

#### 4.1 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 resistances are eliminated.
- Differential resistance can be measured 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

$\rho$  is the resistivity of sample

##### 4.1.1 Case 1 : Bulk material (when $s \ll t$ )

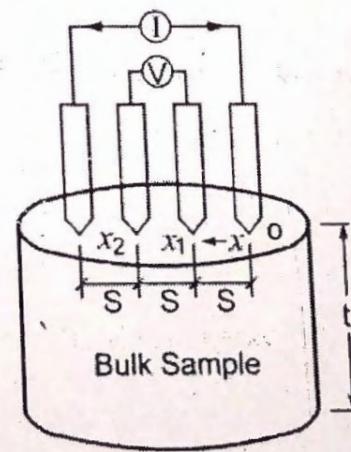


Fig. 1

We know,

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

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

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

**Explanation :**

Current is injected through the outer probes it travels outwards from the point of contact through concentric hemispherical shells of equipotential.

$2\pi x^2$  is the area of hemisphere.

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

$$\therefore R = \frac{\rho}{2\pi} \left( -\frac{1}{x} \right)_{x_1=s}^{x_2=2s}$$

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

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

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

...(1)

where  $s$  is the spacing between each probe.

Due to superposition of current, at the outer two probes, we have

$$R = \frac{V}{2I} \quad \dots(2)$$

Comparing (1) and (2)

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

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

where  $V$  = potential difference between inner probes  
 $I$  = current through outer probes  
 $s$  = spacing between probes  
 $\rho$  = Resistivity of sample

The above expression applies only to semi-infinite volume and not to thin films.

#### 4.1.2 Case (2) : For thin sheet ( $t \ll s$ )

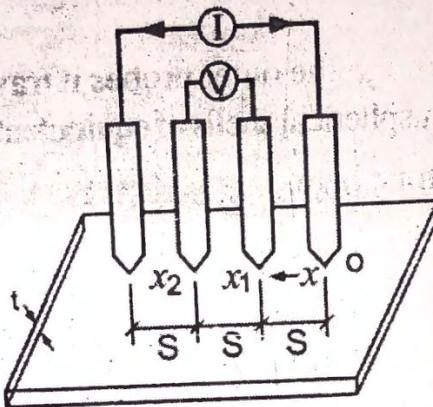


Fig. 2

- For a very thin sample, where  $t \ll s$ , 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 circumference times the thickness of sample.  
ie.  $A = 2\pi xt$

$$\text{So, } dR = \rho \left( \frac{dx}{A} \right) = \rho \left( \frac{dx}{2\pi xt} \right)$$

- On integrating, we get,

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

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

$$\therefore R = \frac{\rho}{2\pi t} [\ln(x)]_{x_1}^{x_2}$$

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

- Because of superposition of current on the outer two probes, we get ... (3)

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

comparing (3) and (4)

$$\frac{V}{2I} = \frac{\rho}{2\pi t} (\ln 2)$$

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

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

- Expression of resistivity for thin film is as above.

#### Advantages :

- 1) Very low resistance values can be measured by this method.
- 2) Accurate value of resistivity can be calculated as contact resistance associated with voltmeter is negligible due to very high impedance of voltmeter.
- 3) It eliminates measurement errors due to probe resistance

#### Applications :

- 1) Remote sensing area
- 2) Resistance thermometers
- 3) Characterization of fuel cell bipolar plates.

## 4.2 Vander Pauw measurement

- This method was first propounded by Leo J. Vander Pauw in 1958.
- It is a technique commonly used to measure the resistivity and hall coefficient of the sample.
- From the measurements 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 charge carriers
- The following conditions must be satisfied to use this technique
  - 1) Sample must have a flat shape of uniform thickness.
  - 2) Sample must not have isolated holes.

- 3) Sample must be homogenous.
- 4) All four contacts must be located at the edges of sample.
- 5) Sample thickness must be much less than the width and length of the sample.

- Four leads are connected to four ohmic contacts as shown below.

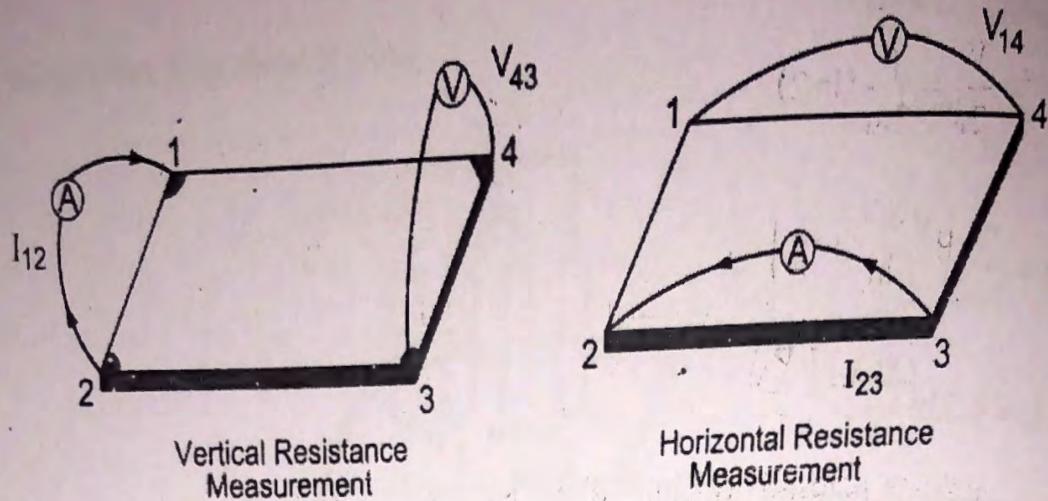


Fig. 3

- The contacts are named 1, 2, 3 and 4 counter clockwise.
- Same batch of wire should be used for all four leads (to reduce thermoelectric effect) and all four ohmic contacts should consist of the same material.
- We will define the following parameters.  
 $\rho$  = sample resistivity (in  $\Omega \text{ cm}$ )  
 $d$  = conducting layer thickness (in cm.)
- $I_{12}$  = positive dc current 'I' injected into contact 1 and taken out of contact 2.
- Similarly, we will define  $I_{23}, I_{34}, I_{41}, I_{21}, I_{14}, I_{43}, I_{32}$ . (in amp. 'A')
- $V_{12}$  = dc voltage measures between contacts 1 and 2 ( $V_1 - V_2$ ) without magnetic field ( $B = 0$ ). Similarly, we can define  
 $V_{21}, V_{43}, V_{34}, V_{14}, V_{41}, V_{23}, V_{32}$ . (in volts, V)

#### 4.2.1 Resistivity Measurements

- Apply current  $I_{21}$  and measure voltage  $V_{34}$ .
- Reverse the current  $I_{12}$  and measure  $V_{43}$
- Repeat for remaining six values of voltages ( $V_{41}, V_{14}, V_{23}, V_{32}, V_{12}, V_{21}$ )
- Eight measurements of voltage yield the following values of resistance.

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

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

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

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

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

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

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

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

- A further improvement in the accuracy of resistance values can be obtained by repeating resistance measurements after switching polarities of both the current source and voltmeters.
- The values of  $R_{vertical}$  and  $R_{horizontal}$  can still be calculated as the averages of the standard and reversed polarity measurement.
- Combining these methods with the reciprocal measurements from above leads to the following.

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

$$R_{horizontal} = \frac{R_{23,14} + R_{41,32} + R_{32,41} + R_{14,23}}{4}$$

- The Vander Pauw formula becomes

$$e^{-\pi R_{vertical}/Rs} + e^{-\pi R_{horizontal}/Rs} = 1$$

where,  $R_s$  = sheet resistance.

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

$$e^{-\pi R/Rs} + e^{-\pi R/Rs} = 1$$

$$2e^{-\pi R/Rs} = 1$$

$$\pi R / R_s = \ln 2$$

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

If conducting layer thickness 'd' is known, the bulk resistivity can be calculated as

$$\rho = R_s \cdot d$$

#### 4.2.2 Hall effect : (Edwin Hall in 1879)

The production of a potential difference across an electrical conductor when a magnetic field is applied in a direction perpendicular to that of the flow of current.

### Background :

- When a charged particle such as an electron is placed in a magnetic field, it experiences a Lorentz force proportional to the strength of the field and the velocity at which it is travelling through it.

$$F = qvB$$

$q$  = charge on particle

$v$  = Velocity, it is travelling at

$B$  = Strength of mag. field

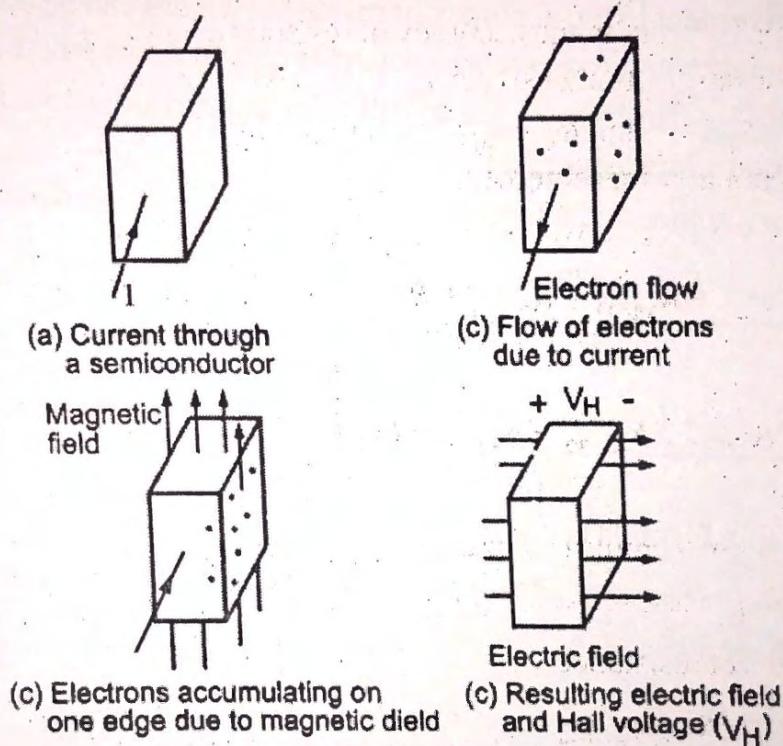


Fig. 4

- When current is applied to a semiconductor it results in steady flow of electrons through the material as shown in (a) and (b).
- The velocity, the electrons are travelling at, is given by

$$V = \frac{I}{nAq}$$

$n$  = electron density

$A$  = cross-sectional area

$q$  = charge

- If an external magnetic field is applied to the material, in a direction perpendicular to the

current flow, the resulting Lorentz force will cause the electrons to accumulate at one edge of the sample.

- So, the Lorentz force experienced by electrons is

$$F = \frac{IB}{nA}$$

- This accumulation will create an electric field across the material due to uneven distribution of charge, as shown in fig. (d).
- This in turn, leads to a potential difference across the material, called the Hall voltage ( $V_H$ ).
- The force on electrons due to electric field balances the Lorentz force.
- Strength of electric field is  $qE$ .

$$\text{ie. } E = \frac{IB}{qnA}$$

- The magnitude of Hall voltage  $V_H$  is the strength of electric field multiplied by width of material.

$$\text{ie. } V_H = wE$$

$$= \frac{wIB}{qnA}$$

$$\therefore V_H = \frac{IB}{qnt} \quad t = \text{thickness of material}$$

- Sheet density is defined as density of electrons multiplied by thickness, so hall voltage in terms of sheet density.

$$V_H = \frac{IB}{qns}$$

#### 4.2.3 Hall measurements :

- The hall measurement, carried out in presence of magnetic field, yields the sheet carrier density ' $n_s$ ' and bulk carrier density 'n' and 'p' (for n-type or p-type) if conducting layer thickness of sample is known.
- The hall voltage for thick or heavily doped samples can be very small. (as small as microvolts).
- The difficulty in obtaining accurate results is not merely the small value of Hall voltage, but the large offset voltage due to non-symmetric contact placement, sample shape.
- To control this problem, it is better to take two sets of hall measurements one for positive and one for negative

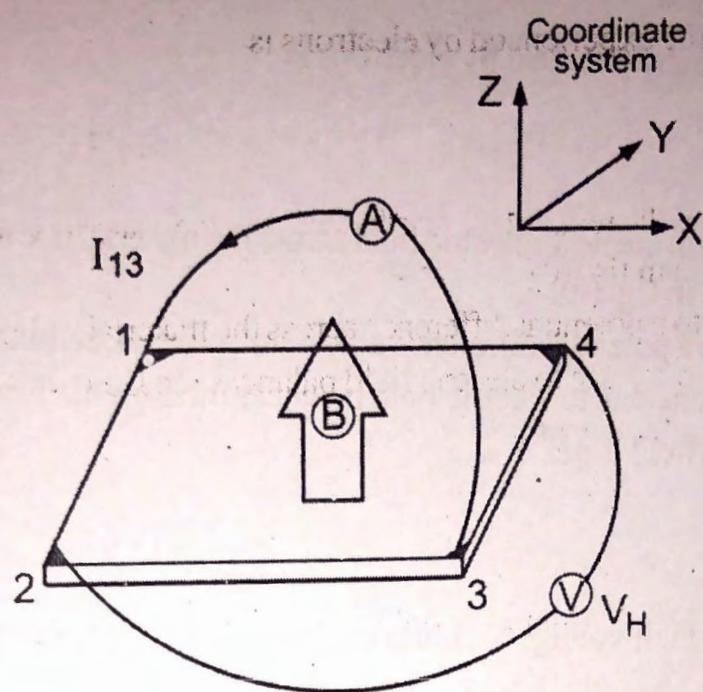


Fig. 5

- $I_{13}$  = DC current injected into lead 1 and taken out from lead 3.  
Similarly, we have  $I_{31}$ ,  $I_{24}$  and  $I_{42}$ .
- $B$  = Constant and uniform magnetic field intensity  
(Positive, when pointing to positive z-axis and negative, when pointing to negating z-axis.)
- $V_{24p}$  = Hall voltage measured between leads 2 and 4, with magnetic field positive for  $I_{13}$ .  
Similarly, we have  $V_{42p}$ ,  $V_{13p}$ ,  $V_{31p}$
- Also, we have  $V_{24N}$ ,  $V_{42N}$ ,  $V_{13N}$ ,  $V_{31N}$ , for magnetic field negative for  $I_{13}$  (ie. when B is reversed)

#### (a) Method :

- Apply a positive magnetic field B.
- Apply a current  $I_{13}$  to leads 1 and 3 and measure  $V_{24p}$
- Apply a current  $I_{31}$  to leads 3 and 1 and measure  $V_{42p}$ .
- Similarly, we can measure  $V_{13p}$  and  $V_{31p}$  for  $I_{42}$  and  $I_{24}$  respectively.
- Now, reverse the magnetic field and take above 4 voltage measurements again.
- The above eight measurements of Hall voltage  $V_{24p}$ ,  $V_{42p}$ ,  $V_{13p}$ ,  $V_{31p}$ ,  $V_{24N}$ ,  $V_{42N}$ ,  $V_{13N}$ ,  $V_{31N}$  determine the sample type (*p* or *n*) and the sheet carrier density ( $n_s$ ).

- Hall mobility can be determined from sheet density and sheet resistance, obtained in resistivity measurement.

### (b) Hall calculations:

- The difference of voltages for the positive and negative fields need to be worked out.

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

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

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

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

Overall hall voltage  $V_H$  is,

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

- The polarity of the hall voltage indicates the type of material.
- If the value is positive, material is p-type and if the value is negative, material is n-type.
- Sheet density can be calculated by Hall voltage as

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

- Hall mobility can also be defined as follows.

We know,  $\sigma = nq\mu$

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

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

But  $n \cdot t = n_s$

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

### Advantages

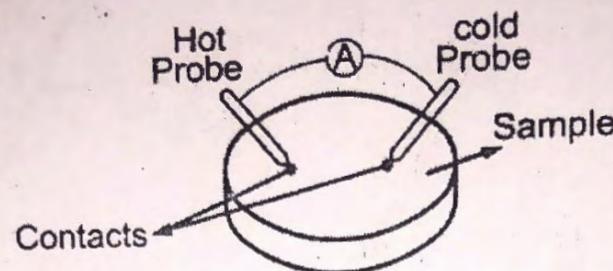
- 1) Only four contacts are required
- 2) No need to measure sample width or distance between contacts.

**Disadvantages :**

- 1) Measurements take about twice as long
- 2) Errors due to contact size and placement can be significant.

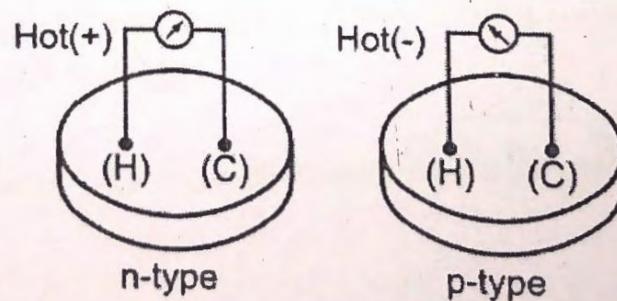
**4.3 Hot-point probe measurement :**

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



**Fig. 6**

- A micro ammeter is attached to the sample and a heat source, such as a 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 carriers i.e. electrons for n-type and holes for p-type.
- If the carriers are positive, the current flow will be in the same direction and if the charge carriers are negative, the current flow will be in opposite direction.



**Fig. 7**

- If the hot side is positive with respect to the cold side, the sample is n-type (as the majority carriers, ie. electrons move to cold side, leaving the hotside 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.

## 4.4 Capacitance Voltage Measurement

Capacitance Voltage Measurement is a method for measurement of junction capacitance of semiconductor junction.

- Also known as capacitance - voltage profiling, CVT is a method in which the applied voltage is varied and capacitance is measured and plotted as a function of voltage.
- The depletion region with 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 depletion width on the applied voltage, provides information on semiconductors internal characteristics like doping profile.
- It is widely used for PN junctions, metal-semiconductor junctions, MOSCAPs and MOSFETs.

### Basics of capacitance - voltage measurements.

- Basically two types of capacitances are associated with PN junctions.

#### a) Junction capacitance :

- The capacitance formed by the depletion region and which changes according to the applied voltage.
- It dominates in reverse bias condition.
- It is also known as depletion-layer capacitance or transition capacitance.

#### b) Diffusion capacitance

- The diffusion capacitance occurs due to the stored charges of minority carriers near the depletion region.
- It dominates in forward bias condition

- We will be discussing Junction capacitance in detail :

#### Case (i) At equilibrium

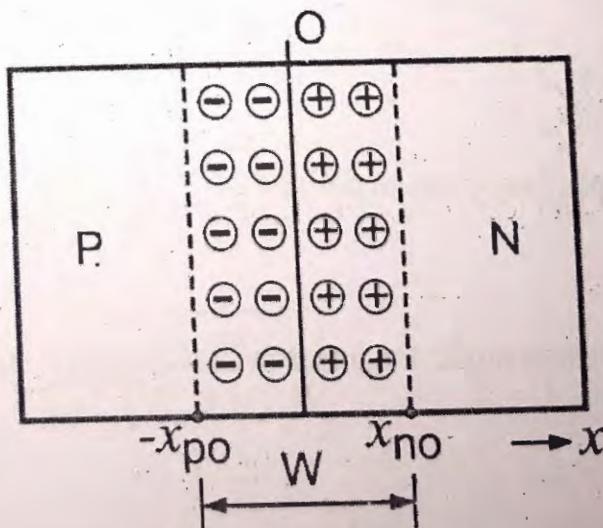


Fig. 8

- As shown in the figure, we can say that total charge on P-side of depletion layer is equal to the total charge of N-side.  
ie.  $|Q_-| = |Q_+|$

$$\therefore q \cdot N_a \cdot x_{po} = q \cdot N_d \cdot x_{no} \quad \dots(1)$$

$$\therefore \frac{x_{no}}{x_{po}} = \frac{N_a}{N_d} \quad \dots(2)$$

$N_a$  = acceptor atoms concentration

$N_d$  = donor atoms concentration

- From the figure, we can say that

$$W = x_{no} + x_{po}$$

By equation (2),

$$x_{no} = \frac{N_a}{N_d} \cdot x_{po}$$

$$\therefore W = x_{po} + \frac{N_a}{N_d} \cdot x_{po}$$

$$\therefore W = x_{po} \left( 1 + \frac{N_a}{N_d} \right)$$

$$\therefore x_{po} = W \left( \frac{N_d}{N_a + N_d} \right) \quad \dots(3)$$

Similarly,

$$\therefore x_{no} = W \left( \frac{N_d}{N_a + N_d} \right) \quad \dots(4)$$

- We know that capacitance can be defined as

$$C = \frac{\epsilon \cdot A}{d}$$

- In case of P-N junction diode, the junction capacitance, at equilibrium can be defined as

$$C_{J_0} = \frac{\epsilon \cdot A}{W}$$

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### Width of depletion layer at equilibrium

$$W = \sqrt{\frac{2\epsilon}{q} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) V_o}$$

where,  $V_o$  = Built-in potential

$\epsilon$  = Permittivity of material

$\epsilon$ , for Si = 11.7

$\epsilon$ , for Ge = 16

$$\epsilon_o = 8.85 \times 10^{-12} \text{ C}^2/\text{N}\cdot\text{m}^2$$

$$V_o = V_T \ln \left( \frac{N_a \cdot N_d}{n_i^2} \right)$$

$V_T$  = Thermal voltage

$$V_T = \frac{k_B T}{q} \quad (\text{Value at room temp.} = 26 \text{ mV})$$

Substituting the value of width of depletion layer,

We get,

$$C_{Jo} = \frac{\epsilon A}{\sqrt{\frac{2\epsilon}{q} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) V_o}}$$

$$\therefore C_{Jo} = \frac{\epsilon \cdot A}{\sqrt{\frac{2\epsilon}{q} \left( \frac{N_a + N_d}{N_a \cdot N_d} \right) V_o}}$$

$$\therefore C_{Jo} = A \sqrt{\frac{q\epsilon}{2} \left( \frac{N_a \cdot N_d}{N_a + N_d} \right) \frac{1}{V_o}}$$

$$\therefore C_{Jo} = \frac{A}{2} \sqrt{2q\epsilon \left( \frac{N_a \cdot N_d}{N_a + N_d} \right) \frac{1}{V_o}}$$

**Case (ii) : Reverse Bias**

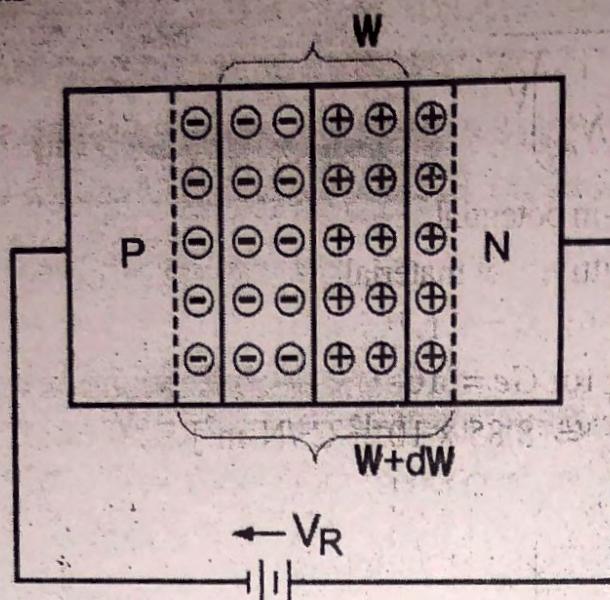


Fig. 9

- For reverse bias, the width of depletion region can be given as

$$W = \frac{2\epsilon}{q} \left( \frac{1}{N_a} + \frac{1}{N_d} \right) (V_R + V_o)$$

- Junction capacitance in reverse bias can be defined as

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

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

$$\therefore C_J = \frac{A}{2} \sqrt{2q\epsilon \left( \frac{N_a \cdot N_d}{N_a + N_d} \right) \left( \frac{1}{V_o} \right) \left( \frac{1}{V_R/V_o + 1} \right)}$$

$$\therefore C_J = \frac{C_{Jo}}{\sqrt{\frac{V_R}{V_o} + 1}}$$

- If the applied voltage ( $V_R$ ) is very high as compared to built in potential ( $V_o$ ),

$$\text{ie. } V_R \gg V_o$$

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

$$\text{ie. } C_J = K \cdot \sqrt{\frac{1}{V_R}}$$

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

$$C_J \propto V_R^{-\frac{1}{2}}$$

Junction capacitance decreases with the increase in reverse voltage.

#### \* Advantages :

- 1) It is simple technique, where not many equipments are required.
- 2) Measurements can be taken directly from the device.
- 3) It is a non-destructive method.

#### \* Disadvantages :

- 1) Doping profile can be extracted only in reverse bias. ie. when conductance is small.
- 2) It is an approximation method and works well for abrupt junctions.

### Abrupt junctions.

It is the one in which doping type changes over a very small distance, compared to the overall extent of depletion region.

### Linearly-graded junction

It is the one in which the impurity concentration does not change suddenly from donors to acceptors, but varies smoothly across the junction.

=> To find width of depletion layer

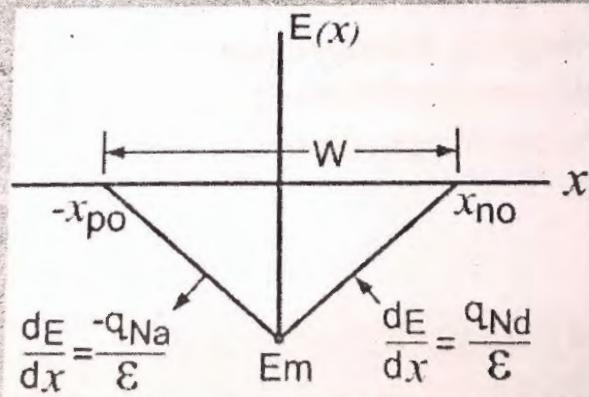


Fig. 10

From the figure, on the p-side of the junction.

$$E_m = \frac{q N_a}{\epsilon} x_{po} \quad \} \text{ From Gauss's Law}$$

on the n-side of junction,

$$E_m = \frac{q N_d}{\epsilon} x_{na} \quad } \text{From Gauss's Law}$$

The voltage drop across the junction

$$V_{pn} = - \int E(x) dx \quad \text{- Poisson's equation}$$

Voltage drop across the junction is the area under  $E(x)$  curve

- Since  $E(x)$  curve is a triangle, we have

$$V_o = \frac{1}{2} E_m \times W$$

$$\therefore V_o = \frac{1}{2} \left( \frac{q N_d x_n}{\epsilon} \right) W$$

$$= \frac{1}{2} \left( \frac{q N_d}{\epsilon} \right) \left( \frac{W}{1 + N_d / N_a} \right) W$$

$$\therefore V_o = \frac{q}{2\epsilon} W^2 \left( \frac{N_a \cdot N_d}{N_a + N_d} \right)$$

$$\therefore W = \frac{2\epsilon}{q} \left( \frac{N_a + N_d}{N_a \cdot N_d} \right) \cdot V_o$$

#### 4.5 Parameter extraction from Diode I-V.

Characteristics :

- The p-n junction I-V characteristics have been studied since many years.
- Parameters like barrier-height in Schottky diode, saturation current and series resistance in case of photovoltaic devices (like Solar cells) can be estimated.

The I-V characteristics can be described by the following equation for semiconductor devices.

$$I = I_o \left[ e^{\frac{V - IR_s}{\eta V_T}} - 1 \right] \quad \dots(1)$$

where,  $V_D = V - IR_s$  = Diode Voltage

$\eta$  = Ideality factor

$V_T$  = Thermal Voltage

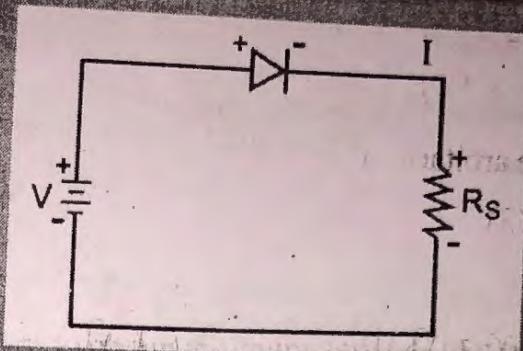


Fig. 11

By Kirchoff's voltage law

$$V - V_D - IR_s = 0$$

$$\therefore V_D = V - IR_s$$

$$\text{Also, } V_T = \frac{k_B T}{q}$$

Value at room temperature is 26 mV

- In the above equation, the factor  $e^{\frac{V - IR_s}{nV_T}}$  is large as compared to 1, so we ignore the factor '1'.

The above equation (1) can be written as

$$I = I_o e^{\left( \frac{V_D}{e^{nV_T}} \right)}$$

or

$$I = I_o \cdot e^{(V - IR_s / nV_T)}$$

$$\frac{I}{I_o} = e^{(V - IR_s / nV_T)}$$

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

Ideality factor ' $\eta$ ' indicates how far the slope of real diode, differs from ideal diode. It is 1 for ideal diodes and greater than 1, for real diodes.

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

- A similar equation can be written as

$$\therefore V' = IRs' + \eta' V_T \ln\left(\frac{I}{I_o'}\right) \quad \dots(3)$$

where,  $V'$ ,  $Rs'$ ,  $\eta'$ ,  $I_o'$  are arbitrary values assumed

From equation (2) and (3)

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

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

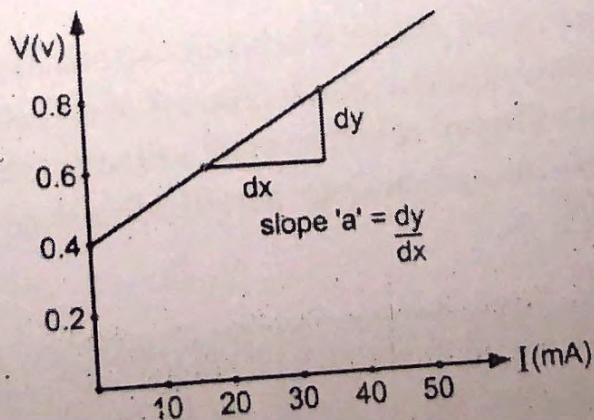
$$= I(Rs' - Rs) + \eta' V_T (\ln I - \ln I_o') - \eta V_T (\ln I - \ln I_o)$$

$$\therefore \Delta V = [I(Rs' - Rs) + (\eta' - \eta)V_T \ln I] + V_T (\eta \ln I_o - \eta' \ln I_o') \quad \dots(4)$$

- when  $\eta - \eta'$ , the curve  $\Delta V = f(I)$  becomes a straight line and we have

$$\Delta V = (R_s' - R_s)I + V_T \cdot \eta \cdot \ln\left(\frac{I_o}{I_o'}\right) \quad \dots(5)$$

- From the above results, we can elaborate a numerical process to extract the parameters  $Rs$ ,  $\eta$  and  $I_o$  of a diode from its characteristics  $V = f(I)$ .
- A theoretical characteristic with  $V' = f(I)$  is considered with arbitrary values  $Rs'$ ,  $\eta'$  &  $I_o'$ .
- Then we vary  $\eta'$  such that is almost close to  $\eta$ , so we can say that  $\Delta V$  is a linear function of current.
- The equation (5) is the equation of a straight line ( $y = mx + c$ ).



$$\text{Slope } 'a' = \frac{dy}{dx}$$

Fig. 12

- Slope 'a' can be found from the graph, along with its origin ordinate 'b' [at  $y = f(o)$ ].
- We can find,

$$R'_s - R_s = a \quad (\text{from slope})$$

$$\therefore \text{ie. } R_s = R'_s - a \quad \dots(6)$$

and  $I_o = I'_o e^{b/\eta V_T}$  (from origin ordinate 'b')

- The above equation leads to obtain the characteristics that fit exactly to the equation (2).

$$\text{ie. } V = IR_s + \eta V_T \ln\left(\frac{I}{I_o}\right)$$

#### 4.6 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 changed, 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 (ie. 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 states  $N_T$  can be given by

$$N_T = \frac{e_p \eta_T}{(e_n + e_p)} \quad e_p = \text{hole emission rate}$$

$e_n$  = electron emission rate

$\eta_T$  = density of filled traps under steady states.

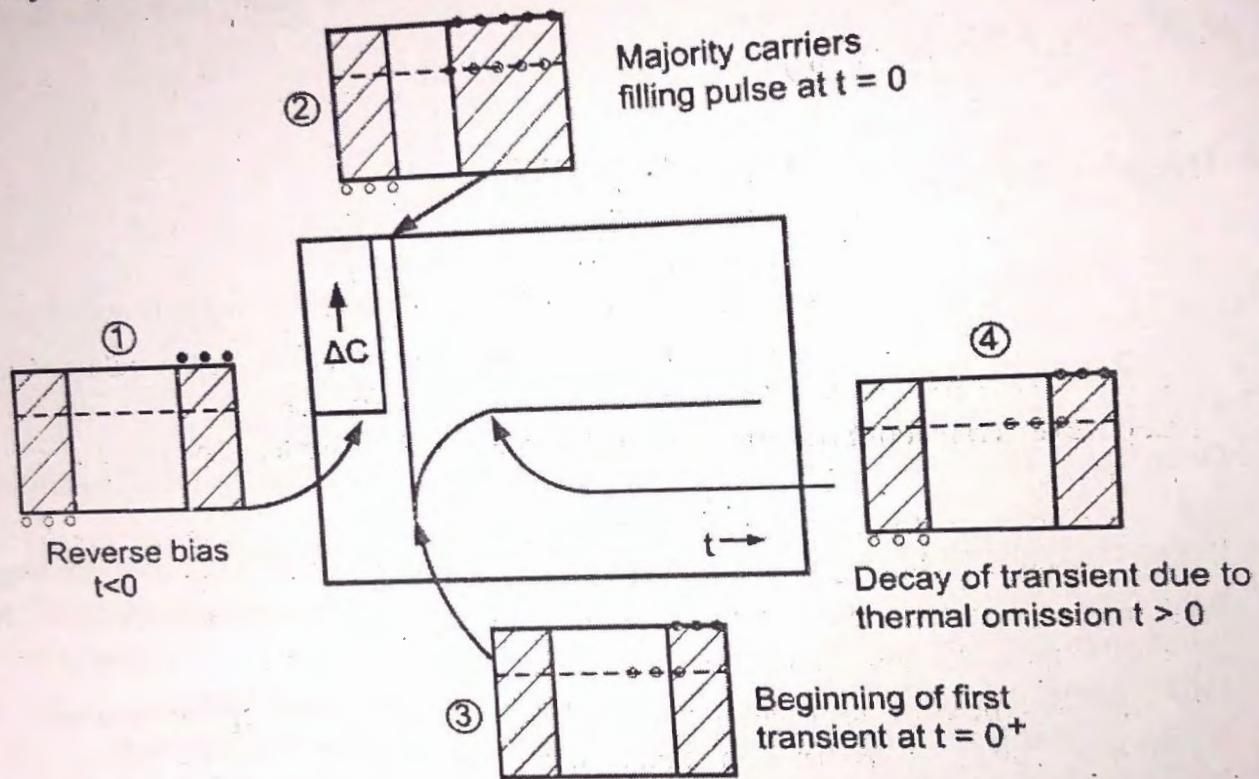
- If the system is disturbed from steady state, there is a change in no. of ' $\eta_T$ ', leading to a change in total charge in depletion layer, thus changing the capacitance.

**\* Basic Analysis**

Let us consider, an asymmetric diode ie. 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. ie. 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.

**Fig. 13****From the 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 ( $t = 0$ ). There is a sudden rise in capacitance due to decrease in depletion region.

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

$$\frac{d\eta_T}{dt} = c_n (N_T - \eta_T)$$

where  $c_n$  = capture time const. of  $e^-p$ .

- 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. This variation is given as

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

- $n_T$  exponentially decreases 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

$$C = Co \left( 1 - \frac{n_T}{2N_D} \right) \quad (Co = \text{capacitance at reverse bias.})$$

- As  $n_i$  varies with time, we have

$$C(t) = Co \left( 1 - \frac{n_T}{2N_D} e^{(-t/\tau)} \right) \quad (\tau = \text{time constant})$$

$$\tau = 1/en$$

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.

#### 4.7 UV – $V_{is}$ Spectroscopy

##### Ultraviolet visible spectroscopy

- The above method is used to measure the energy bandgap of different materials, by measuring absorption spectrum.
- 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 ultraviolet-visible spectroscopy is called UV– $V_{is}$  spectro photometer.

It measures the intensity of light passing through the sample ( $I$ ) and compares it to the calibrated intensity ( $I_o$ )

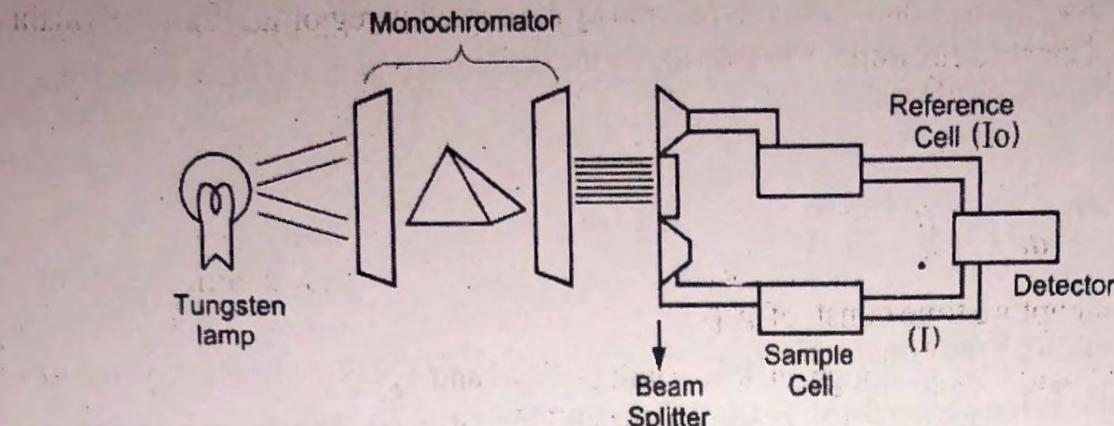


Fig. 14

- A light of wavelength ( $\lambda$ ) and Energy ( $h\nu$ ) 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 ratio of intensities is called transmittance ( $T$ ).

$$\text{ie. } T = \frac{I}{I_o} \quad \dots(1)$$

If %T is plotted 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.

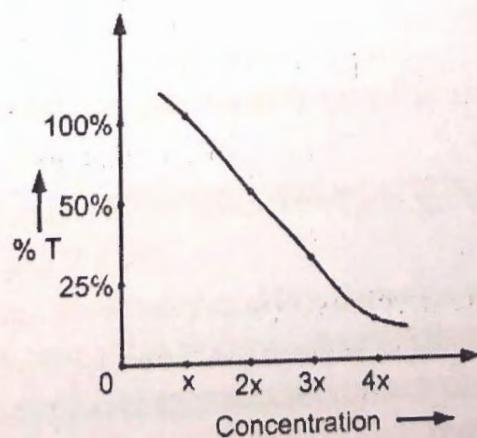


Fig. 15

- As it is difficult to extract characteristics from the exponential relation, we define a relation absorbance (Abs) or (A)

$$\text{Absorbance (Abs)} = \log\left(\frac{I_o}{I}\right)$$

$$\text{or Abs} = -\log\left(\frac{I}{I_o}\right) \quad \dots(2)$$

- The Tauc's relation is used to determine the bandgap in semiconductors.
- It states

$$\alpha h\nu = (h\nu - E_g)^n$$

ie.  $\alpha = \frac{(h\nu - E_g)^n}{h\nu}$ , where  $\alpha$  = absorption coefficient

$x$  = thickness of sample

The term ' $n$ ' in equation (3) denotes the nature of transition.

For direct transitions,  $n = \frac{1}{2}$ .