EXPERIMENT

BAND GAP OF A SEMICONDUCTOR (GE)

AIM: To calculate the band gap energy (Eg) in Germanium (Ge) Semiconductor.

THEORY:

Solids are classified into three main groups namely metals, insulators and semiconductors, on the basis of their energy bands. Energy bands of any solid are obtained from solution of Schrödinger's equation for that solid, and represent the electron Eigen energies as a function of the electron wave vector [i.e. momentum].

The results of a hypothetical quantum-mechanical calculation of electron energy as a function of the lattice spacing for silicon as shown in Fig 4.l This schematic is very instructive for qualitative understanding of the occurrence of energy bands and forbidden energy gaps. In an ideal gas, each isolated atom has its discrete electron energy levels [two levels are shown on the far right of the diagram]. These Eigen energies expand into energy bands, as we decrease the interatomic spacing to form a solid.

As the interatomic spacing is reduced, the interaction between atoms takes place, and keeps increasing. Finally, in a solid, atoms very strongly interact with each other, and the valence [the outermost] electrons can not claim to belong to any particular atom. What this means is that if the solid has N atoms, each atomic level must split [to remove degeneracy] into N sub-levels, very closely spaced to each other [as N is a very large number] to accommodate electron levels of N atoms. This is how an energy band of very closely spaced sub-levels evolves. The energy range between the allowed energy bands is the forbidden energy gap or band gap Eg. In the quantum –mechanical picture, electrons cannot have any energy in the forbidden energy range.

The highest completely filled [i.e. occupied with electrons] energy band at **0 K** is called valence band, and the next higher band is called the conduction band. Fig.4.2 illustrates the basic differences between the 3 classes of solids in terms of the valence and conduction bands. In Fig.4.2, the abscissa is some x- direction in the solid, while the ordinate is the electron energy. As Fig.2c indicates, the metals are characterized by overlapping conduction and valence bands or partially filled conduction bands. The shaded area represents energy levels occupied by electrons. The non-metals, i.e. semiconductors and insulators, are characterized by completely empty conduction bands at **0 K**. Semiconductors have lower band gap than insulators, as indicated in Figs. 4.2a and 4.2b.

When an electron or a hole [i.e. a missing electron] responds to an applied electric field, it accelerates, and gains kinetic energy. [A force acts on a charge carrier in an electric field.] This means that it is excited to a higher energy state. So, only those electrons and holes can respond to an applied electric field that have empty higher states available for excitation. [Note that Pauli's exclusion principle requires that no two electrons can have the same Eigen energy, that too, only if they have opposite spins.] In a moderate electric field, gain in the kinetic energy is a very small fraction of the band gap energy. For this reason, the valence electrons in a non-metal at 0 K cannot respond to an applied electric, as they see no higher states to which they can be excited. For this reason, a non-metal is a perfect insulator at 0 K, as it has no conduction electrons or free carriers. [A free carrier is free to respond to an applied electric field.]

At room temperature [i.e. 300K], thermal vibrations break a minute fraction of the covalent bonds in a semiconductor. In other words, the thermal energy kT excites a very small fraction of valance, electrons in a semiconductor over the band gap Eg into the conduction band. This fraction naturally depends upon the values of Eg and kT. This is known as thermal generation of free carriers. So thermal generation always gives rise to electron-hole pairs, i.e. equal numbers of conduction electrons and holes are created. The number of such pairs per unit volume is known as the intrinsic carrier density, n_i, which is given by:

$$\boldsymbol{n_i = C\, exp\left[\frac{-E_g}{2KT}\right]}$$

C is a constant and has same unit as n_i, i.e. cm^{-3}, K is Boltzmann's constant, and T is absolute temperature. From equation [l], it follows that for a semiconductor at 300K, the conduction band is slightly filled with electrons, and the valance band is slightly empty for electrons, or slightly filled with holes, as illustrated in Fig.4.2. A conduction electron is free carrier because it has empty higher states to which it can be excited to by gain in kinetic energy.

A hole [which is always in the valance band] is also a free carrier, as it can be excited to all states filled by electrons. Note that in the energy band diagram, going up increases the electron potential energy, -q.V, but decreases the hole potential energy, q.V, where V is the electrostatic potential. When a conduction electron has no kinetic energy, then it is at the conduction band lower edge, E_C. Similarly, when a hole has no kinetic energy, then it is at the valance band upper edge, E_V.

The free carrier density in the pure semiconductor is n_i . The conductivity of a pure semiconductor is therefore proportional to n_i, while the resistivity, q, will be inversely proportional to it. Therefore:

$$\boldsymbol{\rho = K \exp\left[\frac{E_g}{2kT}\right]}$$

K is a constant. A plot of ln (q) versus l/T will therefore be a straight line, whose slope will be Eg/2kT. Hence the band gap of a semiconductor can be determined from measurement of resistivity, q as a function of temperature T.

Four Point Probe Resistivity Measurement:

The resistivity of a solid is obtained experimentally by passing a current through the solid, and measuring the current through and the voltage drop across the solid. This measurement is easier for metal. But for non-metal, the contact between metal current lead and non-metal sample act as high resistance junction. A metal semiconductor contact is a Schottky barrier diode. This a complication, because if the voltage is measured between the two current leads, then this will not only include the voltage drop across the semiconductor , but also the large voltage drop across the two metal semiconductor contacts. For this reason the semiconductor resistivity measurements involves four equidistant probes, as shown in Fig 4.4. The two outer probes carry the current from a constant current generator, while the two inner probes are used for voltage measurement by a very high input resistance, then, there is no current flowing through the voltmeter. Ideally the voltmeter should infinite resistance then there is no current flowing through the voltmeter, hence there will be no voltage drop across the metal- semiconductor contacts at the voltage probes. This will ensure correct measurement of the voltage drop in the semiconductor in the region between the two inner probes.

Note the current enters/leaves the semiconductor at the probes flowing vertically, while in the central region the two outer probes, it flows horizontally. Also, the current flux density is not uniform. These complications result in the following relation between the resistivity q, the probes spacing d, the current I, and the voltage V between the two inner probes.

$$\boldsymbol{Q = 2\pi \left(\frac{d.V}{I}\right) .(\textbf{correction factor})}$$

EXPERIMENTAL SETUP:

The semiconductor sample in the the form of wafer. The band gap of Ge is about 0.66 at 300K.The four-probe set is spring-loaded, with collinear and equally spaced probes, and Zn-coated probe tips. The set is mounted on a stand, current and voltage leads are provided [see Fig4]. The probe set and the sample stage are arranged in a small box- type oven. The oven temperature can be varied from 300 to 475 K. The control cabinet has three units: [i] constant current generator; [ii] digital millivoltmeter (with high input resistance) cum milliammeter; and [iii] oven power supply.

PROCEDURE:

1. Set the current to 5-6 mA.
2. Switch in the oven on Low heating rate setting.
3. During the rise of the temperature of the oven from 70-170^{0}C (343 K-443 K) at X-10 setting, note the voltage (mV) from the digital display with the interval of 10^{0}C rise in temperature (10 readings).
4. Calculate the resistivity, q using the following relation:

$$\boldsymbol{\rho = 181\left(\frac{V}{I}\right)}$$

where V is in volts and I is in mA. (The value of q would be in ohm.cm)

5. Plot Log 10 q Vs (1000 / T) and calculate the slope of the straight line.

[Please note that the above equation is obtained from eq.(3) for d = 0.2 cm, a correction factor of 0.145]

6. From the slope of the linear region of this plot, calculate Eg (in eV) by the following relation.

$$\boldsymbol{\rho = K\, exp\left[\frac{E_g}{2kT}\right]}$$

$$\boldsymbol{E_g = 0.4\left[\frac{d\log\rho}{d(1000/T)}\right]}$$

[In the above equation q is in ohm.cm and T in K].

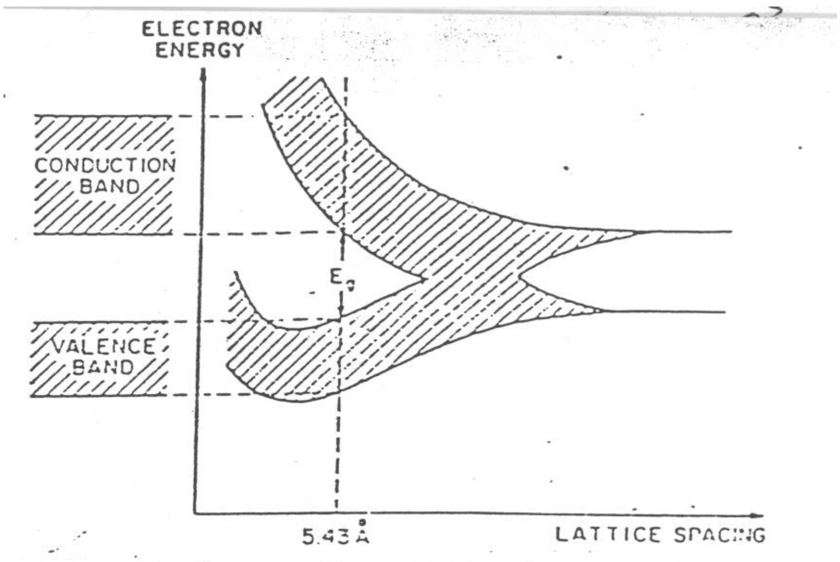

Fig 4.1 Formation of energy bands as a diamond lattice crystal is formed by bringing together isolated silicon atoms.

QUESTIONS:

1. What is the advantage of Four Probe method over the other conventional methods?
2. Explain the behaviour of the Log 10 q Vs (1000 / T) plot.

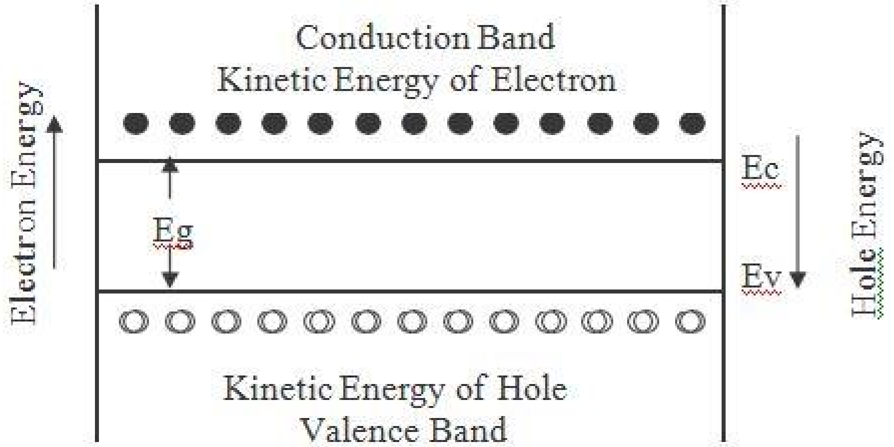

Fig 4.2. The potential energy and Kinetic energy in energy band representation.

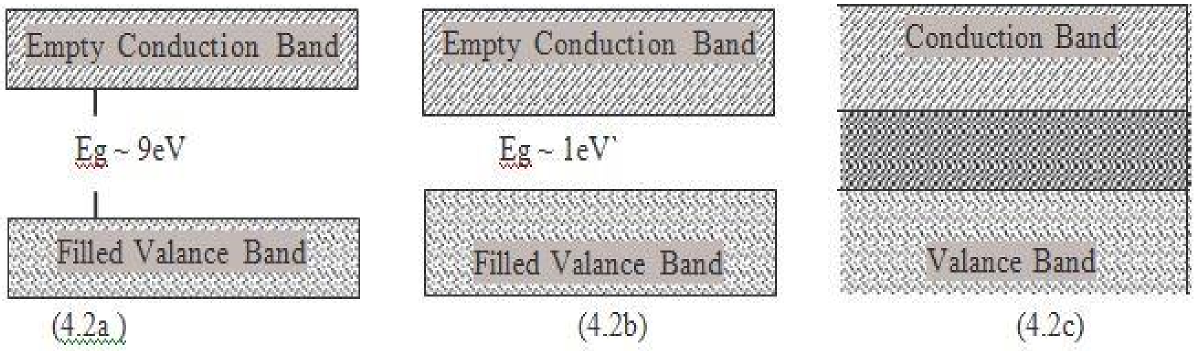

Fig4.3. Schematic energy band representation of (a)Insulator(b)semiconductor(c)conductors

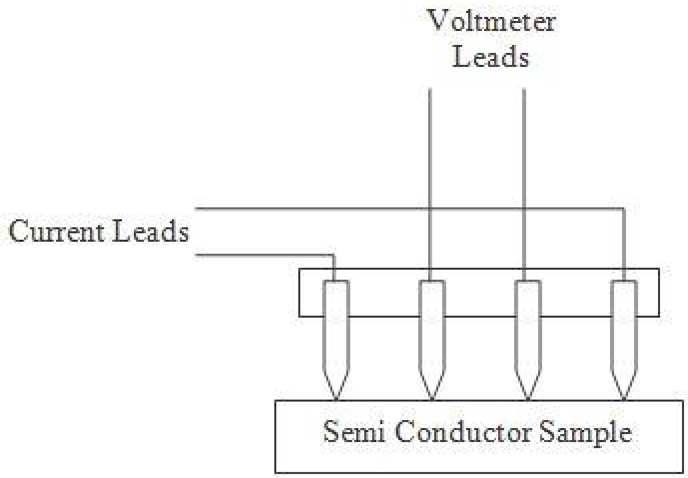

Fig. 4.4 The four point probe setup