Consider the action of the magnetic field on electric current flowing in an extrinsic semiconductor. The moment the electric field is switched on, an electric current is established, the density of which is

$$\mathbf{j} = \sigma \mathbf{E} \qquad (35.15)$$

The charge carriers acquire a directional velocity v_d (drift velocity) in the direction of the field in case of holes and against the field in case of electrons (Fig. 35.6).

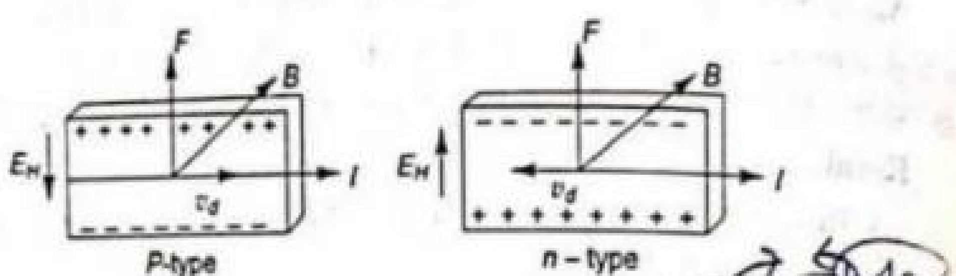

Fig. 35.6

When the magnetic field is switched on, a force perpendicular to both v_d and **B** begins to act on electrons and holes.

$$\mathbf{F} = e(v_d \times \mathbf{B}) \qquad (35.16)$$

This is called *Lorentz force* whose direction is given by the Flemming's left hand rule.

If the thumb, index finger and middle finger of the left hand are held at right angles to each other, and the index finger points in the direction of the magnetic field **B** *while the middle finger in the direction of current* **I**, *then the thumb will indicate the direction of the Lorentz force* **F**.

Since for electrons, both e and v_d are negative and for holes both are positive, the Lorentz force is same for both type of carriers, i.e., the *Lorentz force is independent of the charge carrier's sign, being dependent only on the direction of I and B*. In Fig. 35.6 **F** is directed upwards for both n-type and p-type semiconductors, i.e. *the electrons and holes are deflected in the same direction under the effects of a given electric and magnetic field.*

The opposite faces of the sample will become charged as shown in Fig. 35.6, and as a result an electric field E_H will be established. *This field is called the Hall-field and this phenomenon is called the Hall-effect.* The value of E_H will continue to grow until the Lorentz force is compensated by the oppositely directed electric force qE_H (or eE_H).

i.e., $$eE_H = F \qquad (35.17)$$

[*Note:* Remember that the charge e on the carriers is positive for holes and negative for electrons. Thus while E_H is oppositely directed in p-type and n type semiconductors (Fig. 35.6), the electric force eE_H is in the same direction for both and that is in a direction opposite to that of the Lorentz force.]

Clearly, the Hall field is a function of the applied magnetic field B and the current density j i.e.,

$$E_H \propto jB$$

or $$E_H = R_H\, jB \qquad (35.18)$$

where R_H is the constant of proportionality and is called *Hall Coefficient.*

Thus the Hall coefficient may be numerically defined as the Hall electric field produced by unit current density and unit magnetic field. It is measured in units $\Omega\, m^3\, Weber^{-1}$ or $m^3\, coul^{-1}$.

From Eqn. (35.16) and (35.17), we have,

$$e E_H = F = e v_d B$$

$$= e \mu EB \quad \left(\text{as } \mu = \frac{v_d}{E}\right) \qquad (35.19)$$

From (35.18) and (35.19), we have

$$R_H j = \mu E$$

$$R_H = \frac{\mu E}{j}$$

$$= \frac{\mu E}{\sigma E}$$

$$R_H = \frac{1}{ne} \quad (\text{as } \sigma = ne\mu) \qquad (35.20)$$

Here σ and n denote the electrical conductivity and the carrier concentration of the semiconductor respectively.

Experiment 35.2: To determine the Hall coefficient and the Hall angle for the given sample of a semiconductor.

Apparatus: A thin semi-conductor rectangular slab (length > 3 × width), a constant current power supply (0–20 mA), an electromagnet, calibrated fluxmeter to measure the magnetic field, a digital milliammeter, a digital millivoltmeter, a voltmeter, two simple keys and connecting wires.

Theory: Hall effect is a magneto-electric effect as discussed earlier.

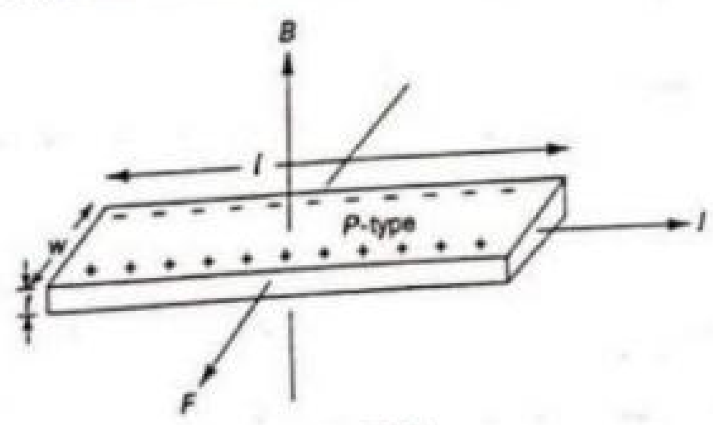

Fig. 35.7

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If a current I is passed in x direction of the speciment and magnetic field B is applied in y direction, then a potential difference, called the Hall Voltage V_H is produced in z-direction. The sign of this voltage depends on the nature of the charge carriers, and can be used to find out whether the sample is p-type or n-type.

Suppose, the semiconductor specimen is a slab of length l, width w and thickness t. As already discussed [Eqn. (35.18)], the Hall field is given by, $E_H = R_H jB$ where $j = \frac{I}{wt}$ is the current density and B is the applied magnetic field. R_H is the *Hall coefficient* and is given by,

$$R_H = \frac{1}{ne}$$

$$\therefore \qquad E_H = R_H \frac{I}{wt} B$$

As wE_H is equal to the Hall voltage V_H, the Hall's coefficiently R_H is given by,

$$R_H = \frac{V_H}{I} \frac{t}{B} \qquad (35.21)$$

Since the quantities on the R.H.S. can be found experimentally, the Hall coefficient R_H can be determined.

Hall angle A charge carrier (electron or hole) is under the influence of two electric fields simultaneously, applied electric field **E** and Hall field $\mathbf{E}_H$ at right angles to each other. The resultant electric field $\mathbf{E}' = \mathbf{E} + \mathbf{E}_H$ will make an angle ϕ with x-axis or with I. The angle ϕ which $\mathbf{E}'$ makes with the direction of current is termed as *Hall angle*.

Thus $$\tan \phi = \frac{E_H}{E} = \frac{V_H/w}{V/l} = \frac{V_H}{V} \frac{l}{w} \qquad (35.22)$$

Thus measuring V_H and V simultaneously for a given I and B the Hall's angle can be determined.

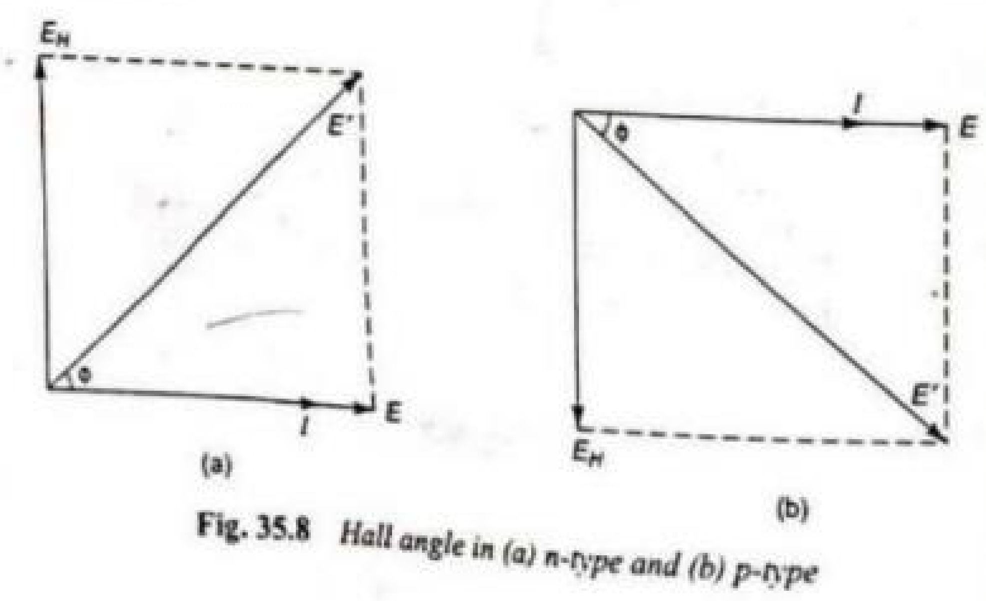

Fig. 35.8 *Hall angle in (a) n-type and (b) p-type*

Procedure

1. Place the semiconductor sample at the centre between the pole-pieces of the electromagnet with the help of a stand such that the magnetic field is perpendicular to the face of the sample i.e., B is along the thickness of the sample. Make the connections as shown in Fig. 35.9 and switch on the constant current power supply. The current flows along the length of the specimen.

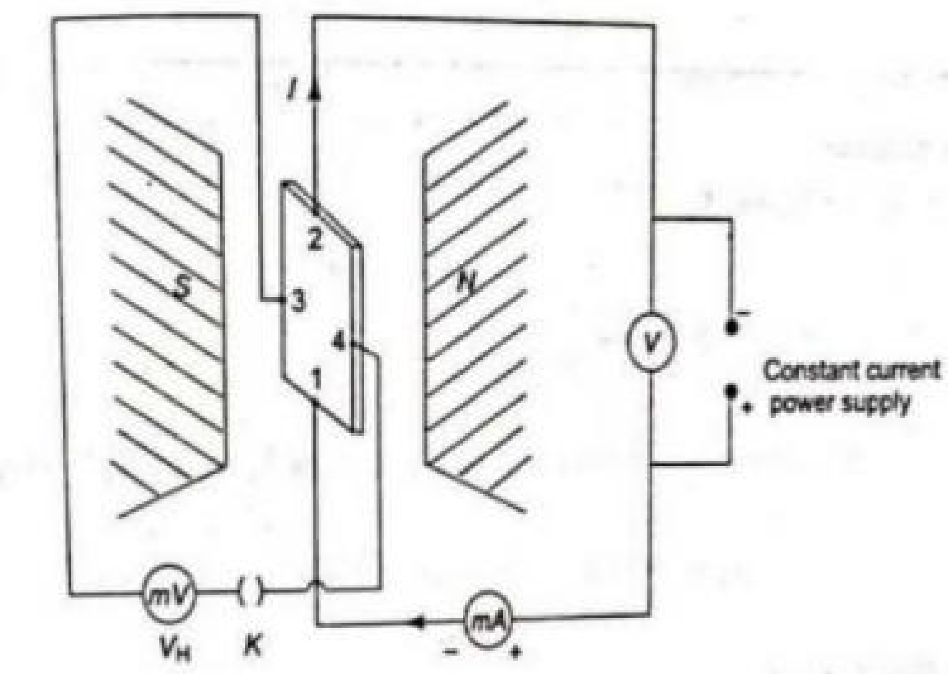

Fig. 35.9

2. Note down the applied voltage V and the current I through the sample.
3. Close the key K. The voltage appearing along the width of the sample (between the points 3 and 4) is called the offset voltage. Note it down.
4. Open the key K, switch on the electromagnet and wait for 2–3 minutes. Close the key K and measure the Hall voltage developed along the width of the specimen. Subtract the offset voltage from it to get the corrected Hall-voltage V_H.
5. Repeat the steps 2 to 4 by varying the current in small steps and measure the corresponding voltage V and Hall voltage V_H.
6. Measure the magnetic field strength B with the help of a Gauss-meter or flux-meter. Convert it to Weber/m^2 by using the relation 1 Gauss = 10^{-4} Weber/m^2.
7. Measure the length, width and thickness of the specimen with the help of vernier callipers and screw gauge.
8. Plot a graph with I along x-axis and V_H along y-axis.
9. Plot a graph with V along x-axis and V_H along y-axis.

Observations

Length of the sample l = ... cm = ... m
Width of the sample w = ... cm = ... m
Thickness of the sample t = ... cm = ... m
Magnetic field B = ... Wb/m^2

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S. No.	Pot. diff. V (mV)	Current I (mA)	Offset Voltage (mV)	Hall Voltage (mV)	Corrected Hall voltage V_H (mV)
1.					
2.					
3.					
4.					
5.					
6.					

Calculations

For Hall coefficient R_H

$$R_H = \frac{V_H}{I}\frac{t}{B}$$

$\frac{V_H}{I}$ is given by the slope of the straight line in the V_H versus I plot (Fig. 35.10).

$$\therefore \quad R_H = \text{Slope} \times \frac{t}{B} = \ldots\ \Omega\, m^3\, Wb^{-1}$$

For Hall angle ϕ

$$\tan\phi = \frac{V_H}{V}\frac{l}{w}$$

$\frac{V_H}{V}$ is given by the slope of the straight line in the V_H versus V plot (Fig. 35.11).

$$\therefore \quad \tan\phi = \text{Slope} \times \frac{l}{w} = \ldots$$

or $\phi = \ldots$ degree

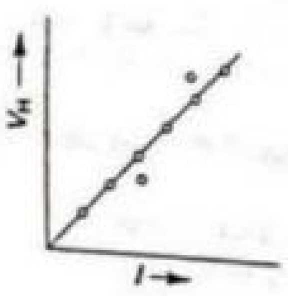

Fig. 35.10

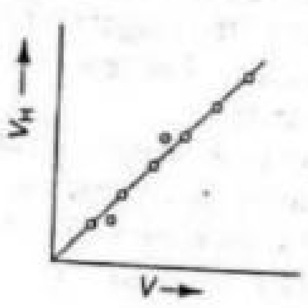

Fig. 35.11

Result: (*i*) The Hall coefficient $R_H = \ldots\ \Omega\ m^3\ Wb^{-1}$ (or m^3/Coul)
(*ii*) Hall angle $\phi = \ldots$ degree

Precautions and Sources of Error

1. Hall voltage developed is very small and hence it must be measured very carefully by a high input impedance ($\approx$ 1 MΩ) device such as electronic digital voltmeter or electrometer.
2. Sometimes V_H is not zero for zero magnetic field. This is due to imperfect alignment between the contacts for measuring V_H. This offset voltage should be taken care of.
3. The theory assumes that all the carriers are moving only lengthwise. Practically it has been found that a closer to ideal situation may be obtained if the length of the sample is at least three times its width.
4. Reading for V_H should be taken 2–3 minutes after switching on the magnetic field.
5. While determining the Hall coefficient, variation of V_H with I is preferred over the variation of V_H with B due to the difficulties arising in the accurate determination of B.
6. For no field readings, care should be taken that no remanent field exists in the electromagnet when switched off.
7. The magnetic field should be measured carefully.
8. The current through the sample should not be large enough to cause heating.

Weak Points

The measurement of the field with a gauss-meter is the least accurate measurement in the experiment and might introduce some error. Also the voltage appearing between the Hall probes is not generally the Hall-voltage alone. There are other galvano-magnetic and thermomagnetic effects which can produce voltage between the Hall probes. In addition *IR* drop due to probe misalignment and thermoelectric voltage due to transverse thermal gradient may be present. All these can be eliminated by taking four readings of V_H, two by reversing the current through the sample and two by reversing the direction of the magnetic field. Taking the average of the four readings would eliminate all the above effects and would give the correct Hall-voltage.

Experiment 35.3: To study the Hall effect and hence to determine the carrier concentration *n*, the electrical conductivity σ, the mobility of charge carriers μ and the conductivity-type for the given sample of a semiconductor.

Apparatus: Same as in Experiment 35.2.

Theory: All these parameters can be found from the same observations as taken in the previous experiment.

For carrier concentration

From the value of the Hall coefficient R_H, the carrier concentration *n* of the sample can be obtained from the relation.

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