

Semiconductors

35.1 ENERGY BANDS IN SOLIDS

In the atoms of a solid, the electrons in the inner shells are strongly bounded to their nuclei while the electrons in the outer-most shells are not strongly bounded. The electrons in the outermost shell are called *valence electrons*. The band formed by a series of energy levels containing the valence electrons is known as the *valence band*. The valence band may also be defined as the *highest filled band*.

The permitted energy band next to the valence band is called the *conduction band*. The electrons occupying this band are free to move and are called *conduction electrons*. The conduction band may be defined as the *lowest unfilled band*. This band may be empty or partially filled.

The two bands, i.e., conduction band and the valence band are separated by a region or a gap called the *forbidden band* or the *band gap*. This has got its name as no electron can exist in this band.

35.2 CONDUCTORS, SEMICONDUCTORS AND INSULATORS

All solids can be classified as conductors, semiconductors and insulators which can be described on the basis of their band diagram.

- 1. Insulators**—In case of insulators, the forbidden energy band is very wide (Fig. 35.1 (a)). This is due to the fact that the valence electrons in these materials are bound very tightly to their parent atoms. A large amount of energy is required to break these bonds or for an electron in valence band to jump to conduction band. This is the reason that at room temperature, conduction band is completely empty and free electrons are not available to conduct electricity. The band gap in insulators is of the order of 6 eV and resistivity is of the order of $10^7 \Omega\text{-m}$ or still higher.
- 2. Semiconductors**: In semi-conductors, the forbidden band is very small (Fig. 35.1 (b)). Germanium and silicon are the examples of semiconductors. In Germanium, the forbidden band is of the order of 0.7 eV while in case of silicon, it is of the order of 1.1 eV. The electrical properties of semiconductors lie between insulators and good conductors. Because of the small band gap, electrons can easily jump from valence band to conduction band on the application of an electric field. The resistivity of semiconductors have intermediate values and is of the order of $(10^{-6} - 10^6) \Omega\text{-m}$. As a rule, the conductivity of semiconductors increases when energy is supplied to them in the form of heat, illumination or nuclear radiation.

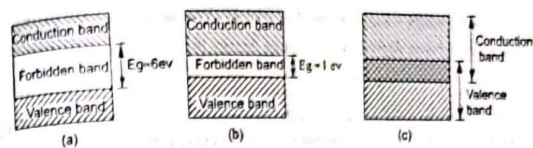


Fig. 35.1 Energy band structure of (a) an insulator (b) semiconductor and (c) conductor

- 3. Conductors**: In case of conductors, there is no forbidden band and the valence band and conduction band overlap each other (Fig. 35.1 (c)). Here, plenty of electrons are available for conduction of electricity. Due to this reason, conductors or metals have very low resistivity (of the order of $10^{-7} \Omega\text{-m}$ or still lower). When heated, their conductivity decreases due to increase in the random motion of electrons.

Another difference between a metal and a semiconductor is that in metals, the total current is simply a flow of electrons. Whereas in semiconductors, there are two types of conduction mechanisms—either electrons or holes can act as charge carriers. This is termed *bipolar conductivity*.

35.3 INTRINSIC AND EXTRINSIC SEMICONDUCTORS

A pure semiconductor in which the number of holes and the number of electrons are equal is termed *intrinsic semiconductor*. However, the number of holes and electrons are made unequal by adding some impurity during the process of crystallization called *doping*. The added impurity is very small, of the order of one impurity atom per million atoms of pure semiconductor. Such semiconductors are called *extrinsic semiconductors*. The impurity which supplies free electrons is termed as donor and semiconductor with donor impurity (e.g. arsenic) is called *n-type semiconductor*. The impurity which supplies holes is termed as acceptor and the semiconductor with acceptor impurity (e.g. indium) is called a *p-type semiconductor*. The charge carriers whose concentration dominates in a semiconductor are called *majority carriers*. Charge carriers of the opposite sign are called *minority carriers*. Naturally, electrons are majority carriers in n-type semiconductors while holes are minority carriers.

35.4 ELECTRICAL PROPERTIES OF SEMICONDUCTORS

Electrical properties of a semiconductor include the carrier concentration n , the carrier mobility μ and the electrical conductivity σ (or resistivity ρ). These for pure germanium and silicon at room temperature are listed in Table 20 of Appendix-2.

Carrier Concentration (n)

Number of charge carriers per unit volume of a semiconductor is known as its *charge density* or *carrier concentration*. It is measured in units of m^{-3} or cm^{-3} .

In an intrinsic semiconductor at equilibrium, the density of electrons is equal to the density of holes. So the intrinsic carrier concentration n_i is given as

$n_i = n = p$ where n and p denote the electron and hole density respectively. The temperature dependence of charge density is found to be of the form,

$$n = A T^{3/2} e^{-E_g/2kT} \quad (35.1)$$

Here E_g is the band gap and k is the Boltzmann's constant. It is clear that n increases exponentially with temperature. Here the exponential term dominates and the effect of $T^{3/2}$ term is negligible.

Intrinsic Conductivity (σ)

The relation between the electrical conductivity and the resistance of a specimen is given by

$$\sigma = \frac{l}{RA} \quad (35.2)$$

where l and A are respectively the length and the cross sectional area of the specimen.

Thus, we can define the conductivity of a material as the conductance $\left(\frac{1}{R}\right)$ of a unit cube of the material. The S.I unit of conductivity is $\Omega^{-1} m^{-1}$.

The electrical conductivity σ of a pure and perfect semiconductor is due to intrinsic charge carriers, that is due to electrons and holes. Such conductivity is termed intrinsic. Since there are two types of charge carriers in the intrinsic semiconductor, its conductivity σ is the sum of σ_n due to free electrons and σ_p due to holes.

$$\text{i.e., } \sigma = \sigma_n + \sigma_p$$

The temperature dependence of the conductivity σ is almost completely determined by the temperature dependence of the carrier concentration and can be written as,

$$\sigma = \sigma_0 e^{-E_g/2kT} \quad (35.3)$$

where σ_0 is a constant for the semiconductor and is independent of temperature.

Mobility (μ)

Mobility of charge carriers is defined as the drift velocity per unit applied electric field. It is measured in units $m^2 V^{-1} sec^{-1}$. It is observed that

$$\mu \propto T^{-3/2} \quad (35.4)$$

35.5 RELATION BETWEEN CONDUCTIVITY, CARRIER CONCENTRATION AND MOBILITY

Considering the current density J i.e., the current flowing across unit area of the specimen, one can write

$$J = \frac{I}{A} = nev \quad (35.5)$$

where I is the current, A the cross-sectional area of the specimen, n its carrier concentration and v the drift velocity of the carriers.

From the definition of mobility

$$\mu = \frac{v}{E} = \frac{v}{V/l} \quad (35.6)$$

where V is the voltage applied across the specimen of length l . From Eqs (35.5) and (35.6), we have

$$\begin{aligned} \mu &= \frac{vl}{V} = \frac{I}{neA} \cdot \frac{l}{V} \\ &= \frac{1}{neA} \frac{l}{R} \\ &= \frac{1}{ne} \sigma \end{aligned}$$

where σ is the conductivity and R the resistance of a specimen of length l and cross-sectional area A .

$$\therefore \sigma = ne\mu \quad (35.7)$$

Eqn. (35.7) gives the relation between the electrical conductivity, carrier concentration and carrier mobility of a specimen.

Experiment 35.1: To study the variation of resistivity of a Ge crystal with temperature by Four-Probe method and hence to determine the band-gap E_g for it.

Apparatus: A thin Ge crystal with smooth surface, a four-probe arrangement, a digital electronic millivoltmeter, a constant current source (0–10 mA), an oven with its power supply and a thermometer (0–200°C).

Theory: A four-point collinear probe and the appropriate test equipment can be used to determine both the resistivity and conductivity-type. Here we limit our discussion to the Four-Point Probe method for the measurement of resistivity.

The Four-Point Probe Method

The four-point probe or Kelvin-Probe method is the most common method to measure a semiconductor material's resistivity. The four-point probe is preferable over a two-point probe because the contact and spreading resistances associated with the two point probe are large and the true resistivity can't be accurately separated from the measured resistivity. In a four-point probe very little contact and spreading resistance is associated with the voltage probes and hence one can obtain a fairly accurate calculation of the resistivity. Using four probes eliminates measurement errors due to the probe resistance, the spreading resistance under each probe, and the contact resistance between each metal probe and semiconductor material.

The four probe arrangement is shown in Fig. 35.2. The four probes are equally spaced and collinear and coated with hard conducting materials (zinc, tungsten carbide or osmium) at the tip. The probes make spring contacts with the sample and are mounted in a teflon bush for good electrical insulation from each other. Since no

soldering is required for the contacts, any error in resistivity measurements due to contamination of the surface, rectification and change of properties is avoided. The sample is in the form of a thin wafer with non-conducting bottom surface. A heater is used to change the temperature of the sample from room temperature to $\sim 200^\circ\text{C}$.

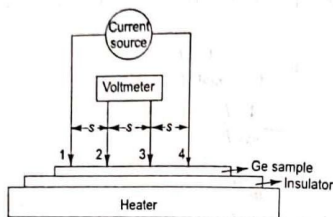


Fig. 35.2

Resistivity Measurement for a Large Sample

Current I from a constant current source is passed through the outer two probes and the voltage V is measured between the inner two probes. Then the resistivity ρ of the sample is obtained in the following way:-

The floating potential V_f at a distance r from an electrode carrying a current I in a material of resistivity ρ' is given by

$$V_f = \frac{\rho' I}{2\pi r} \quad (35.8)$$

In the model shown in Fig. 35.2, there are two current-carrying electrodes, numbered 1 and 4, and the floating potential V_f at any point in the semiconductor is the difference between the potential induced by each of the electrodes (as they carry current of equal magnitude but in opposite direction). Thus

$$V_f = \frac{\rho' I}{2\pi} \left(\frac{1}{r_1} - \frac{1}{r_4} \right)$$

where r_1 is the distance of the point from probe 1 and r_4 is its distance from probe 4.

The floating potentials at probe 2, V_{f2} , and at probe 3, V_{f3} , can be calculated from the above Eqn. by substituting the proper distances as follows.

$$V_{f2} = \frac{\rho' I}{2\pi} \left(\frac{1}{s} - \frac{1}{2s} \right)$$

$$V_{f3} = \frac{\rho' I}{2\pi} \left(\frac{1}{2s} - \frac{1}{s} \right)$$

The potential difference V between probes 2 and 3 is then

$$V = V_{f2} - V_{f3}$$

$$\begin{aligned} &= \frac{\rho' I}{2\pi} \left(\frac{1}{s} - \frac{1}{2s} - \frac{1}{2s} + \frac{1}{s} \right) \\ &= \frac{\rho' I}{2\pi s} \end{aligned}$$

and so the resistivity ρ' is given as,

$$\rho' = \frac{V}{I} \times 2\pi s \quad (35.9)$$

Normally, the samples used in laboratories are not large enough to consider them infinite and therefore Eqn. (35.9) is not applicable. Many methods have been developed to give the resistivity of a specimen of finite size. The most common method is given below.

Correction for the Finite Size

This method applies to the sample whose bottom surface is non-conducting. The corrected resistivity is given by

$$\rho = \frac{\rho'}{F(t/s)} \quad (35.10)$$

where the correction divisor $F(t/s)$ is a function of the ratio of thickness t of the sample to the probe-spacing s and is given by

$$F(t/s) = 1 + 4 \sum_{n=1}^{\infty} \frac{1}{\left[\left(\frac{s}{t} \right)^2 + n^2 \right] \sqrt{\left(\frac{s}{t} \right)^2 + (2n)^2}} \quad (35.11)$$

This function $F(t/s)$ is tabulated in Table 35.1 and plotted in Fig. 35.3(a) and (b). Use Graph in Fig. 35.3 (b) if (t/s) is between 0.1 and 1.0.

For an infinitely thin sample $F(t/s)$ approaches to a value $\frac{2s}{t} \ln 2$.

Table 35.1

t/s	$F(t/s)$
0.100	13.863
0.141	9.704
0.200	6.931
0.333	4.159
0.500	2.780
1.000	1.504
1.414	1.223
2.000	1.094
3.333	1.0228
5.000	1.0070
10.000	1.00045

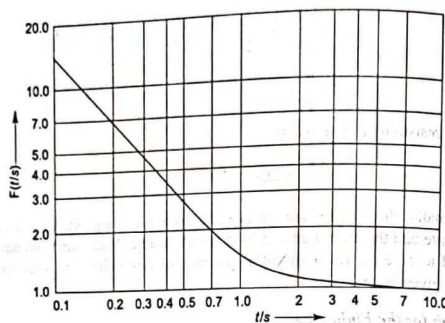


Fig. 35.3(a)

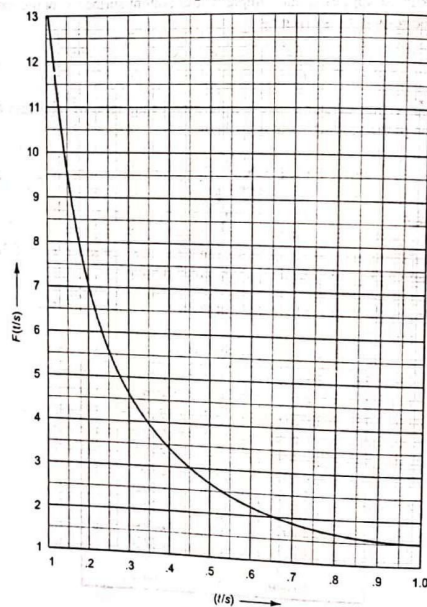


Fig. 35.3(b)

Thus from Eqns. 35.9 and 35.10, we have for resistivity,

$$\rho = \frac{V}{I} \times \frac{2\pi s}{F(t/s)} \quad (35.12)$$

Since t and s are known for the sample and V and I are measured in the experiment, ρ can be evaluated.

The formula for the variation of resistivity with temperature can be obtained by taking the inverse of both the sides of Eqn. 35.3. Thus, we have,

$$\rho = \rho_0 e^{\frac{E_g}{2kT}} \quad (35.13)$$

or

$$\ln \rho = \ln \rho_0 + \frac{E_g}{2kT}$$

or

$$\log_{10} \rho = \log_{10} \rho_0 + \frac{E_g}{2 \times 2.303 \times kT} \quad (35.14)$$

So a graph between $\frac{1}{T}$ and $\log_{10} \rho$ would be a straight line. From the slope of this line, the band gap E_g can be determined.

Procedure

1. First take out the four probe arrangement from the oven and put it on a plane surface. Now put the sample on the base plate of the Four Probe arrangement such that the non-conducting surface of the crystal is on the plate side and the four probes are in the middle of the crystal. Apply pressure slightly so that the probes clearly make contact with the sample and then tighten the screw. Now check the continuity between the sample and four probes by a multimeter. If the contacts are loose tighten the screws provided on top of the base stand till the four probes touch the crystal.
2. Put the four probe arrangement in the oven and check the continuity between each pair of leads provided for current and voltage again.
3. Put the thermometer in the hole provided for it to measure the oven temperature.
4. Connect the probes 1 and 4 to the constant current source.
5. Connect a digital millivoltmeter between the probes 2 and 3.
6. Switch on the current source and set the current to say 4 mA.
7. Note down the voltage V in the voltmeter.
8. Switch on the oven and note down V for different temperatures while heating the sample. Take observations till the temperature is $\sim 200^\circ\text{C}$.
9. Switch off the oven and repeat the observations while cooling the sample. Find the mean voltage V for each temperature.
10. Repeat the experiment for another value of current say 6 mA.
11. From the values of t and s supplied by the manufacturer, find the correction divisor F (using the Table 35.1 or the graphs in Figs. 35.3(a) and (b)). Calculate ρ for each reading and draw a graph between ρ and T to see the variation of resistivity with temperature.
12. Plot a graph between $\frac{10^3}{T}$ and $\log_{10} \rho$.

Observations

Least count of the thermometer = ... °C
 Distance between the probes, s = ... cm.
 Thickness of the crystal t = ... cm.
 t/s = ...
 Correction divisor, $F(t/s)$ = ...

$$\frac{2\pi s}{F(t/s)} = D = \dots \text{cm} = \dots \text{m.}$$

Set ICurrent I = ... mA.

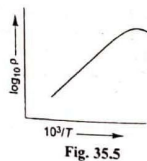
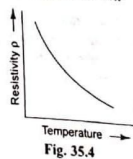
S. No.	Temp T (°C)	Temp. T (K)	Voltage V (mV)		Mean V (mV)	Resistivity $\rho = \frac{V}{I} \times D$ ($\Omega \text{ m}$)	$\frac{1}{T} \times 10^3$ (K^{-1})	$\log_{10} \rho$
			while heating	while cooling				
1								
2								
3								
.								
.								
.								
.								
.								
.								

Set II Make a similar table for $I = 6 \text{ mA}$.**Calculations**

$$\ln \rho = \ln \rho_0 + \frac{E_g}{2kT} \quad (i)$$

$$\text{or } \log_{10} \rho = \log_{10} \rho_0 + \frac{E_g}{2 \times 2.303 \times kT} \quad (ii)$$

The graph in Fig. 35.4 gives the variation of resistivity with temperature. A plot between $10^3/T$ along x-axis and $\log_{10} \rho$ along y-axis for one of the sets is shown in Fig. 35.5. As is evident from Eqn. (ii), the straight line portion of this graph has a slope equal to



$$E_g = 2 \times 2.303 \times 10^3 \times k \times \text{slope}$$

$$\text{Putting } k = 8.54 \times 10^{-5} \text{ eV/K}$$

$$E_g = 0.3934 \times \text{slope}$$

$$= \dots \text{ eV for Set I}$$

$$= \dots \text{ eV for Set II}$$

$$\text{Mean } E_g = \dots \text{ eV}$$

Note: As is seen in Fig. 35.5, the graph between $10^3/T$ and $\log_{10} \rho$ is linear only for high temperatures ($T \geq 100^\circ\text{C}$). This linear portion is to be used for calculations. It is evident that we need to heat the sample much above 100°C to get the results.

Result

(i) Resistivity ρ for the given sample of the semiconductor decreases with increasing temperature.

(ii) The band gap E_g for the given semiconductor at room temperature = ... eV.

Actual value = ...
 % Error = ...

Precautions and Sources of Error

1. Current should be constant while performing the experiment.
2. Readings should be taken not only while heating the sample but also while cooling it. Better results are expected while cooling since more stable conditions prevail.
3. The top of the sample should be cleaned very carefully with the finest quality sand paper to remove any coating formed on it.
4. The pressure on the probes should be just appropriate to make a contact. Too much pressure can break the crystal.
5. The sample should be heated to a temperature near about $180\text{--}200^\circ\text{C}$.
6. The tip of thermometer should be well inside the hole and temperature should be read carefully.
7. It is assumed here that the bottom of the sample is non-conducting.
8. The surface on which the probes rest should be flat with no surface leakage.
9. The four probes should lie in a straight line.

Weak Points

The resistivity of the sample may not be uniform in the area of measurement and may affect the results. Although probes are preferred in place of soldered contacts, the main disadvantage with them is that they may be noisy. This problem can, however be overcome by keeping the contacts clean and firm.

35.6 HALL EFFECT

The conductivity measurements are not sufficient for the determination of the number density of charge carriers (n) and their mobility (μ). Moreover these measurements do not give any information about the sign of the majority charge carriers. The Hall effect supplies all this information.