Observing Hall Effect in Semiconductors (General Physics)

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The Hall effect is a physical phenomena describing conduction of charge in semiconductor materials. Hall effect helps determine the polarity of charge carriers, defining the type (*p*-type or *n*-type) and mechanism of charge conduction. The Hall effect also has many interesting applications in sensing magnetic fields. Nowadays, Hall effect devices are used in the products that we come across several times in our daily life. These products range from personal electronic gadgets to satellites, automobiles to aeroplanes and home appliances to medical equipment.

The goal of this experiment is to introduce students to Hall Effect sensing. It will take you through the basic concepts of semiconductor physics such as charge carriers, drift velocity, mobility and Hall voltage. It will also introduce you to useful components such as the Hall probe, Gaussmeter, electromagnets and power supplies. The Hall probe with a Gaussmeter is used to measure the strength of a magnetic field.

KEYWORDS

Hall effect · semiconductor material · charge carrier concentration · Hall voltage · Hall coefficient

APPROXIMATE PERFORMANCE TIME 4 Hours

1 Experimental Objectives

The objectives of this experiment are:

1. To study Hall effect in a semiconductor and to measure the,

(a) Hall voltage, V_H
(b) Hall coefficient, R_H

2. to determine the type of majority carriers in the given semiconductor sample, and

3. to determine the charge carrier density per unit volume in the given semiconductor sample.

2 Theoretical Background

2.1 Insulators, Semiconductors and conductors

In a single atom, electrons occupy a discrete set of energy levels. When several atoms make a molecule, the energy levels get so close that they form energy bands. The valence electrons, bounded to individual atoms, are in *valence band*. Whereas the free or delocalized electrons are present in the *conduction band*. Materials may be differentiated by their *band gap*: which is the difference between the valence and conduction bands and where no energy levels are present. For an electron to jump from the valence band to the conduction band requires an energy equivalent to the band gap. A simplified diagram of the electronic band structure of insulators, conductors and semiconductors is shown in Figure 1.

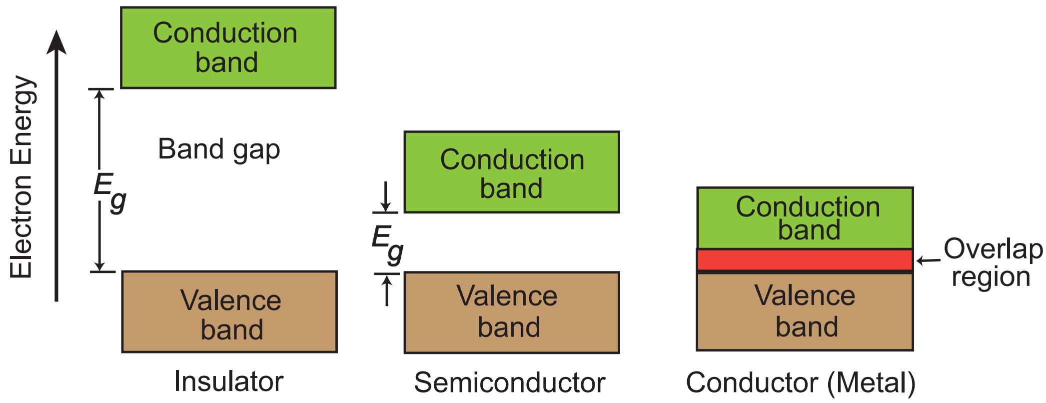


Figure 1: Electronic band diagram in insulators, semiconductors and conductors at absolute zero temperature (0 K).

Examples of E_g

Material	E_g(eV)
SiO_2	9
Si_3N_4	5
Si	1.12
Ge	0.66

In insulators (e.g. SiO_2, silicon nitride), valence and conduction bands are separated by a large band gap (E_g) while in conductors (e.g. copper, gold and silver etc.) there is no band gap separating conduction band from the valence band. In conductors, electrons at higher energy states in the valance band can freely move inside the conduction band. That's why metals are good conductors and electrons are the majority charge carrier. Generally, insulators have a band gap larger than 4 eV and semiconductors, which are inbetween insulators and conductors, have a band gap less than 4 eV.

2.2 Intrinsic and extrinsic semiconductors

A semiconductor in its pure form is known as an *intrinsic semiconductor*. Inside an intrinsic semiconductor at any temperature above absolute zero an electron, in the valance band, can overcome E_g and jump into the conduction band. In the process, it leaves an electron deficiency in the valence band this is called a *hole*. In an intrinsic semiconductor, the numbers of electrons in conduction band and holes in valence band are always equal. This scenario is shown in Figure 2(a). If a voltage is applied across an intrinsic semiconductor, both the electrons and the holes will contribute toward the electric current.

Some impurities can be added to an intrinsic semiconductor imparting different

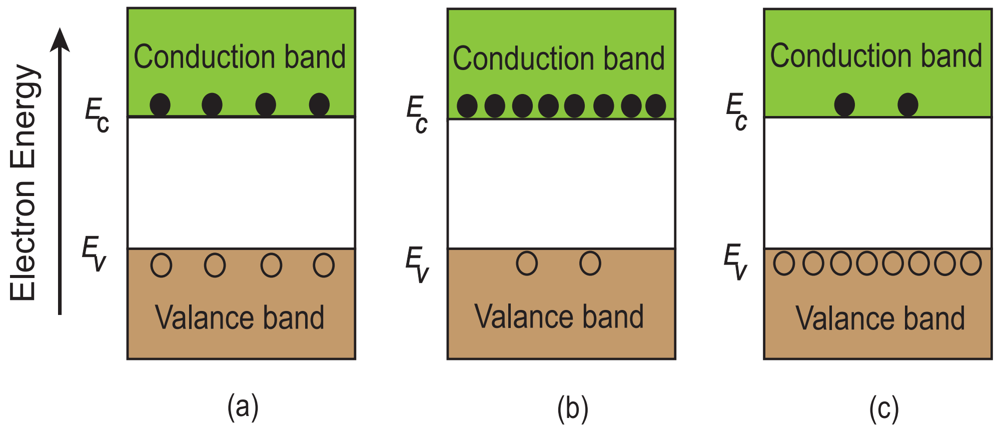
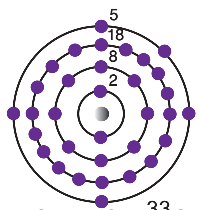
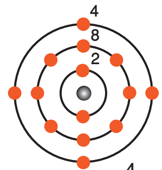


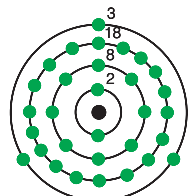
Figure 2: Energy band diagrams for (a) intrinsic, (b) *n*-type, and (c) *p*-type semiconductors. E_c and E_v are the edges of the conduction and valence bands, respectively. ○ Represent holes and ● represent electrons.



Arsenic (^{33}As)



Silicon (^{4}Si)



Gallium (^{31}Ga)

electrical properties. This process of adding impurities is called *doping* and the resulting semiconductor is called *extrinsic semiconductor*. Depending on the nature of the dopant atoms an extrinsic semiconductor could be of two types.

***n*-type semiconductor:** If conduction electrons are the majority charge carriers then the extrinsic semiconductor is an *n*-type semiconductor. The band diagram is illustrated in Figure 2(b).

***p*-type semiconductor:** If instead, holes are the majority charge carriers then the extrinsic semiconductor is a *p*-type semiconductor, the band diagram is illustrated in Figure 2(c).

Q 1. Considering the atomic structure of pure Silicon (Si), Gallium (Ga) and Arsenic (As), how are *n*-type and *p*-type semiconductors made?

2.3 The Hall Effect

In 1879, Edwin Hall observed that if a magnetic field is applied at right angle to the direction of current flowing in a conductor, an electric field is created in the direction perpendicular to both the applied magnetic field and the flowing current. This means that moving charge carriers experience a sideways force.

We now formalize the geometry a little bit. Consider a crystal of a *p*-type semiconductor material having positive charge carriers, moving along the *y*-axis with a drift velocity $\mathbf{v}_\mathrm{d}$, as depicted in Figure 3. If a magnetic field $\mathbf{B}_\mathrm{z}$ is applied along the

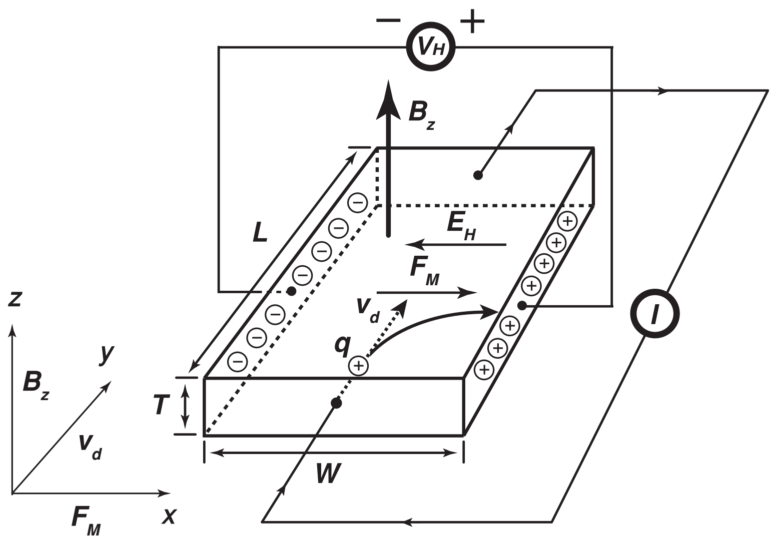


Figure 3: Illustration of Hall effect measurement in a *p*-type semiconductor crystal with length L, width W and thickness T.

z-axis (traverse to the charge flow) then the resultant magnetic force $\mathbf{F}_\mathrm{M}$ on the positive charge q is given by,

$$\mathbf{F}_\mathrm{M} = q(\mathbf{v}_\mathrm{d} \times \mathbf{B}_\mathrm{z}) \tag{1}$$

where q is the magnitude of the charge. The force $\mathbf{F}_\mathrm{M}$ pushes the charge in the *x*-direction, towards the right edge of the semiconductor crystal. As a result, the positive charge starts to accumulate on the right edge and negative charge on the opposite left edge of the crystal. This gives rise to an electric field E_H between the two opposite sides, called the Hall field. If a voltmeter is connected to these two opposite edges, it would register the presence of a potential difference. This potential difference is called the Hall voltage, V_H.

2.4 The Hall coefficient and carrier concentration

To fully understand the Hall effect, it is important to first define some quantities.

When the induced force $\mathbf{F}_{\mathrm{M}}$, called the Lorentz force, and the force due to electric field E_H becomes equal, we then have established the equilibrium condition,

$$qv_dB_z = qE_H \tag{2}$$

and

$$V_H = WE_H = v_dB_zW \tag{3}$$

In equilibrium, the deflection of charges towards the right is balanced by the opposing electric field (E_H) preventing further accumulation of charges. The current density ($J = I/A$) is related to the number of charge carriers per unit volume, n,

$$J = nqv_d \tag{4}$$

and the current I is given by,

$$I = nqv_dA \tag{5}$$

where A is the cross sectional area, the width W multiplied by the thickness T of the crystal. Substituting these values into Equation 6, we obtain

$$V_H = \frac{IB_z}{nqT} \tag{6}$$

We can define the Hall coefficient, $R_H = 1/nq$, resulting in

$$V_H = \frac{R_HIB_z}{T} \tag{7}$$

This relationship shows that (a) higher the applied field B_z, larger is the Hall voltage and (b) the Hall voltage is inversely proportional to the charge carrier concentration n. If we know R_H for a material, we can use V_H as a measure of the magnetic field. This is called magnetic field sensing.
Furthermore, the charge carrier concentration n can be related to the Hall coefficient by,

$$n = \frac{1}{qR_H} \tag{8}$$

Q 2. What would be the expression for the Hall coefficient in a n-type semiconductor crystal?

The Hall coefficient is a scale measuring the magnitude of the Hall effect. Table 1 lists the Hall coefficients of various metals. Note that all the metals, listed in the Table 1, have negative values. Can you think why?

Metal	R_H ($\times 10^{-11}$) [$m^3 A^{-1} s^{-1}$]
Ag	-9.0
Au	-7.2
Cu	-5.5
Al	-3.5
Na	-25
Mg	-9.4

Table 1: Hall coefficient of selected metals.

The Hall effect also provides a mean to determine the charge carrier concentration in a material. Table 2 lists the carrier concentration of some typical metals and semiconductors.

The Hall voltage depends on the product of two quantities, current density J and

Material	Type	Carrier concentration (m^{-3})
Ag	Metal	5.58×10^{28}
Au	Metal	5.90×10^{28}
Cu	Metal	8.45×10^{28}
Si	Semiconductor	1.5×10^{16}
Ge	Semiconductor	2.1×10^{18}
GaAs	Semiconductor	1.1×10^{13}

Table 2: Carrier concentration in metals and intrinsic semiconductors at 300 K.

transverse applied magnetic field B_z. This implies that the Hall effect provides a natural method to multiply two independently variable quantities which is in practice quite useful. One obvious application is measuring of power dissipated in a load, where the current and voltage are multiplied. Similarly, the strength of magnetic fields can be measured by using Hall probes. Hall probes are the devices based on the Hall effect principle. The Hall effect is also used in magnetically actuated electronic switches which have applications in ignition systems, speed controllers, position detectors, alignment controls etc.

Q 3. Why do Hall effect devices always employ semiconductor materials for sensing? Why do metals, listed in Table 1, have negative Hall coefficient?

Q 4. Name a device that uses Hall effect and is not already mentioned in this manual?

Q 5. Consider a 1 mm thick semiconductor sample, placed in magnetic field of

4 kG. If the linear straight line fit, in the current vs Hall voltage plot gives a slope of 1.2 mV/A, what is the Hall coefficient for the semiconductor sample and compare it with the values of typical metals given in Table 1?

Q 6. A rectangular *n*-type germanium bar has a thickness of 2 mm. A current of 10 mA passes along the bar and a magnetic field of 1 kG is applied perpendicular to the current flow. The Hall voltage developed is 1 mV. Calculate the Hall constant and the electron density in the semiconductor bar.

3 The Experiment

3.1 Overview of the experiment

In this experiment we shall measure the Hall effect in a semiconductor crystal.

A *p*-type Germanium (Ge) crystal is mounted on a printed circuit board (PCB). The crystal is 6 mm long, 4 mm wide and 0.5 mm thick. All necessary connections for applying a constant current through the crystal and measuring the Hall voltage are provided on the circuit board. The magnetic field is applied through two pole pieces of an electromagnet, connected to a power supply. Figure 4 shows the arrangement of the experimental setup.

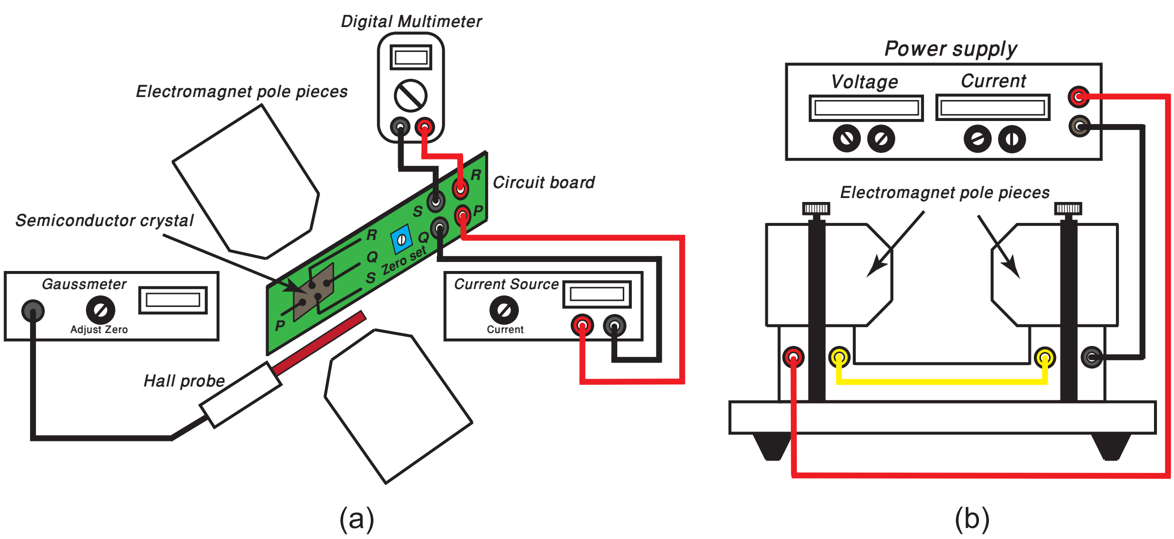


Figure 4: Experimental setup: (a) The crystal mounting PCB is placed vertically between the pole pieces of electromagnet along with the Hall probe, (b) schematic diagram of the electromagnet, connected with a power supply.

3.2 List of Equipment

The equipment that we will use in this experiment has been obtained from INDO-SAW (Osaw Industrial Products Pvt. Ltd, India). The equipment includes;

1. Electromagnet:

    - The electromagnet consists of two pole pieces and each pole piece has a coil of insulated wire with 400 turns. In order to generate a magnetic field, the coils must be connected to a power supply.

2. Semiconductor crystal and its mount:

    - A *p*-type Germanium (Ge) crystal with a length (L) of 6 mm, width (W) of 4 mm and thickness (T) of 0.5 mm is mounted on a PCB.
    - Two pairs of connectors are provided on the PCB to supply current to the crystal, from a constant current source, and record Hall voltage across the crystal with a digital multimeter. Figure 5 is a close-up photograph of PCB.

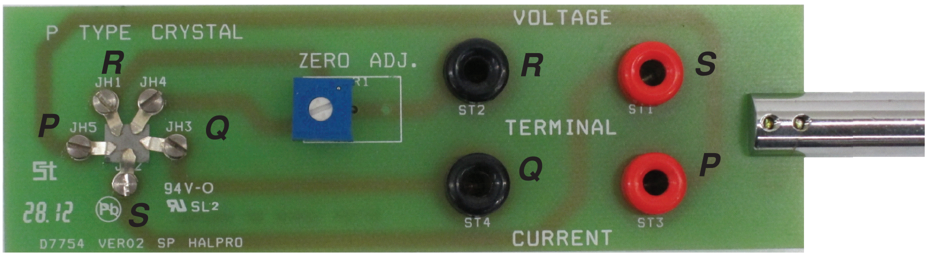


Figure 5: Printed circuit board with the Ge crystal, zero adjust and connectors to supply current and record Hall voltage. Current, through the Ge crystal, is applied through the contacts P and Q while Hall voltage is recorded across the contacts R and S.

- To cancel out the effect of spontaneous magnetization of pole pieces at no applied current, the PCB is also provided with a zero adjust.

3. Hall probe and Gaussmeter (with resolution settings of $1\times$ and $10\times$) to measure the magnetic field during the experiment.

    - The Hall probe itself contains a Hall sensor at its tip, which feeds the induced Hall voltage signals to the Gaussmeter. The Gaussmeter then converts the sensed Hall voltage to the strength of applied magnetic field, using a calibration mechanism that is inbuilt in the Gaussmeter.

4. Digital voltmeter for Hall voltage measurement.

5. Unipolar power supply (0-16 V, 5 A) for powering up the electromagnet.

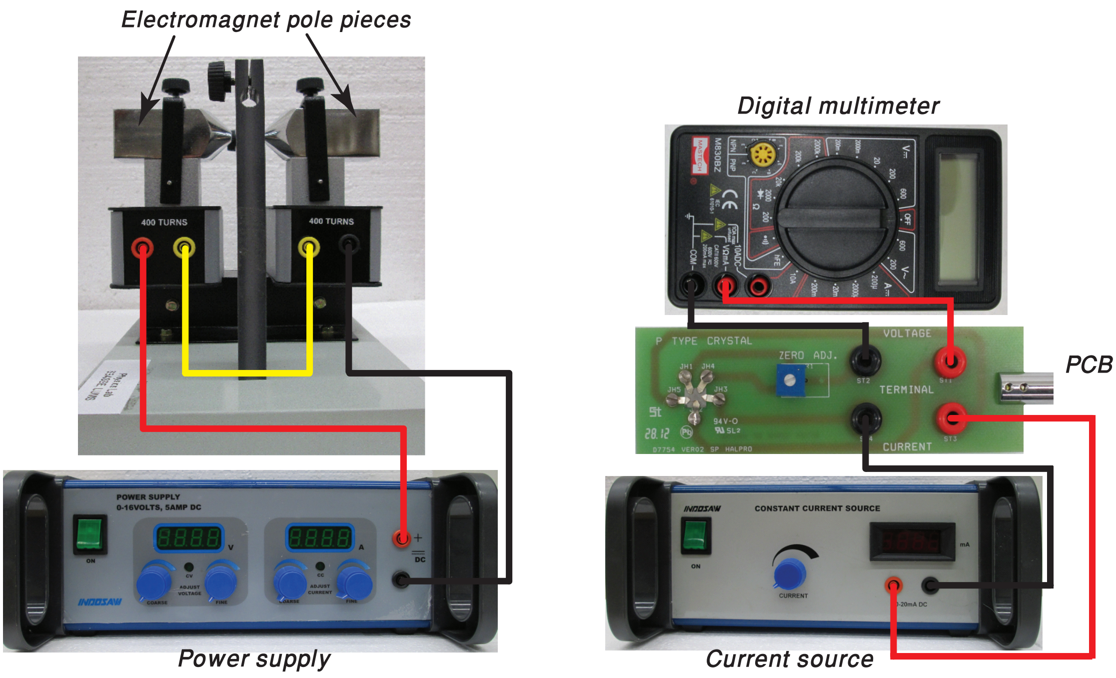
6. Constant current source to supply a DC current to the semiconductor crystal.

Q 7. If the Hall probe is place between the pole pieces and no current is applied to the electromagnets then, apparently, the Gaussmeter should show 0 G reading. Why does the Gaussmeter show some readings in this situation?

3.3 Experimental Procedure

1. Connect the Hall probe with the Gaussmeter. It may show some initial readings because the Hall sensor embedded in the Hall probe is very sensitive to any magnetic field in its surrounding, even signals from a cell phone or current in nearby electric cables can affect the readings. These initial readings can be neutralized by a knob on the Gaussmeter or simply subtracted from further readings acquired during the experiment.

2. Connect the electromagnet to the power supply, with the provided connecting cables. Use Figure 6(a) as your guide.



(a) (b)

Figure 6: Connection of the power supply with the electromagnet.

3. Place the Hall probe vertically in the electromagnets and make sure that Gaussmeter displays 0 G (at 1× resolution).

4. Dependence of the magnetic field on the current through the electromagnet:

   - First increase the current from the power supply, in steps of 0.2 A, from 0 A to 3.4 A and then decrease the current from 3.4 A to 0 A, again with the same step size. Record the readings from the Gaussmeter. Tabulate current verses magnetic field.
   - Now switch connecting cables that are connected to the power supply, i.e. plug red cable in the negative terminal and black cable in the positive terminal on the power supply. This would give a reverse bias to the electromagnet and result in a reverse (negative) magnetic field.
   - Repeat whole process as stated in the above step and tabulate the current verses magnetic field.

   Q 8. Plot a graph of current through the electromagnet and the measured magnetic field. Describe the resulting graph.

5. Hall voltage measurements:

   - Connect the PCB with the current source and digital multimeter to record Hall voltage corresponding to the applied current through the semiconductor crystal. The scheme is shown in Figure 6(b).
   - Place the PCB vertically between pole pieces of electromagnet, along with the Hall probe. Make sure that both pole pieces are at same distance from the crystal and pole pieces are properly aligned with the crystal.
   - Set the magnetic field at zero by keeping power to the electromagnet at zero. If the Hall voltage is not zero at 0 G magnetic field, due to the presence of parasitic magnetic fields in the surrounding environment, set it to 0 mV using the Zero Adjust knob.
   - Set the current through the crystal at 10 mA from the constant current source. Increase the magnetic field from 0 G to 1800 G, with a step of 100 G, by increasing power through the electromagnet and record the Hall voltage from digital multimeter. Tabulate magnetic field verses Hall voltage.
   - Now set the magnetic field at 1500 G from the power supply. Increase the current through the crystal from 0 mA to 10 mA, with a step of 0.5 mA, and record the Hall voltage from digital multimeter.
   - Tabulate current through the crystal verses the measured Hall voltage.

Q 9. Plot a graph of applied magnetic field and Hall voltage at constant current through the crystal.
Q 10. Plot a graph of current through the crystal and Hall voltage at constant applied magnetic field.
Q 11. Calculate the charge carrier concentration in the given p-type Ge crystal. Also calculate the uncertainties in the measurement of charge carrier concentration.

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