# Hall Effect

## Experiment No. 12

**Object :** **To study the Hall effect and to determine Hall coefficient, carrier density and mobility of a given semiconductor (N–type) material using Hall effect set-up.**

**Apparatus :** *A rectangular slab of specimen crystal to about 7 mm × 2 mm × 0.2 mm dimensions, an electromagnet capable of producing magnetic field of the order of $10^3 - 10^4$ gauss, a battery, two plug keys, milliammeter, millivoltmeter or an electronic voltmeter, a voltmeter for measuring applied potential difference, rheostat, search coil, a calibrated fluxmeter or a ballistic galvanometer to measure the magnetic field and connection wires.*

**Description of the Apparatus and Circuit :** A schematic diagram of the apparatus and their associated circuit is shown in fig. 12.1. The rectangular slab of semiconductor crystal (*N*-type) of dimensions about 7 mm × 2 mm × 0.2 mm is placed between the pole pieces of a strong electromagnet capable of producing

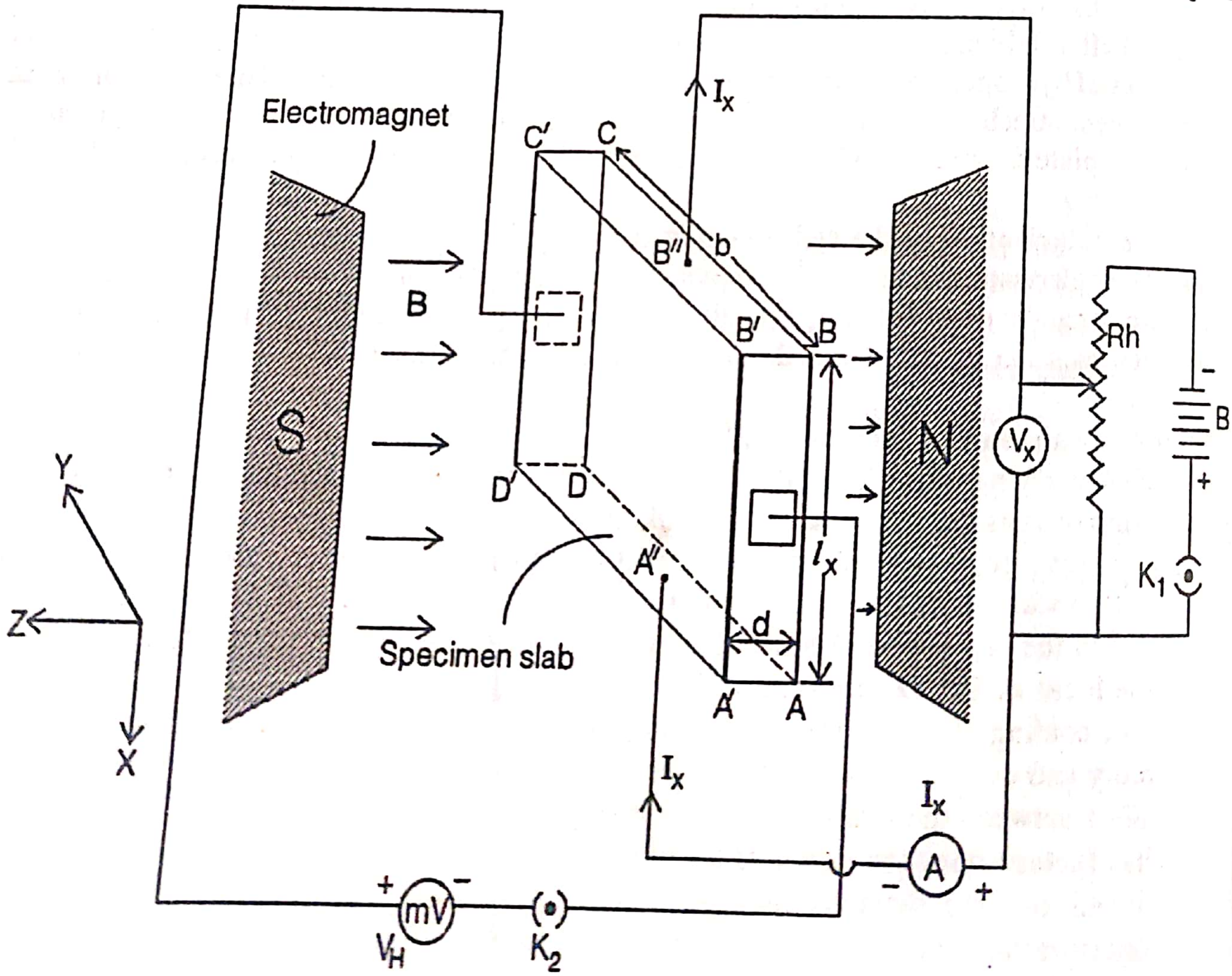


Fig. 12.1

magnetic field of the order of $10^3 - 10^4$ gauss. A battery in series with a key $K_1$ is connected across the fixed terminals of the rheostat *Rh* used as a potential divider. The voltmeter *V* of the potential divider in series with an ammeter *A* is connected across the length of the specimen slab for measuring the applied voltage $V_x$ and the current $I_x$ passing in *X*-direction through it. To measure the Hall Voltage $V_H$ along *Y*-axis, a millivoltmeter in series with a plug key $K_2$ is connected as shown in fig. 12.1.

A stabilised source having variable voltage is used to fed current in the electromagnet (not shown). Either a calibrated fluxmeter is used to measure magnetic field or the deflection of a suitable ballistic galvenometer is calibrated to give the value of magnetic field.

## Principle and Theory

**Principle :** When a current carrying conductor is placed in a magnetic field, acting in a direction perpendicular to the direction of the current, a potential difference is developed across those faces of the conductor which are at right angle to both current and magnetic field. This phenomenon is called Hall effect and the induced potential difference is called Hall Voltage.

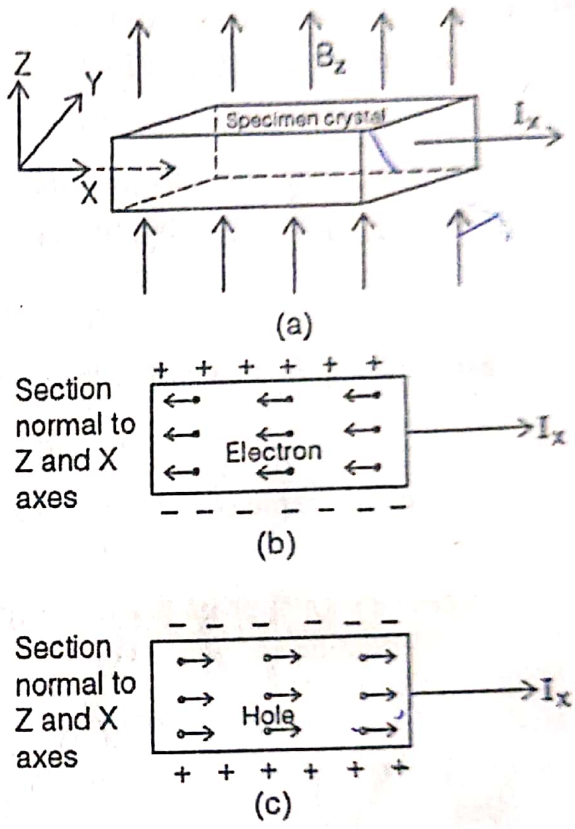


Fig. 12.2

If the current flows in *X*-direction and magnetic field is applied along *Z*-direction, then the voltage is developed across those faces which are perpendicular to *X*-axis (Fig. 12.2a). The sign of the Hall voltage so developed decides the nature of the charge carriers, that is, whether the induced current is due to the motion of electrons towards the left (Fig 12.2b) or due to the motion of the holes towards the right (Fig. 12.2c) within the bar.

**Theory :** The electric field $E_x$ applied along *X*-direction exerts a force on the charge carriers (say electrons, each of charge *e*) due to which electrons acquire a drift velocity $v_x$ in *X*-direction. The charge moving with drift velocity $v_x$ experiences a magnetic force $\vec{F}_m$ perpendicular to both the velocity $v_x$ and magnetic field induction $\vec{B}_z$ and is given by

$$\vec{F}_m = q(\vec{v} \times \vec{B}) = e(v_x i \times B_z k)$$
$$= -ev_x B_z j$$

This force acts along negative *Y*-axis due to which electrons on which it is exerted drift from positive *Y*-axis toward negative *Y*-axis. Thus, an induced electric field, called Hall electric field, $E_H$ is established which causes a Hall potential difference $V_H$ across the positive and negative *Y*-axes with positive *Y*-axis being at high potential difference (Fig. 12.2b). If the charge carriers are holes then the polarity of potential difference is reversed, that is, the surface towards the negative *Y*-axis would be at higher potential [Fig 12.2 c] than the surface towards the positive *Y*-axis. Hall electric field so produced opposes the drifting of the electrons and very soon an equilibrium is reached due to the establishment of the condition of balance between the magnetic force $e(\vec{v} \times \vec{B})$ on the electrons along negative *Y*-axis and the electric force $eE_H$ along positive *Y*-axis and consequently drift velocity acquires a steady value. In this situation the net force acting on the electrons would be zero, that is,

$$e\vec{E}_H + e\vec{v}_x \times \vec{B}_z = 0$$

or

$$\vec{E}_H = -(\vec{v}_x \times \vec{B}_z)$$

In terms of magnitude

$$E_H = v_x B_z \quad \text{......(1)}$$

If $b$ is the breadth of the specimen slab in $Y$-direction, then

$$E_H = \frac{V_H}{b} \quad \text{or} \quad V_H = bE_H$$

where $V_H$ is the Hall potential difference.

Substituting the value of $E_H$ from equation (1) in the above equation, we have

$$V_H = b\, v_x B_z \quad \text{......(2)}$$

If $n$ is the number of charge carriers (electrons) per unit volume, then current density $J_x$ is related with the drift velocity $v_x (= v_d)$ of the electrons as

$$v_x = -\frac{J_x}{ne} \quad \text{......(3)}$$

Substituting the value of $v_x$ from equation (3) in equation (1), we get

$$E_H = \left(-\frac{1}{ne}\right) J_x B_z \quad \text{......(4)}$$

The quantity $1/ne$ is called **Hall coefficient** for the material of the specimen slab and represented as

$$R_H = -1/ne$$

Negative sign appears due to the consideration of electrons as charge carriers.

From equation (4), we have

$$R_H = \frac{E_H}{J_x B_z} \quad \text{......(5)}$$

But

$$J_x = \frac{\text{Current}}{\text{Area of cross section}} = \frac{I_x}{bd}$$

$$\therefore \quad R_H = \frac{(V_H/b)}{(I_x/bd)B_z} = \frac{V_H}{I_x}\frac{d}{B_z} \text{ ohm-m}^3\text{/weber} \quad \text{......(6)}$$

where $B_z$ is in weber/m$^2$ and $d$ in meter.

The ratio $V_H/I_x$ is determined graphically.

**Hall Angle :** A charge carrier (electron or hole) is under the influence of simultaneously applied electric field $E_x$ and Hall electric field $E_H$ at right angles to each other. Therefore, the drift velocity $v_x$ of the charge carriers makes an angle with $X$-direction. This angle is called **Hall angle** and is expressed as

$$\phi = \frac{E_H}{E_x}$$

If $l_x$ be the length of the slab and $V_x$ the potential applied across $X$-direction, then

$$\text{Hall angle,} \quad \phi = \frac{E_H}{E_x} = \frac{(V_H/b)}{(V_x/l_x)} = \frac{V_H}{V_x}\frac{l_x}{b} \text{ rad} \quad \text{......(7)}$$

**Hall Mobility :** The drift velocity acquired by the charge carriers in unit applied electric field is called the mobility of the charged carriers and is denoted by $m_\mu$

$$\therefore \qquad m_\mu = \frac{v_x}{E_x} \quad \text{or} \quad v_x = m_\mu E_x$$

Substituting, this value of $v_x$ in equation (2), we get

$$V_H = b m_\mu E_x B_z \quad \text{or} \quad E_H = \frac{V_H}{b} = m_\mu E_x B_z$$

Substituting the value of $E_H$ from equation (5) in the above equation, we get

$$R_H J_x B_z = m_\mu E_x B_z$$

$$\therefore \qquad m_\mu = R_H \frac{J_x}{E_x} = R_H . \sigma \qquad \text{.......(8)}$$

where $\sigma = \frac{J_x}{E_x}$ is called the **electric conductivity** of the specimen slab.

Substituting the value of $R_H$ from equation (6) in the above equation, we get

$$m_\mu = \left(\frac{V_H}{I_x} \cdot \frac{d}{B_z}\right) \frac{J_x}{E_x} = \frac{E_H b}{J_x bd} \cdot \frac{d}{B_z} \cdot \frac{J_x}{E_x} = \left(\frac{E_H}{E_x}\right) \frac{1}{B_z} = \frac{\phi}{B_z} \text{ rad-m}^2\text{/weber} \qquad \text{.......(9)}$$

Thus, on substituting known values of $\phi$ and $B_z$ Hall mobility can be determined.

**Formula Used :** *When a specimen rectangular slab of semiconductor with length $l_x$ (AB) along X-axis, breadth b (BC) along Y-axis and thickness d(AA') along Z-axis (Fig. 12.2) be placed in a magnetic field B (applied along Z-axis) and if $I_x$ current is made to flow along X-axis in the slab, then a voltage, called Hall voltage, $V_H$ is developed across the faces which are normal to Y-axis. This Hall voltage is measured with the help of millivoltmeter connected in the circuit. The allied parameters such Hall coefficient $R_H$, number of charge carriers per unit volume n, Hall angle $\phi$ and mobility of charge carriers $m_\mu$ are determined by using following relations :*

1. *Hall coefficient :* $$R_H = \frac{V_H}{I_x} \cdot \frac{d}{B_z} \text{ ohm-m}^3\text{/weber}$$

   *If $\mu$ is the permeability of the medium of the slab, then actual magnetic field within the rectangular slab is* $$B_z = \mu B$$

2. *Number of charge carriers per unit volume n in the semiconductor slab is calculated as*

   $$n = \frac{1}{e R_H}$$

   *where e is the charge on the electron or hole and equal to $1.6 \times 10^{-19}$ coulomb.*

3. *Hall angle :* $$\phi = \frac{V_H}{V_x} \frac{l_x}{b} \text{ radian}$$

   *where $V_x$ is the potential difference applied across the specimen length.*

4. *Mobility of charge carriers : $m_\mu = \phi / B_z$ rad-m$^2$/weber*

   *where $B_z$ is determined by a gaussmeter or fluxmeter or ballistic galvanometer.*

*The electrical conductivity of the specimen slab $\sigma$ is calculated as*

$$\sigma = \frac{m\mu}{R_H} \ mho\ m^{-1}$$

**Procedure**

1. Connect each component of the apparatus in according to the circuit diagram shown in fig. 12.1.
2. Measure the dimensions of the specimen slab, that is, length $l_x$ along $X$-axis, breadth $b$ along $Y$-axis and thickness $d$ along $Z$-axis in meters.
3. Place the specimen well within the pole pieces of electromagnet and ensure that the fields are in crossed setting (that is, they are mutually perpendicular to each other).
4. Now the magnetic field is applied along $Z$-axis of the slab by switching on the circuit of the electromagnet. Allow some current $I_x$ in the specimen along $X$-axis with the help of rheostat $Rh$ and by closing key $K_1$. The current $I_x$ in ammeter and potential difference $V_x$ developed across the specimen length is measured. The corresponding Hall potential difference $V_H(V_y)$ is also recorded by closing the key $K_2$.
5. Change the value of $I_x$ in steps by rheostat $Rh$ and corresponding values of $V_x$ and Hall voltage $V_H$ are noted. A graph showing the variation of $V_H$ with $I_x$ is plotted. The slope of the graph gives the value of $V_H/I_x$.
6. Repeat the above process for different values of $B_z$ and find $V_H/I_x$ for each set of observation by plotting separate graphs.
7. The magnetic field strength $B_z$ of the electromagnet is measured with a gaussmeter or fluxmeter or ballistic galvanometer. If it is measured with gaussmeter, then the value of $B$ is converted in the units of weber/m² (1 gauss = $10^{-4}$ weber/m²).

**Measurement of magnetic field by Ballistic galvanometer**

If the magnetic field is measured with ballistic galvanometer, then ballistic galvanometer is pre calibrated to find $B$. The deflection of ballistic galvanometer is calibrated in terms of standard magnetic field. For this a graph is plotted between the deflection and the known magnetic field. The graph will be a straight line. Now the deflection with unknown field is noted and the corresponding value of magnetic field is calculated from the calibrated graph. The actual field inside the slab is found by using the relation.

$$B_z = \mu B$$

where $B$ is the observed magnetic field and $\mu$ the permeability of the specimen slab.

**Measurement of Magnetic field by Fluxmeter :** The magnetic field between the pole pieces of an electromagnet is also measured with the help of fluxmeter and search coil in the following manner :

The experimental arrangement for measuring the magnetic field between the pole pieces of an electromagnet is shown in fig. 12.3. A small closely wound coil, known as search coil is place in the gap between the pole pieces with its plane normal to the field and is connected with the fluxmeter. The deflection in the fluxmeter is measured with the help of a pointer moving over the scale, which is calibrated in terms of number of turns. The current in the electromagnet circuit is

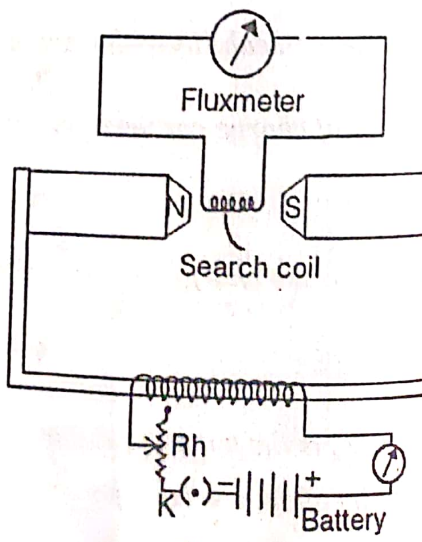


Fig. 12.3

varied by means of a rheostat $Rh$ and the corresponding deflection is noted. The current is measured by means of an ammeter $A$ connected in the circuit.

Suppose $\theta$ be the deflection produced in the fluxmeter when a current of I amp. is fed to the electromagnet and if one division of the fluxmeter scale corresponds to $n$ turns, then total flux passing through the search coil will be $\theta \times n$. Let $A$ be the area of cross-section of each turn of the search coil and $N$ the total number of turns. The magnetic field $B$ in the search coil is given by

$$B = \frac{\theta \times n}{A \times N} \text{ Oersted}$$

Since the different value of current $I$ gives different value of deflection in the fluxmeter, we get different values of $B$ corresponding to different values of $I$.

A graph is plotted by taking the values of $I$ along $X$-axis and corresponding values of magnetic field $B$ along $Y$-axis (Fig. 12.4) which gives a straight line. The curve so obtained is the calibration curve for the fluxmeter. With the help of this curve one can readily obtained magnetic field for a given value of current.

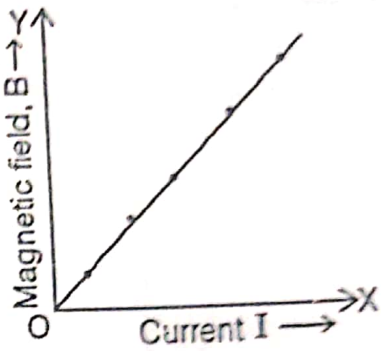

Fig. 12.4

The actual field inside the specimen crystal is obtained by using the relation

$$B_z = \mu B$$

where $B$ is the magnetic field measured by fluxmeter.

## Observations

*Length of the specimen slab along X-axis,* $l_x = \ldots$ *meter*

*Breadth of the specimen slab along Y-axis,* $b = \ldots$ *meter*

*Thickness of the specimen slab along Z-axis,* $d = \ldots$ *meter*

*Permeability of the medium of the specimen,* $\mu = \ldots$

*Number of turns correspond to one division of the fluxmeter scale,* $n = \ldots$

*Total number of turns in the search coil,* $N = \ldots$

*Mean area of the search coil,* $A = \ldots\ m^2$

**Table A : For the measurement of magnetic field B by Fluxmeter**

| S.No. | Current in the ammeter I (amp) | Deflection in the fluxmeter $\theta$ | Magneticfield B(= $\theta$n/AN) |
|---|---|---|---|
| 1. | ........ | ........ | ........ |
| 2. | ........ | ........ | ........ |
| 3. | ........ | ........ | ........ |
| 4. | ........ | ........ | ........ |

**Note :** *Plot a graph between B and I.*

**Table B : For the measurement of Hall Voltage $V_H$**

| S.No. | Magnetic field B* measured with fluxmeter = ... Weber/m$^2$ Actual magnetic field, $B_z = \mu B$ = ... Weber/m$^2$ | | |
|---|---|---|---|
| | Current $I_x$ in the specimen (amp) | Applied potential difference, $V_x$ (Volt) | Hall Voltage Devoloped $V_H (= V_y)$ (Volt) |
| 1. | ... | ... | ... |
| 2. | ... | ... | ... |
| 3. | ... | ... | ... |
| 4. | ... | ... | ... |
| 5. | ... | ... | ... |
| 6. | ... | ... | ... |
| 7. | ... | ... | ... |
| 8. | ... | ... | ... |

*For different values of $B$ similar tables are constructed.

**Calculations :** *A graph is plotted by taking $I_x$ along X-axis and the corresponding Hall voltage $V_H$ along Y-axis, which will be a straight line as shown in Fig. 12.5.*

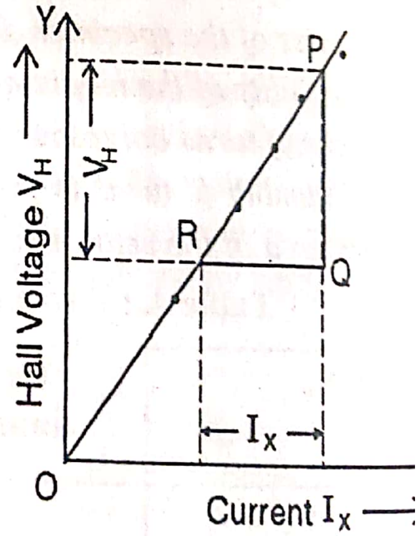


Fig. 12.5

*The slope of the curve* $= \dfrac{PQ}{RQ} = \dfrac{V_H}{I_x} = \ldots$

*The Hall coefficient is*

$$R_H = \frac{V_H}{I_x} \cdot \frac{d}{B_z} = \left(\frac{PQ}{RQ}\right)\frac{d}{B_z} = \ldots \text{ ohm-m}^3/\text{weber}$$

*The number of charge carriers per unit volume is*

$$n = \frac{1}{eR_H} = \frac{1}{1.6 \times 10^{-19} R_H} = \ldots$$

*Hall angle,* $\phi = \dfrac{V_H}{V_x} \cdot \dfrac{l_x}{b} = \ldots$ *rad*

*Mobality of charge carriers,* $m_\mu = \dfrac{\phi}{B_z} = \ldots$ *rad m$^2$ weber$^{-1}$*

*The electrical conductivity of the specimen slab* $\sigma = \dfrac{m_\mu}{R_H} = \ldots$ *mho-m$^{-1}$*

$\frac{V_H d}{I B_z}$

**Results :** *The experimentally observed values of the various allied parameters are :*

$\frac{V_H t}{V I b}$

1. *Hall Coefficient* $R_H$ = ... *ohm-m³/weber*
2. *Number of charge carriers per unit volume,* $n$ = ...
3. *Hall angle* $\phi$ = ... *rad*
4. *Mobility of charge carriers,* $m_\mu$ = ... *rad-m³/weber*
5. *Electrical conductivity of the specimen slab,* $\sigma$ = ... *mho/m*

## Precautions and Sources of Error

1. *Hall voltage should be measured very carefully and accurately either by a millivoltmeter or by a potentiometer.*
2. *The distance between the pole pieces of the electromagnet should not be changed during the whole experiment.*
3. *Magnetic field should be kept constant for one set of observations.*
4. *Current passing through the experimental slab of the semiconductor should be strictly within the permissible limit.*

## Viva-Voce

**Q. 1. What are you doing ?**

**Ans :** Sir, I am studying Hall effect in a semiconductor.

**Q. 2. What is Hall effect ?**

**Ans :** When a current carrying conductor is placed in a transverse magnetic field a potential difference is developed across the conductor in the direction perpendicular to both current and magnetic field. This phenomenon is called Hall effect.

**Q. 3. On what factor the sign of Hall potential difference depends ?**

**Ans :** The sign of Hall potential difference depends upon the nature of charge carriers. It decides whether a specimen semiconductor is of *n*-type or *p*-type.

**Q. 4. Why is the Hall potential difference developed when a transverse magnetic field is applied to a current carrying conductor ?**

**Ans :** When a current carrying conductor is placed in a transverse magnetic field, the magnetic field exerts a deflecting force $\vec{F}$ on the charge carriers $[\vec{F} = e(\vec{V}_d \times \vec{B})]$ in a direction perpendicular to both drift velocity $\vec{v}_d$ and applied magnetic field $\vec{B}$. The forces cause those charges to drift from one surface to the other on which they are being exerted. Thus, the excess negative charge at one surface and the corresponding excess of positive charge on the opposite surface creates an electric field which causes a Hall potential difference.

**Q. 5. How will you determine the direction of the force exerted on the charge carriers ?**

**Ans :** The direction of the force exerted on the charge carriers is determined by Fleming's left hand rule.

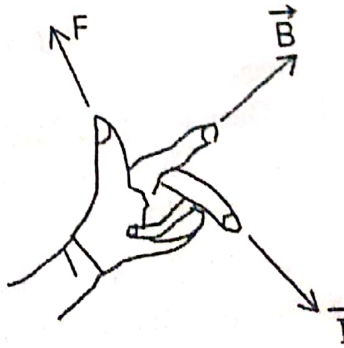


Fig. 12.6

**Q. 6. What is Fleming left hand rule ?**

**Ans :** If we stretch the fore finger, the middle finger and thumb of the left hand mutually at right angles to one another such that the fore-finger points in the direction of magnetic field $\vec{B}$ and the middle finger in the direction of current $I$, then the thumb will point in the direction of the force $\vec{F}$ acting on the conductor (Fig. 12.6).

**Q. 7. What are allied parameters in your experiment ?**

Ans : The allied parameters of this experiment are; Hall voltage $V_H$, Hall coefficient $R_H$, number of charge carriers per unit volume $n$, Hall angle $\phi$ and mobility of charge carriers $m_{\mu}$.

**Q. 8. What is Hall coefficient ?**

Ans : Hall coefficient, $R_H$ is numerically equal to the Hall electric field $E_H$ induced in a specimen crystal by unit current density ($J_x = 1$ amp/m$^2$) when it is placed transversely in a magnetic field of 1 weber/m$^2$.

**Q. 9. What is the unit of Hall coefficient ?**

Ans : The unit of Hall coefficient $R_H$ is ohm-m$^3$/weber or m$^3$/coulomb when the magnetic field is measured in weber/m$^2$.

**Q. 10. What happens to the induced Hall electric field when the strength of applied magnetic field is increased ?**

Ans : When the strength of applied magnetic field is increased, the induced Hall electric field in the conductor also increases ($E_H \propto B_z$).

**Q. 11. What happens to the induced electric field when the current per unit area in the specimen slab (current density $J_x$) is increased ?**

Ans : When the current per unit area in the specimen slab (current density) is increased, the induced Hall electric field also increases ($E_H \propto J_x$).

**Q. 12. What happens to the Hall coefficient when the number of charge carriers (say electrons) per unit volume is decreased ?**

Ans : Hall coefficient increases with the decrease of number of charge carriers per unit volume ($R_H \propto 1/n$).

**Q. 13. How does the concentration of charge carriers can be increased in a semi conductor ?**

Ans : The concentration of charge carriers can be increased by increasing the temperature and b illuminating the semiconductor. Both these methods generate new electron and hole pairs.

**Q. 14. How does the conductivity of a specimen semiconductor depends on the carriers concentration**

Ans : Conductivity of a semiconductor is proportional to the concentration of charge carrie (electrons or holes). Therefore, the conductivity may be increased by increasing either electro or holes.

**Q. 15. What do you mean by mobility of a charge carrier ?**

Ans : The mobility of a charge carrier is defined as the drift velocity acquired by a unit appli electric field, (that is, $m_{\mu} = v_x/E_x$). It may also be defined as the ratio of average drift velocity the charge carriers to the applied electric field.

**Q. 16. How does the mobility of a charge carrier depends on the electrical conductivity of t specimen ?**

Ans : The mobility of a charge carrier increases with the increase of electrical conductivity of t specimen.

**Q. 17. How will you determine the mobility of charge carrier in your experiment ?**

Ans : The mobility of charge carrier is determined by determining the Hall angle $\phi$ or the angle m by the drift velocity of the charge carrier with the direction of flow of current in the specin conductor and by the magnetic field $B_z$ in which the specimen is placed.

**Q. 18. What is the unit of mobility of charge carriers ?**

Ans : The unit of mobility is m$^2$/(volt-sec) or radian-m$^2$-weber$^{-1}$.

**Q. 19. What is Hall angle ?**

**Ans :** When a transverse magnetic field is applied to a current carrying conductor, then the charge carriers (electrons or holes) come under the influence of simultaneous applied electric field $E_x$ and induced Hall electric field $E_H$ at right angles to each other. In this situation the angle made by the drift velocity of the charge carrier with the $X$-direction is called Hall angle and represented as

$$\phi = \frac{E_H}{E_x}$$

**Q. 20. How does the magnetic field measured in your experiment ?**

**Ans :** A stabilized source having variable voltage is used to fed suitable current in the electromagnet. Either a calibrated fluxmeter or the deflection of a suitable ballistic galvanometer is calibrated to measure the value of magnetic field.

**Q. 21. What are the importance of Hall effect ?**

**Ans :** The Hall effect has following importance :

1. The sign of the Hall potential difference developed determines the nature of the charge carriers.
2. The mobility of charge carriers is measured directly.
3. It can be used to decide whether the specimen is a metal, semiconductor or an insulator.
4. With the help of Hall coefficient $R_H$ the number of charge carriers per unit volume can be determined.
5. With the help of Hall potential difference one can calculate the magnetic field.

**Q. 22. Which type of the charge carrier has greater mobility ?**

**Ans :** In the semiconductor, the electron mobility is greater than hole mobility.

**Q. 23. How does the mobality of charge carriers (electrons and holes) varies with the rise of temperature in semiconductors ?**

**Ans :** Mobility of electrons and holes in semiconductor decreases with the increase of temperature.

**Q. 24. Why does the conductivity of a semiconductor increases with the rise in temperature ?**

**Ans :** With the rise in temperature the carrier concentration increases and thus the conductivity of a semiconductor increases with the rise of temperature.

**Q. 25. What do you mean by ohmic contact ?**

**Ans :** In the semiconductor diodes it is assumed that the external applied bias voltage is completely available across the junction. To achieve this we use metal ohmic contacts at the two ends of the crystal. These contacts are so manufactured that the contact potential across these addition junctions is constant, that is, independent of the magnitude and direction of current. Such a contact is called ohmic contact.

**Q. 26. What happens if the junction is short circuited ?**

**Ans :** When the $PN$ junction is short circuited (or when $P$ and $N$ terminals are joined directly) no current can flow in the circuit and potential across the junction remain the same and is equal to its value under open circuit conditions.

❑