Expt. No 3: **Four probe method**

Aim:

1) To determine the energy gap and electrical resistively of a given semiconductor using a four probe technique.
2) Comment on the correction factor used and on the variation of resistivity with respect to 1/T in general and low temperature in particular and comment.
3) Use the slope of the linear part of the graph to determine the resistivity. Use the Least Square Fit method to find the graph.

Apparatus:

Four probe arrangement, semiconductor specimen, oven, constant current source, thermometer etc.

Theory:

The properties of bulk material used for the fabrication of transistor and other semiconductor devices are essential in determining the characteristics of the completed devices. Resistivity measurement is an important parameter to determine suitability of semiconductor crystal. The resistivity must be measured accurately since its value is critical in many devices. The value of some transistor parameters, like the equivalent base resistance, is linearly related to resistivity.

The electrical properties of semiconductors involve the motion of charged particles within them. Therefore, we must have an understanding of the forces which controls the motion of these particles. It is of course, the physical structure of the solid which exerts their control. Atoms, of which a solid is composed, consist of positively charged nuclei with electrons orbiting around them. An electron in an atom has only discrete values of energy. There is a forbidden energy region in between two consecutive allowed energy levels. In solid atoms are very closely packed. Hence each atom interacts with a large number of surrounding atoms. As a result, each energy level splits in to many number of energy level. Hence each discrete energy level of an atom transforms in to an energy band for the solid.

The highest energy band which is completely filled at zero Kelvin is called valence band. The next higher band which may be partially filled or completely empty is called conduction band. The difference between the highest energy in a given band and the lowest energy in the next higher band is called the band gap between the two bands. On the basis of energy band structure solids are classified as conductors, semiconductors and insulators.

At absolute zero, semiconductors are pure insulators. As the temperature is increased thermal energy create vibrations in crystal lattice and few electrons, which acquire sufficient vibrational energy break their covalent bond, become free, and move to the conduction band. The energy required to rupture the covalent bond is designated as energy gap '$\mathbf{E_g}$'. The energy less than E_g is not acceptable or one cannot have partially ruptured covalent bond, hence this energy is also called as forbidden energy gap. As the temperature increases above room temperature more and more covalent bonds are broken and conduction increases rapidly and resistivity falls. We have, at temperature T > 0K,

$$\rho\,(T) = \rho_0 \exp\left(\frac{E_g}{2k_B T}\right) \qquad (1)$$

Where, ρ (T) is resistivity at temperature T.

ρ_0 is resistivity at absolute zero

E_g is forbidden energy gap of a semiconductor

k is Boltzmann constant.

Four Probe Method:

High resistance or rectification appears fairly often in electrical contacts to semiconductors and in fact is one of the major problems. Soldered probe contacts may disturb the current flow and affect the sample properties. Many conventional methods for measuring resistivity are unsatisfactory for semiconductors because of metal –semiconductor contacts are usually rectifying in nature. Also there is generally minority carrier injection by the current carrying contacts. An excess concentration of minority carriers will affect the potential of other contacts and modulate the resistance of the materials.

The four probe method overcomes the difficulties mentioned above and also offers several other advantages. It permits measurements of resistivity in samples having a wide variety of shapes, including the resistivity of small volumes within bigger pieces of semiconductor. In this manner the resistivity on both sides of p-n junction can be determined with more accuracy before the material is cut into bars for making devices. This method of measurement is also applicable for elemental as we as compound semiconductor materials.

The basic model for the measurement of resistivity is shown below. Four sharp probes are placed on the flat surface of the material to be measured, current is passed

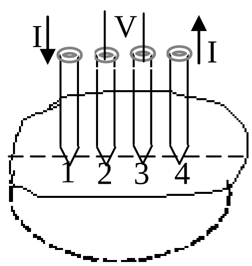


Figure : A

through the outer probes and the potential is measured across the inner probes. A nominal value of probe spacing which has been found satisfactory is an equal distance of 1.5 mm between adjacent probes. This permits measurement with reasonable resistivity of n- and p- type semiconductor from 0.001 to 50 ohm-cm.

In order to use this method in semiconductor crystals or slices it is necessary to assume that:

a. The resistivity of the material is uniform in the area of measurement.
b. The surface on which the probe rests is flat with no surface leakage.
c. The four probes used for resistivity measurement contact the surface that lie in a straight line.
d. The diameter of the contact between the metallic probes and the semiconductor should be negligibly small compared with the distance between the probes.
e. The surfaces of the crystal may be either conducting or non-conducting.

For such an arrangement, the floating potential V_f a distance r from the electrode (probe) carrying current I in a material of resistivity ρ_0 is given by,

$$V_f = \frac{\rho_0 I}{2\pi r} \tag{1}$$

In this model there are two current carrying electrodes, numbered 1 and 4 (Fig. A), and the floating potential V_f at any point in the semiconductor is the difference between the potential induced by each of the electrodes. Since they carry currents of equal magnitude but in opposite directions thus:

$$V_f = \frac{\rho_0 I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_4}\right), \tag{2}$$

where r_1 and r_4 are the distance from probe 1 and 4 respectively.
The floating potentials at probe (2) V_{f2} and at probe (3) V_{f3} can be calculated from Eq. (2) by substituting the proper distances as follows;

$$V_{f2} = \frac{\rho_0 I}{2\pi}\left(\frac{1}{S_1} - \frac{1}{S_2 + S_3}\right) \tag{3}$$

$$V_{f3} = \frac{\rho_0 I}{2\pi}\left(\frac{1}{S_1 + S_2} - \frac{1}{S_3}\right) \tag{4}$$

The potential difference V between probes is then,
$V = V_{f2} - V_{f3}$

$$V = \frac{\rho_0 I}{2\pi}\left(\frac{1}{S_1} + \frac{1}{S_3} - \frac{1}{S_1 + S_3} - \frac{1}{S_1 + S_2}\right) \tag{5}$$

and the resistivity ρ_0 is computed as (From Eq.1)

$$\rho_0 = \frac{V}{I}\frac{2\pi}{\left(\frac{1}{S_1} + \frac{1}{S_3} - \frac{1}{S_1 + S_3} - \frac{1}{S_1 + S_2}\right)} \tag{6}$$

If the spacing between the probes are equal; ($S_1=S_2=S_3= S$)

$$\rho_0 = \frac{V}{I} 2\pi S \tag{7}$$

The correction factor for the slice kept on non-conducting surface has to be included to get the correct resistivity of the sample. The correction factor is denoted by f (W/S) which depends on the probe distance and the thickness of the sample; it decreases as W/S increases (for sample kept on conducting surface f (W/S) increases with W/S). For the sample with W = 1 mm and probe spacing S = 1.5 mm f(W/S) = 2.34.

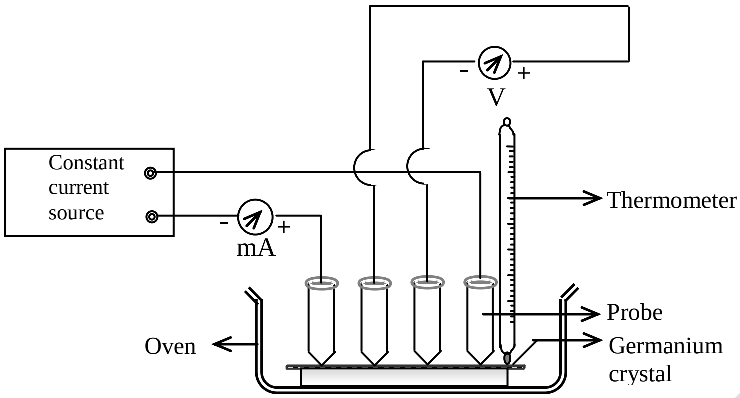
$$\rho = \frac{\rho_0}{f(W/S)} \tag{8}$$

which is purely the resistivity of the sample.

Procedure:

- Connect the outer pair of probes to the constant power supply and the inner pair of probe to the voltage terminals.
- Place the four probe arrangement in the oven and fix the thermometer in the oven through the hole provided.
- Switch on the constant current power supply and adjust the desired value (Say 0.5mA)
- Connect the oven power supply and heat it up to 130 ^{0}C . Rate of heating may be selected with the help of band switch of the oven power supply.
- Measure the inner probe voltage for various decreasing temperatures (by 10 ^{0}C).
- Plot a graph of ln ρ as a function of 1/T.
- Calculate the energy gap of a given semiconductor using a formula: $E_g = 2k_B$ x slope.

Circuit diagram:



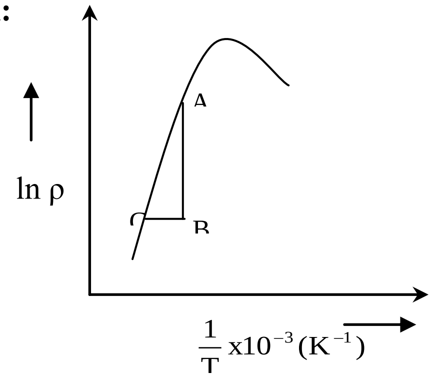
Record of observations:

1. Distance between the probes(S) = 1.5mm =0.15 ±   cm
2. Thickness of the crystal (w) = 1 ±   mm
3. Current (I) = ----------------------±   mA   (constant)
4. Correction factor f(w/S) =2.34

Tabulation:

SL.NO.	TEMPERATURE		VOLTAGE IN MV	$\rho_0 = (V/I)\times 2\pi S$ Ohm-Cm	$\rho = \frac{\rho_0}{f(w/S)}$	**ln** ρ	$\frac{1}{T}$ K^{-1}
	^{0}C	K					
Error	±	±	±				
1	130						
2	120						
3	110						
4	100						
5	90						
6	80						
7	70						
8	60						
9	50						
10	40						

Nature of graph:



Calculation: Given k_B=1.38x10^{-23}J/K

Eg = 2. (k_B) . (Slope) (from the graph)

= --------------- Joules

= ………… / 1.6 x 10^{-19}

= **eV**

Viva questions:

1) Define semiconductor.
2) Define energy gap. Is it temperature dependent?
3) What do you mean by conduction band and valence band?
4) Why current decreases with decrease of temperature in case of semiconductor?
5) What is the characteristic difference between metals and semiconductors from the consideration of temperature coefficient of resistivity?
6) Does semiconductor obey Ohm's law?
7) What do you mean by extrinsic and intrinsic semiconductor?
8) What are n-type and p-type semiconductors?
9) Is an extrinsic semiconductor electrically neutral?
10) What are semimetals? How it is different from semiconductor?
11) What are the advantages of four probe method?