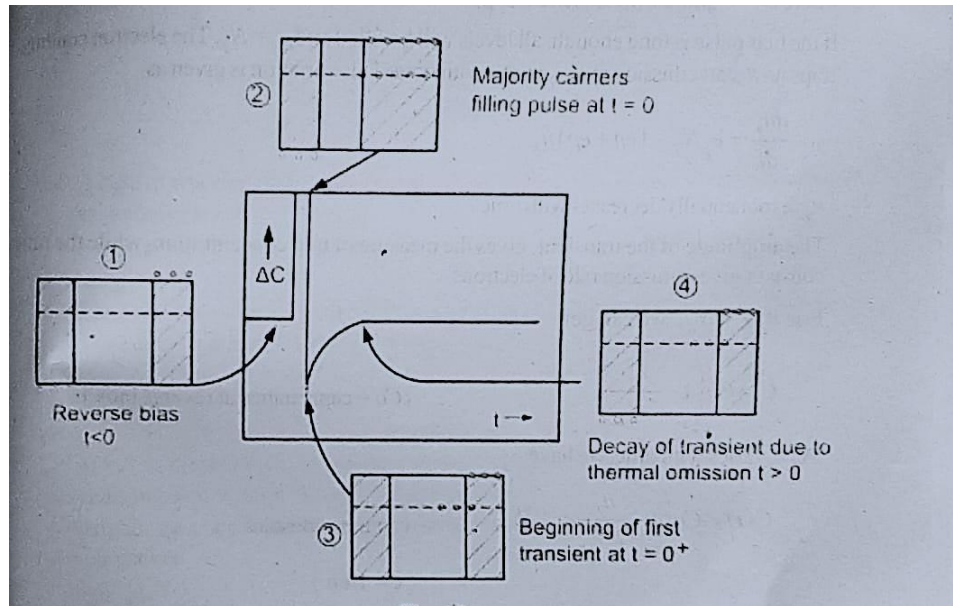
Where, e_p = hole emission rate

e_n = electron emission rate

n_T = density of filled traps under steady states

- ✓ If the system is distributed from steady state, there is a change in no. of $'n_T'$. Leading to a change in total charge in depletion layer, thus changing the capacitance.

❖ **Basic Analysis:**

- ✓ Let us consider, an asymmetric diode i.e. the one in which one side is heavily doped as compared to the other.

- ✓ We are assuming a diode in which p-side is heavily doped as compared to n-side, so the width of depletion layer is more on the n-side. I.e. space charge region (SCR) is more on n-side.

- ✓ The following figure, shows the four processes of generating capacitance transient, due to majority carrier levels.

Majority carriers
filling pulse at t = 0

② ΔC

① Reverse bias
t<0

④ Decay of transient due to
thermal omission t > 0

③ Beginning of first
transient at t = 0⁺

- ✓ From figure, Process (1) shows that traps in the space charge region are empty because no free carriers are available for capture$(t < 0)$.

- ✓ Process (2) Reverse bias is reduced and the electrons are captured in traps$(t = 0)$.

- ✓ Process (3) When the reverse bias is restored, the capacitance drops to a minimum value as electrons are trapped$(t = 0^+)$.

- ✓ Process (4) Decay of transient due to thermal emission of trapped electrons$(t > 0)$.

- ✓ Suppose we have a reverse bias V_R applied to the sample and decrease it to zero for a short time. The electrons will flow into what was previously the depletion region and the levels in this volume will capture electrons.

- ✓ So we get,

$$\frac{dn_T}{dt} = c_n \left(N_T - n_T \right)$$

- ✓ Where, c_n = capture time const. of $e^- \rho$.

- ✓ If the bias pulse is long enough, all levels will be filled and $N_T = n_T$. The electron emitting traps now start emission and n_T varies with time. The variation is given as,

$$\frac{dn_T}{dt} = e_p N_T - (e_n + e_p) n_T$$

Where, n_T = exponentially decrease with time.

- The amplitude of the transient, gives the measure of trap concentration, while the time constant gives emission rate of electrons.

- For, $n_T \ll N_d$, we can get

$$C = C_0 \left(1 - \frac{n_T}{2N_D}\right)$$

Where, C_0 = capacitance at reverse bios.

- As n_i varies with time, we have

$$C(t) = C_0 \left(1 - \frac{n_T}{2N_D} e^{-t/\tau}\right)$$

$$\text{Where, } \tau = \text{Time constant} = \frac{1}{e_n}$$

- Thus the emission rates and trap concentrations can be determined from the changes in capacitance of p-n junction. These changes are in the form of capacitance transients.

4.6   Hot Point Probe measurement:

- A hot point probe is a method of determining quickly weather a semiconductor sample is n-type or p-type.

- Basic principle lying behind the hot probe method is Seebeck Effect.
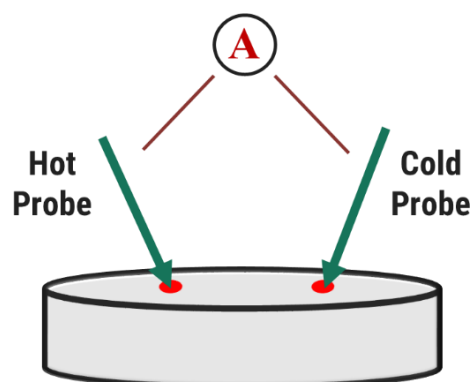
- A micro ammeter is attached to the sample and a heat source, such as soldering iron is placed on one of the leads.

- The heat source will cause the charge carriers to move to the cold probe.

- ✓ This diffusion of charge carriers causes a current flow.

- ✓ The net current will depend on the majority charge carriers i.e. electrons for n-type semiconductor and holes for p-type semiconductor.

- ✓ If the carriers are positive, the current flow will be in same direction and if the charge carriers are negative, the current will flow in opposite direction.
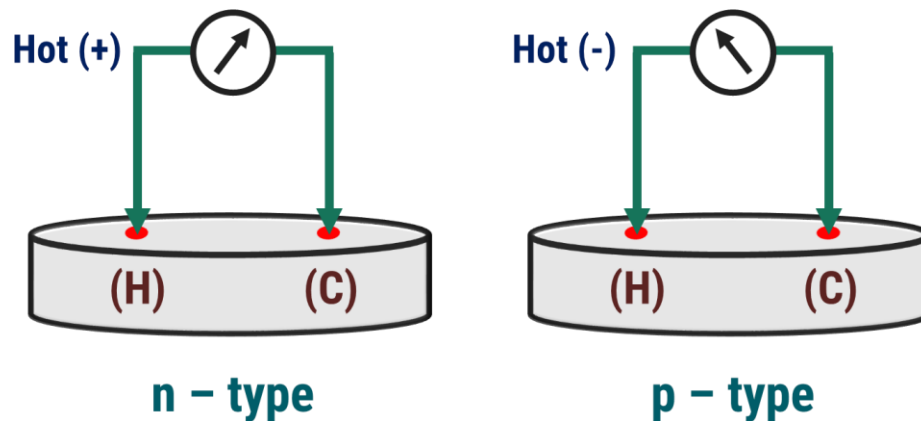
- ✓ If the hot side is positive with respect to the cold side, the sample is n-type (as the majority charge carriers i.e. electrons move to cold side, leaving the hot side positive).

- ✓ If the hot side is negative, the sample is P-type.

- ✓ The sample type can be determined by the direction of deflection in current meter.

4.7   Capacitance Voltage Measurements:

- ✓ Capacitance–voltage profiling (or C–V profiling, sometimes CV profiling) is a technique for characterizing semiconductor materials and devices.

- ✓ Hillibrand and Gold first described the use of capacitance -voltage (C–V) methods to determine the majority carrier concentration in semiconductors. C–V measurements are capable of yielding quantitative information about the diffusion potential and doping concentration in semiconductor materials.

- ✓ The technique employs p-n junctions, metal-semiconductor (MS) junctions (Schottky barriers), electrolyte-semiconductor junctions, metal-insulator-semiconductor (MIS) capacitors, and MIS field effect transistors (MISFETSs).

- ✓ The applied voltage is varied, and the capacitance is measured and plotted as a function of voltage.

- ✓ The technique uses a depletion region, a region which is empty of conducting electrons and holes, but may contain ionized donors and electrically active defects or traps.

- ✓ The depletion region with its ionized charges inside behaves like a capacitor. By varying the voltage applied to the junction it is possible to vary the depletion width.

- ✓ The dependence of the depletion width upon the applied voltage provides information on the semiconductor's internal characteristics, such as its doping profile and electrically active defect densities.

- ✓ Measurements may be done at DC, or using both DC and a small-signal AC signal (the conductance method), or using a large-signal transient voltage.

4.8   UV – Vis Spectroscopy:

- ✓ UV- Vis Spectroscopy is related to the interaction of light with matter.

- ✓ As light is absorbed by matter, the result is an increase in the energy content of the atoms or molecules.

- ✓ This method is used to measure the energy band gap of different materials, by measuring absorption spectrum.

- ✓ UV – Vis (λ) = 2000 – 8000 Å

- ✓ Bandgap refers to the energy difference between bottom of conduction band and top of valence band, through which electrons are able to jump from one band to another.

- ✓ The instrument used in UV-Vis spectroscopy is called UV-Vis spectro-photometer.

- ✓ It measure the intensity of light after passing through a sample (I), and compares it to the intensity of light before it passes through the sample (I_0).

- ✓ A light of wavelength (λ) and energy (hv) is made to pass through monochromator to get a parallel beam.
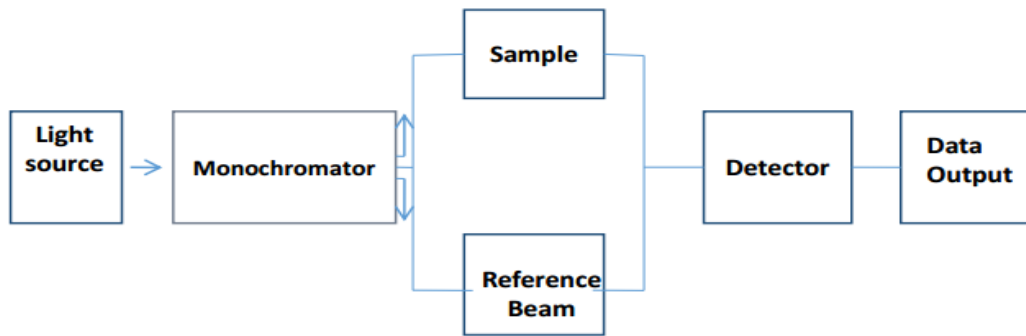
- ✓ It then passes through a beam splitter and is incident on two cells, a reference cell and a sample cell.

- ✓ The intensities of light from reference and sample cells is collected by the detector.

- ✓ The ration of intensities is called transmittance (T).

i.e. $T = \dfrac{I}{I_0}$

- ✓ The transmittance (T) is usually expressed in percentage (%T).

- ✓ If we plot %T w.r.t. to concentration of sample, we get an exponential decrease in transmittance, with an increase in concentration.

- ✓ Higher the concentration, more is the absorption so less is the value of I, through the sample cell.

concentration ---->
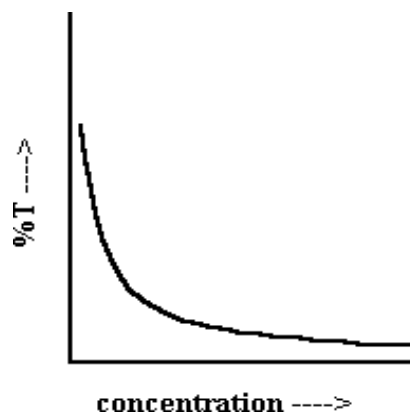
- ✓ As it is difficult to extract characteristics from the exponential relation, we define a relation absorption (A).

Absorption $(A) = \log\left(\dfrac{I_0}{I}\right)$

- ✓ The Tauc's relation is used to determine the bandgap (E_g) in semiconductor.

$$\alpha \, hv = A \, (hv - E_g)^n$$

$$\alpha = \frac{A \, (hv - E_g)^n}{hv}$$

✓ Rearranging above relation, we can have

$$(\alpha \, hv)^{\frac{1}{n}} = A^{\frac{1}{n}} \, hv - A^{\frac{1}{n}} \, E_g$$

Where, α = absorption coefficient and is given by $\alpha = \dfrac{\ln\left(\frac{1}{T}\right)}{x}$

$$T = \text{Transmittance} = \frac{I}{I_0}$$

✓ n = 1/2, 2, 3/2, and 3 for direct allowed, indirect allowed, direct forbidden, and indirect forbidden transitions respectively.

✓ Now, we can plot a graph of $(\alpha \, hv)^{1/n}$ along x-axis vs hv (along y axis), we will get slop as $A^{1/n}$ and y intercept as $A^{1/n} E_g$. Dividing y intercept by A^n we can estimate the band gap.