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4.1 FOUR-POINT PROBE METHOD :

- The four-point probe method Fig. 4.1 is used to measure the resistivity of semiconducting materials.
- In this method four probes are used.
- The distance between each probe is equal to S .
- A voltmeter is connected between inner two probes.
- A Direct Current source is connected between the outer two probes.
- To measure the resistivity of a sample, a constant current I goes through the outer two probes and the voltage drop between the inner two probes V is measured.
- The differential resistance can be written as :

$$dR = \rho \left(\frac{dx}{A} \right) \quad \dots (1)$$

where, dR is the resistance between two points with the distance of dx , A is the area that the current goes through and ρ is the resistivity of the sample material.

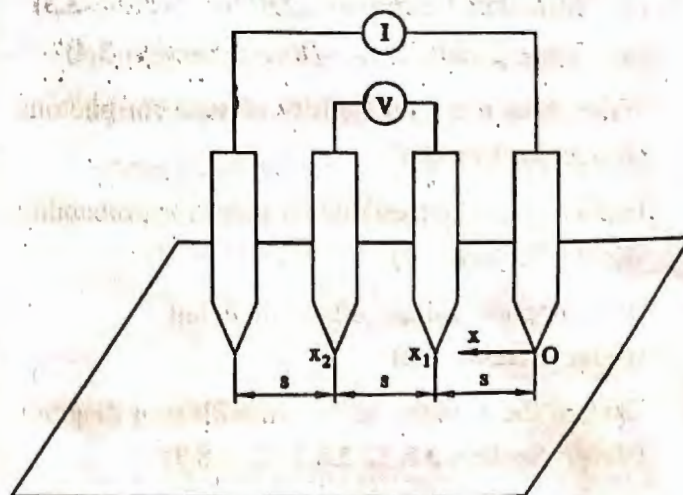


FIG. 4.1 : FOUR-POINT PROBE SYSTEM

• Taking integration on both sides of equation (1), we get

$$\begin{aligned}
 R &= \int_{x_1}^{x_2} \rho \left(\frac{dx}{A} \right) \\
 &= \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x^2} \\
 &= \frac{\rho}{2\pi} \left(-\frac{1}{x} \right) \Big|_{x_1}^{x_2} \\
 &= \frac{\rho}{2\pi} \left[-\frac{1}{x} \right]_{x_1=s}^{x_2=2s} \\
 &= \frac{\rho}{2\pi} \left[-\frac{1}{2s} + \frac{1}{s} \right] \\
 &= \frac{\rho}{2\pi} \left[\frac{-1+2}{2s} \right] \\
 &= \frac{\rho}{2\pi} \left[\frac{1}{2s} \right] \\
 &= \frac{\rho}{4\pi s} \quad \dots (2)
 \end{aligned}$$

where, s equal to the spacing between each probe.

- Due to the superposition of current at the outer two probes, the measured resistance can be calculated by :

$$R = \frac{V}{2I} \quad \dots (3)$$

- Comparing equation (2) and (3), we get.
- Therefore, the resistivity of a bulk sample is.

$$\frac{\rho}{4\pi s} = \frac{V}{2I} \quad \dots (4)$$

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

where, V = Potential difference between inner probes.

I = Current through the outer pair of probes.

s = Spacing between point probes.

ρ = Resistivity

- For a very thin sample where $t \ll s$, we get a current ring instead of a current sphere. Therefore, the area is the circumference of the circle times the thickness of the sample which gives :

$$A = 2\pi x t \quad \dots (5)$$

$$\begin{aligned}
 R &= \int_{x_1}^{x_2} \rho \left(\frac{dx}{A} \right) \\
 &= \int_{x_1}^{x_2} \rho \frac{dx}{2\pi x t} \\
 &= \int_s^{2s} \frac{\rho}{2\pi t} \cdot \frac{dx}{x} \quad [\because X_1 = s, X_2 = 2s] \\
 &= \frac{\rho}{2\pi t} \ln(x) \Big|_s^{2s} \\
 &= \frac{\rho}{2\pi t} \ln 2 \quad \dots (6)
 \end{aligned}$$

- Now comparing equation (3) with equation (6), we get.

- Again, with the superposition of the current, the resistivity of the thin sample is :

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

$$\therefore \boxed{\rho = \frac{\pi t}{\ln 2} \left(\frac{V}{I} \right)} \quad \dots (7)$$

- The sheet resistance of the sample can be expressed as :

$$R_s = \frac{\rho}{t} = \frac{\pi}{\ln 2} \left(\frac{V}{I} \right) = 4.53 \left(\frac{V}{I} \right) \quad \dots (8)$$

$$\text{where, } \frac{\pi}{\ln 2} = 4.53$$

Advantages :

1. To measure very low resistance value, this method is used.
2. In this method, very little contact resistance is associated with the voltage probes so accurate value of the resistivity should be calculated.
3. This method eliminates measurement errors due to the probe resistance.

Applications :

1. Remote sensing areas.
2. Induction hardening process.
3. Accurate geometry factor estimation.

4.2 VAN DER PAUW METHOD :

- The Van Der Pauw Method is a technique commonly used to measure the resistivity and the Hall coefficient of a sample.
- From the above method, the following properties of the material can be calculated :

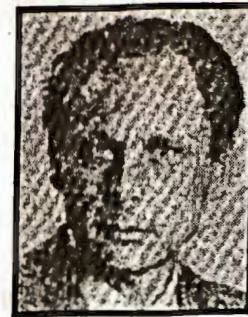
1. The resistivity of the material
2. The doping type (i.e. whether it is a P-type or N-type material)
3. The mobility of the majority carrier

- The method was first propounded by Leo J. Van Der Pauw in 1958.
- The following equipments are required :
 1. An electromagnet (500 to 5000 Gauss).
 2. Constant current source ranging from 10 μA to 100 mA.
 3. High input impedance voltmeter ranging from 1 μV to 1 V.
 4. Sample temperature measuring probe.

4.2.1 Definitions of Resistivity Measurements :

- Four leads are connected to the four ohmic contacts on the sample.
- They are named as 1, 2, 3 and 4 counter clockwise as shown in Fig. 4.2(a).
- It is important to use the same batch of wire for all four leads in order to minimize the thermoelectric effect.
- Similarly, all four ohmic contacts should consist of the same material.
- We define the following parameters (see Fig. 4.2).
 1. ρ = sample resistivity (in $\Omega \cdot \text{cm}$)
 2. d = conducting layer thickness (in cm)
 3. I_{12} = positive dc current I injected into contact 1 and taken out of contact 2. Similarly, for I_{23} , I_{34} , I_{41} , I_{21} , I_{14} , I_{43} , I_{32} (in amperes, A)
 4. V_{12} = dc voltage measured between contacts 1 and 2 ($V_1 - V_2$) without applied magnetic field ($B = 0$). Likewise for V_{23} , V_{34} , V_{41} , V_{21} , V_{14} , V_{42} , V_{32} (in volts, V).

LEO. J. VAN DER PAUW



Leo. J. Van Der Pauw

Leo J. Van Der Pauw was born in Rotterdam, The Netherlands, in December 1927. He received the Ir. degree in physical engineering and the Ph. D. degree in technical sciences from Delft Technical University, Delft, The Netherlands, in 1951 and 1968, respectively.

Since 1953 he has been with Philips Research Laboratories, Eindhoven, The Netherlands, where he has been working in the fields of solid-state physics, computer science, and applied mathematics.

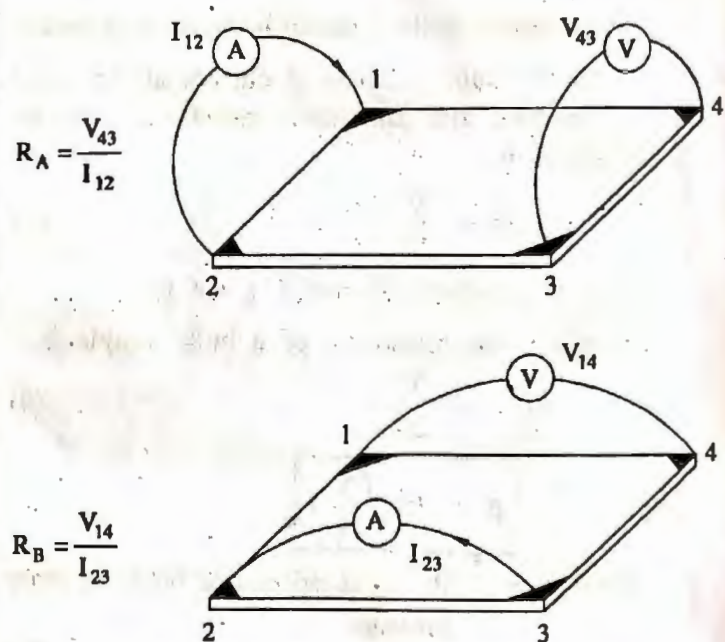


FIG. 4.2 : SCHEMATIC OF A VAN DER PAUW CONFIGURATION USED IN THE DETERMINATION OF TWO CHARACTERISTICS R_A AND R_B

4.3 RESISTIVITY MEASUREMENTS :

1. Apply the current I_{21} and measure voltage V_{34} .
2. Reverse the polarity of the current (I_{12}) and measure V_{43} .
3. Repeat for the remaining six values (V_{41} , V_{14} , V_{12} , V_{21} , V_{23} , V_{32}).

Eight measurements of voltage yield the following eight values of resistance, all of which must be positive.

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

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

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

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

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

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

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

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

Note that with thin switching arrangement the voltmeter is reading only positive voltages, so the meter must be carefully, zeroed.

Because the second half of this sequence of measurements is redundant, it permits important consistency checks on measurement repeatability, ohmic contact quality and sample uniformity.

Measurement consistency following current reversal requires that :

$$R_{21, 34} = R_{12, 43}$$

$$R_{43, 12} = R_{34, 21}$$

$$R_{32, 41} = R_{23, 14}$$

$$R_{14, 23} = R_{41, 32}$$

- The reciprocity theorem requires that :

$$R_{21, 34} + R_{12, 43}$$

$$R_{43, 12} + R_{34, 21}$$

$$\text{and } R_{32, 41} + R_{23, 14}$$

$$R_{14, 23} + R_{41, 32}$$

- If any of the above fail to be true within 5%, investigate the source of error.

4.3.1 Resistivity Calculations :

- The sheet resistance R_s can be determined from the two characteristic resistance

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

$$\text{and } R_B = \frac{(R_{32, 41} + R_{23, 14} + R_{14, 23} + R_{41, 32})}{4}$$

$$R_s = \frac{\pi \cdot R}{\ln 2} \quad [\because R = R_A = R_B]$$

- If the conducting layer thickness d is known, the bulk resistivity $\rho = R_s d$ can be calculated from R_s .

4.3.2 Definitions for Hall Measurements :

- The Hall measurement, carried out in the presence of a magnetic field, yields the sheet carrier density n_s and the bulk carrier density n or p (for n-type and p-type sample) if the conducting layer thickness of the sample is known.
- The Hall voltage for thick and heavily doped samples can be quite small (of the order of microvolts).
- The difficulty in obtaining accurate results is not merely the small magnitude of the Hall voltage since good quality digital voltmeters on the market today are quite adequate.
- The more severe problem comes from the large offset voltage caused by non symmetric contact placement, sample shape, and sometimes non uniform temperature.
- The most common way to control this problem is to acquire two sets of Hall measurements, one for positive and one for negative magnetic field direction. The relevant definitions are as follows (Fig. 4.3).

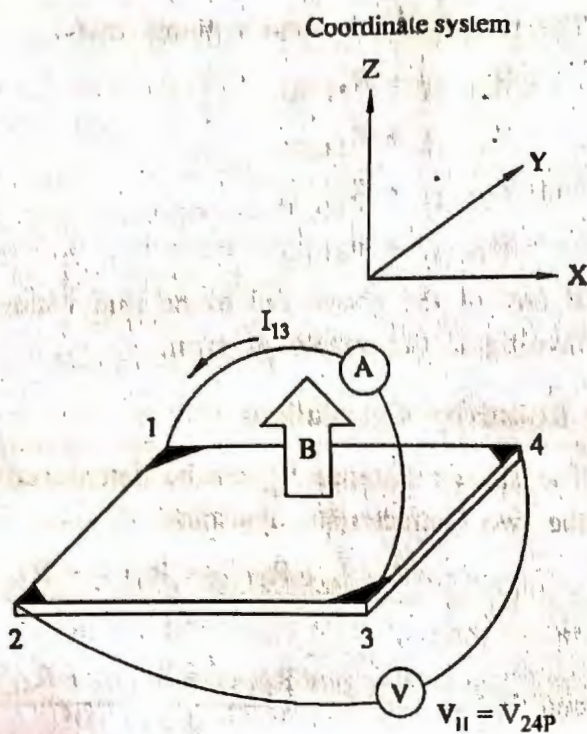


FIG. 4.3 : SCHEMATIC OF A VAN DER PAUW CONFIGURATION USED IN THE DETERMINATION OF THE HALL VOLTAGE V_H

I_{13} = dc current injected into lead 1 and taken out of lead 3. Similarly, for I_{31} , I_{32} , I_{24} .

B = Constant and uniform magnetic field applied parallel to z-axis (true for positive Z-axis – Ve for – Ve Z-axis).

$V_H = V_{24P} =$ Hall voltage measured between leads 2 and 4 with magnetic field positive for I_{13} , similarly for V_{42P} , V_{13P} and V_{31P} .

- Similar, definitions for V_{24N} , V_{42N} , V_{13N} and V_{31N} apply when the magnetic field B is reversed.

Syllabus Topic : Hall Mobility

4.4 HALL MEASUREMENTS :

- The procedure for the Hall measurement is :
 1. Apply a positive magnetic field B .
 2. Apply a current I_{13} to leads 1 and 3 and measure V_{24P} .
 3. Apply a current I_{31} to leads 3 and 1 and measure V_{42P} .
 4. Similarly, measure V_{13P} and V_{31P} with I_{42} and I_{24} respectively.

5. Reverse the magnetic field (negative B).

6. Likewise measure V_{24N} , V_{42N} , V_{13N} and V_{31N} with I_{13} , I_{31} , I_{42} and I_{24} respectively.

- The above eight measurements of Hall voltages V_{24P} , V_{42P} , V_{13P} , V_{31P} , V_{24N} , V_{42N} , V_{13N} and V_{31N} determine the sample type (n to p) and the carrier density n_s , the Hall mobility can be determined from the sheet density n_s and sheet resistance R_s obtained from the resistivity measurement.
- This sequence of measurements is redundant in that for a uniform sample, the average Hall voltage from each of the two diagonal sets of contacts should be the same.

4.4.1 Hall Calculations :

- Steps for the calculations of carrier density and Hall mobility are :
- Calculate the following (be careful to maintain the signs of measured voltages to correct for the offset voltage).

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

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

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

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

- The overall Hall voltage is then

$$V_H = \frac{V_C + V_D + V_E + V_F}{8}$$

- The polarity of this Hall voltage indicates the type of material the sample is made of. If it is positive, the material is P-type, and if it is negative, the material is N-type.

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

- The Hall mobility is calculated from the sheet carrier density n_s and the sheet resistance,

$$\mu = \frac{1}{qn_s \cdot R_s} \text{ (in units of cm}^2 \text{ V}^{-1} \text{ S}^{-1}\text{)}$$

Advantages :

1. Only four contacts required.
2. No need to measure sample widths or distances between contacts.
3. Simple geometries can be used.

Disadvantages :

1. Measurements take about twice as long.
2. Errors due to contact size and placement can be significant when using simple geometries.

4.5 HOT-POINT PROBE MEASUREMENT :

- Hot-point probe method is used for determining whether a semiconductor is p-type or n-type.

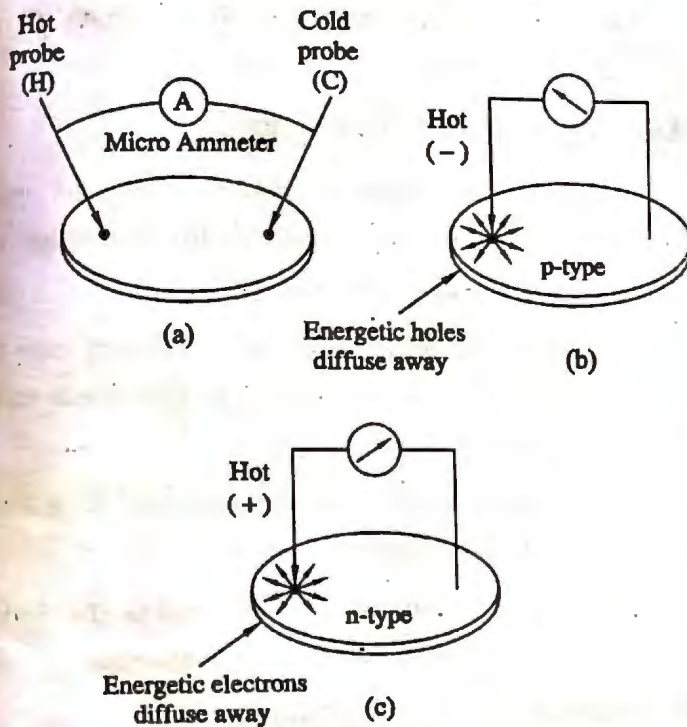


FIG. 4.4 : HOT-POINT PROBE MEASUREMENT

4.6 CAPACITANCE VOLTAGE MEASUREMENT :

- Capacitance voltage measurement (C-V method) is a method for measurement of the barrier capacitance of semiconductor junctions, like p-n junctions, metal-semiconductor junctions and even metal-oxide-semiconductor (MOS) structures.
- In 1942, W. Schottky discovered that impurity distribution can be determined from the C-V measurement.
- This method, is called the C-V technique is widely used to determine impurity distribution of doping profiles of semiconductors devices.
- The C-V technique exploits dependence of width of a space-charge region by a reverse bias.
- This dependence made possible the C-V profiling method on Schottky barrier diodes, P-N junctions, MOS capacitors and MOSFETs.
- Let's consider the asymmetrically doped junction shown in Fig. 4.5.

- The hot point probe (HPP) comprises two test probes, C and H, connected by a microammeter.
- The cool probe C is at room temperature, and H, the hot probe, is heated to a higher temperature electrically.
- When the probes are in contact with the sample, charge carriers tend to diffuse through the sample from H towards C, causing a current to flow.
- The net current will depend primarily on the majority carriers, electrons for n-type and holes for p-type samples.
- Since these carriers are of opposite sign, the direction of net current flow will differ for the two types.
- If H is positive w.r.t. C, the sample is n-type (as show in Fig. 4.4(c)), otherwise it is p-type (as show in Fig. 4.4(b)).
- Thus, the type of the sample can be determined by the direction of deflection of a zero-center current meter.



Walter Hans Schottkyw

Walter Hans Schottky (1886 –1976)

Walter Schottky, a famous name in the fields of electronics and physics .He was a German physicist who played a major role in developing the theory of electron and ion emission phenomena. He made many significant contributions in the areas of semiconductor devices, technical physics and technology. He was awarded the Royal Society's in 1936 for his discovery of the Schrot effect.

WALTER HANS SCHOTTKYW

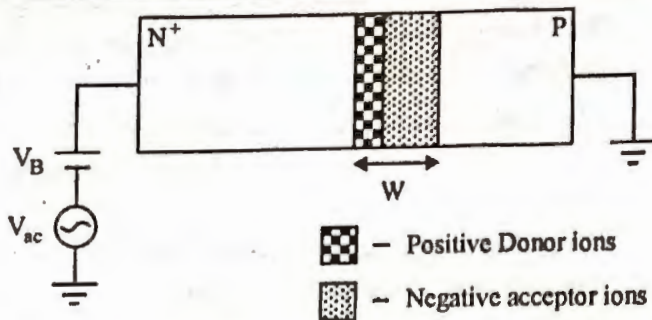


FIG. 4.5 : AN ASYMMETRICALLY DOPED P-N JUNCTION UNDER BIAS CONDITION

- The figure shows a DC voltage bias V_B is applied to the N-side and the P-side connected to ground.
- When V_B is negative (P-N junction is reverse bias) electrons are attracted to the P-side contact, holes are attracted to the other contact.
- As a result, there are more positive donor ions on the N-side, and negative acceptor ions on the P-side appearing at the depletion layer (with reference to the P-N junction in equilibrium).
- For V_B that is more negatively biased, more holes and electrons are attracted to the contacts. This results in an increase in the positive donor and negative acceptor ions at the depletion region.
- This increase in negative bias eventually extends the depletion layer width which in turn increases the depletion-layer charge.
- The reverse bias eventually produces a space-charge region (scr) of width W .
- If the N^+ -side is 100 times more heavily doped than the P-side, thus scr spreading into the P-side can be neglected.
- The differential capacitance C is given by

$$C = \frac{-dQ_s}{dV} \quad \dots (1)$$

- Negative sign accounts for more negatively charge in the semiconductor scr and Q_s is the semiconductor charge increment. In order for the P-N junction to have overall charge neutrality, dQ_s is given by

$$dQ_s = -qAN_A(W)dW \quad \dots (2)$$

- Combining Equation (1) and (2), we get

$$C = \frac{-dQ_s}{dV} = qAN_A(W) \frac{dW}{dV} \quad \dots (3)$$

- In Equation (3), the term $\frac{dN_A(W)}{dV}$ is neglected or is assumed to be zero.
- The capacitance of a P-N junction is given by

$$C = \frac{K_s \epsilon_0 A}{W} \quad \dots (4)$$

where, $K_s \epsilon_0 = 11.7 \times 8.85 \times 10^{-12} \text{ F/m}$, A is area of the P-N junction and W is width of the depletion layer.

Advantages of C-V Technique :

- It is a simple technique where not many equipment are required for extracting the capacitance and voltage.
- Measurements can be taken directly from the device in which doping profile needs to be evaluated.
- Doping profile can be extracted with little data processing.
- It is a non-destruction method as the device is not damaged after measurement.

Disadvantages of C-V Technique :

- It can only extract doping profile of junction in reverse bias, where conductance is small/negligible.
- It is an approximation and only works for abrupt junctions.
- The doping profile near the junction cannot be extracted due to the zero bias space-charge region width.
- The extracted profile is limited in depth by the voltage breakdown of the device. This is serious in heavily doped regions.
- It can only extract doping profile of the less highly doped side.
- Area of device cannot always be accurately determined which affects the doping profile extracted.

4.9 ULTRAVIOLET - VISIBLE (UV - VIS) SPECTROMETER :

- To find the energy band gap of different samples by measuring the absorption spectrum, UV - VIS spectrometer is used.
- The term 'band gap' refers to the energy difference between the top of the valence band to the bottom of the conduction band, Fig. 4.9, in which electrons are able to jump from one band to another.

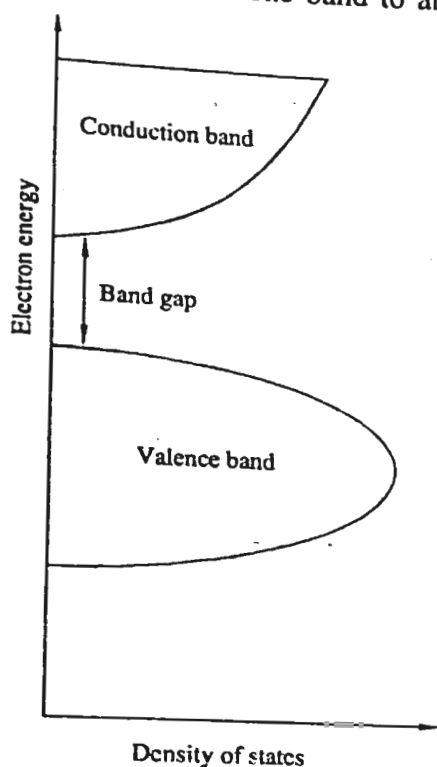


FIG. 4.9 : EXPLANATION OF BAND GAP

- Measuring the band gap is important in semiconductor and nanomaterial industries. The band gap energy for insulators is large (> 4 eV) but lower for semiconductors (< 3 eV).
- A diagram shows the band gap is shown in Fig. 4.9.
- UV - VIS spectrometer measures the intensity of light passing through the sample (I) and compares it to the calibrated intensity (I_0).

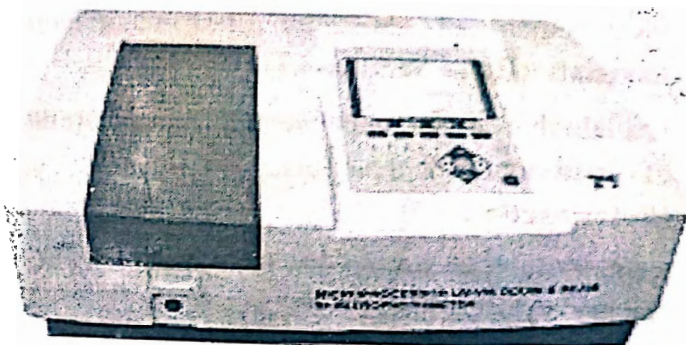


FIG. 4.10 : UV - VIS PHOTO SPECTROMETER

- The ratio $\frac{I}{I_0}$ is called the transmittance for a particular wavelength.
- The absorbance A is defined as,

$$A = -\log \left(\frac{I}{I_0} \right)$$

- The source of UV - VIS light is a tungsten lamp. When the current in the circuit gradually increased from zero.

- The tungsten lamp filament at first can be felt to be emitting warmth, this shows dull red and then gradually brightness until it emits an intense white light.
- Band gap energy,

$$E = \frac{hc}{\lambda}$$

where, $h = 6.62 \times 10^{-34} \text{ Js}$
 $c = 3 \times 10^8 \text{ m/s}$

- Hence, $E = \frac{1.24 \times 10^{-6}}{\lambda} \text{ eV}$, λ in meter
- From the above formula, Band gap of any semiconductor material can be calculated.
- Band gap can be calculated using Trace method as given below :

$$\alpha = \frac{A (h\nu - E_g)^n}{h\nu}$$

where, $\alpha = \frac{I_n \left(\frac{1}{T} \right)}{x} = \text{absorption co-efficient}$

$T = \text{Transmission}$

$x = \text{thickness of sample}$

$E_g = \text{band gap of the material.}$

$h\nu = \text{Photon Energy}$

Absorbance :

$$A = -\log \left(\frac{I}{I_0} \right)$$

$$I = I_0 e^{-t/\delta}$$

where, $I_0 = \text{Intensity of glass plate}$

$I = \text{Intensity of the coated glass plate/sample.}$

$t = \text{thickness of sample}$

$\delta = \text{Skin depth of the material}$

$$= \sqrt{\frac{\rho \lambda}{\pi c \mu}}$$

where, $\rho = \text{Resistivity (for AC, } 2.8 \times 10^{-8} \Omega\text{-m)}$

$\lambda = \text{Wavelength}$

$c = \text{Velocity of light}$

$\mu = \text{Absolute magnetic permeability, (} 1.256 \times 10^{-6} \text{ H/m).}$

EXERCISE

- Explain the four point probe method for measurement of resistivity of semiconducting materials. (Refer Section-4.1)
- Explain the van der pauw method for measurement of resistivity of the materials. (Refer Section-4.3)
- Explain the how to perform Hall measurement by van der pauw method. (Refer Section-4.4)
- Explain Hot point probe measurement for semiconductor. (Refer Section-4.5)
- Write short notes on C-V measurement and how to determine semiconductor parameter. (Refer Section-4.6)
- Explain diode I-V characteristics. (Refer Section-4.7)
- Write short notes on Deep Level Transient Spectroscopy. (Refer Section-4.8)
- Explain how to measure the band gap of the semiconductor sample using UV-VIS. (Refer Section-4.9)

