Hall effect of semiconductors

(I) To determine Hall coefficient of semiconductor at room temperature

(II) To study the variation of Hall coefficient with temperature

Conductivity measurements in semiconductors cannot reveal whether one or both types of carriers are present, nor distinguish between them. However, this information can be obtained from Hall Effect measurements, which are a basic tool for the determination of mobilities. The effect was discovered by E.H. Hall in 1879.

Consider a simple crystal mounted as in the Fig. 4, with a magnetic field H in the z direction perpendicular to contacts 1, 2 and 3, 4. If current is flowing through the crystal in the x direction (by application of a voltage V_x between contacts 1 and 2), a voltage will appear across contacts 3, 4 in the y- direction. It is easy to calculate this (Hall) voltage if it is assumed that all carriers have the same drift velocity. We will do this in two steps: (a) by assuming that carriers of only one type are present, and (b) by assuming that carriers of both types are present.

a) One type of carrier:

The magnetic force on the carriers is $\vec{F}_m = e\vec{E}_m = e\left(\vec{v} \times \vec{H}\right)$ and it is compensated by the force $\vec{F}_h$ due to the Hall field $\vec{E}_H$, $\vec{F}_H = e\vec{E}_H = \vec{F}_m$. As $\vec{v}$ is along the x- axis and $\vec{H}$ along the z-axis, the electric field $\vec{E}_m$ is along the y-axis and is given by $E_m = vH = \mu E_x H$ where μ is the carrier mobility given by $v = \mu E_x$ and E_x is the applied electric field along the x-axis. This electric field is related to the current density and conductivity, $\sigma E_x = J_x$. The Hall coefficient R_H is defined as

$$\left|R_H\right| = \frac{E_m}{J_x H} = \frac{\mu E_x}{J_x} = \frac{\mu}{\sigma} = \frac{1}{ne} \tag{1}$$

We have used the relation $\sigma = ne\mu$. Hence for fixed magnetic field and fixed input current, the Hall voltage is proportional to 1/n. It follows that

$$\mu = R_H \sigma, \tag{2}$$

providing an experimental measurement of the mobility. R_H is expressed in cm^3 $coulomb^{-1}$.

Experimentally the coefficient is given by

$$R_H = \frac{V_y b}{(I_x/bt)H} = \frac{V_y t}{I_x H}, \tag{3}$$

where b and t are respectively the width and the thickness of the sample. In case the voltage across the input is kept constant, it is convenient to define the Hall angle as the ratio of applied and measured voltages:

$$\phi = \frac{V_y}{V_x} = \frac{E_m b}{E_x l} = \mu \frac{b}{l} H \tag{4}$$

where l is the length of the crystal. The Hall angle is thus proportional to the mobility.

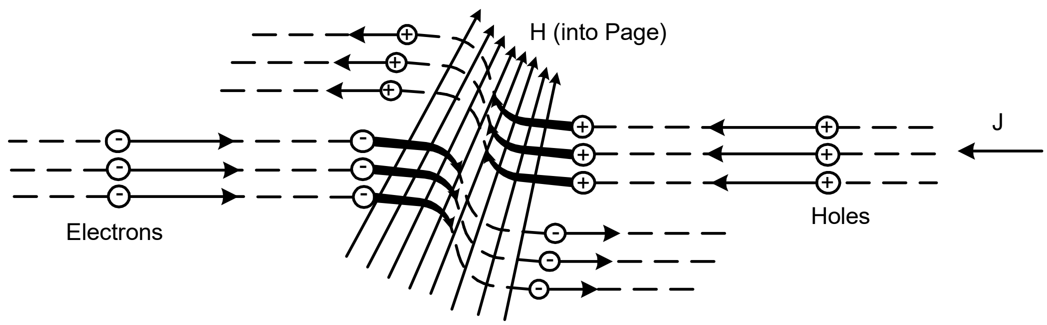

Fig. 1 Carrier separation due to a magnetic field

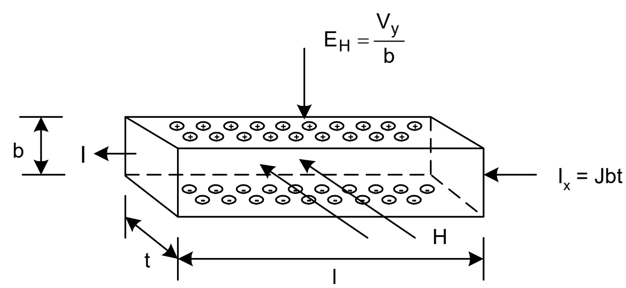

Fig. 2 Sample for studying Hall Effect

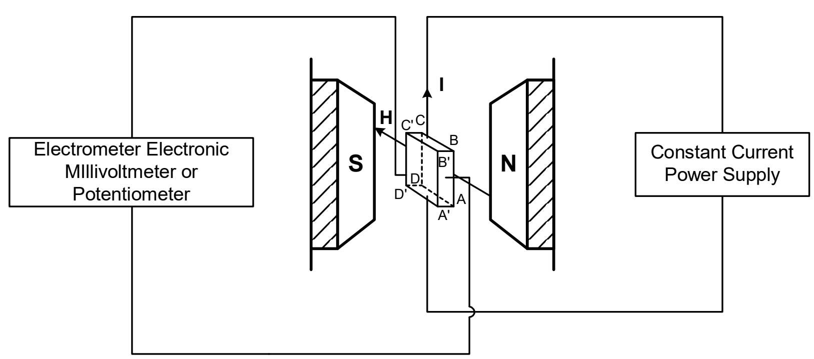

Fig. 3

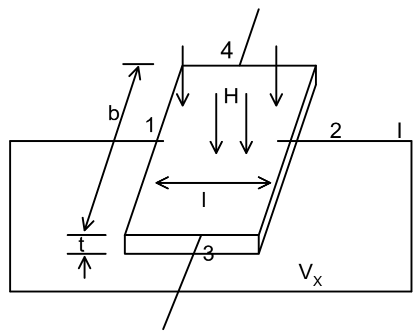

Fig. 4 Schematic arrangement for the measurement of Hall Effect of a crystal

(b) **Two types of carriers**:

Now it is important to recognize that for the same electric field E_x, the Hall voltage for p carriers (holes) will have opposite sign from that for n carriers (electrons). (That is, the Hall coefficient R has a different sign.) Thus, the Hall field E_y will not be able to compensate for the magnetic force on both types of carriers and there will be a transverse motion of carriers; however, the net transverse transfer of charge will remain zero since there is no current through the 3, 4 contacts; this statement is expressed as

$$e(v_y^{+}p - v_y^{-}n) = 0$$

while

$$e(v_x^{+}p - v_x^{-}n) = J_x \quad \text{and} \quad e(\mu^{+}p + \mu^{-}n) = \sigma$$

where the mobility is always a positive number; however, v_x^{+} has the opposite sign from v_x^{-}. It is given by

$$v_y = \frac{s}{\tau} = \left(\frac{1}{2}\frac{F}{m^*}\tau^2\right)\frac{1}{\tau} \ ,$$

where τ is mean time between collisions and m* is the effective of the carriers. Now for holes and electrons, we have

$$\vec{F}^{+} = e[(\vec{v}_x^{+} \times \vec{H}) - \vec{E}_H]$$

$$\vec{F}^{-} = -e[(\vec{v}_x^{-} \times \vec{H}) - \vec{E}_H]$$

If m_h and m_e are effective masses for holes and electrons, respectively, we get

$$v_y^{+} = \frac{1}{2}\frac{e}{m_h}\tau[(\mu^{+}E_xH) - E_H] = \mu^{+}(\mu^{+}E_xH - E_H)$$

$$v_y^{-} = \frac{1}{2}\frac{e}{m_e}\tau[(\mu^{-}E_xH) - E_H] = \mu^{-}(\mu^{-}E_xH + E_H)$$

and

$$\mu^{+}p(\mu^{+}E_xH - E_H) - \mu^{-}n(\mu^{-}E_xH + E_H) = 0$$

or

$$E_H = E_x H \frac{(\mu_h{}^2 p - \mu_e{}^2 n)}{\mu_h p + \mu_e n} , \qquad (5)$$

and for the Hall coefficient R_H

$$R_H = \frac{E_H}{J_x H} = \frac{E_H}{\sigma E_x H} = \frac{\mu_h{}^2 p - \mu_e{}^2 n}{e(\mu_h p + \mu_e n)^2} \qquad (6)$$

Equation 6 correctly reduces to Eq. 1 when only one type of carrier is present.

Since the mobilities μ_h and μ_e are not constants but functions of T, the Hall coefficient given by Eq. 6 is also a function of T and it may become zero and even change sign. In general $\mu_e > \mu_h$ so that inversion may happen only if $p > n$; thus ***"Hall coefficient inversion" is characteristic of only "p-type" semiconductors***.

At the point of zero Hall Coefficient, it is possible to determine the ratio of mobilities μ_e/μ_h in a simple manner.

EXPERIMENTAL TECHNIQUE

(a) Experimental consideration relevant to all measurements on semiconductors

1. Soldered probe contacts, though very much desirable may disturb the current flow (shorting out part of the sample). Soldering directly to the body of the sample can affect the sample properties due to heat and by contamination unless care is taken. These problems can be avoided by using pressure contacts as in the present set-up. The principal drawback of this type of contacts is that they may be noisy. This problem can, however, be managed by keeping the contacts clean and firm.
2. The current through the sample should not be large enough to cause heating. A further precaution is necessary to prevent 'injecting effect' from affecting the measurement. Even good contacts to germanium for example, may have this effect. This can be minimized by keeping the voltage drop at the contacts low. If the surface near the contacts is rough and the electric flow in the crystal is low, these injected carriers will recombine before reaching the measuring probes.

(b) Experimental consideration with the measurements of Hall coefficient.

1. The Hall Probe must be rotated in the field until the position of maximum voltage is reached. This is the position when direction of current in the probe and magnetic field would be perpendicular to each other.
2. The resistance of the sample changes when the magnetic field is turned on. This phenomenon called magneto-resistance is due to the fact that the drift velocity of all carriers is not the same, with magnetic field on, the Hall voltage compensates exactly the Lorentz force for carriers with average velocity. Slower carriers will be over compensated and faster ones under compensated, resulting in trajectories that are not along the applied external field. This results in effective decrease of the mean free path and hence an increase in resistivity.
3. In general, the resistance of the sample is very high and the Hall Voltages are very low. This means that practically there is hardly any current - not more than few micro amperes. Therefore, the Hall Voltage should only be measured with a high input

impedance (≅1M) devices such as electrometer, electronic millivoltmeters or good potentiometers preferably with lamp and scale arrangements.

4. Although the dimensions of the crystal do not appear in the formula except the thickness, but 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 may be taken three times the width of the crystal.

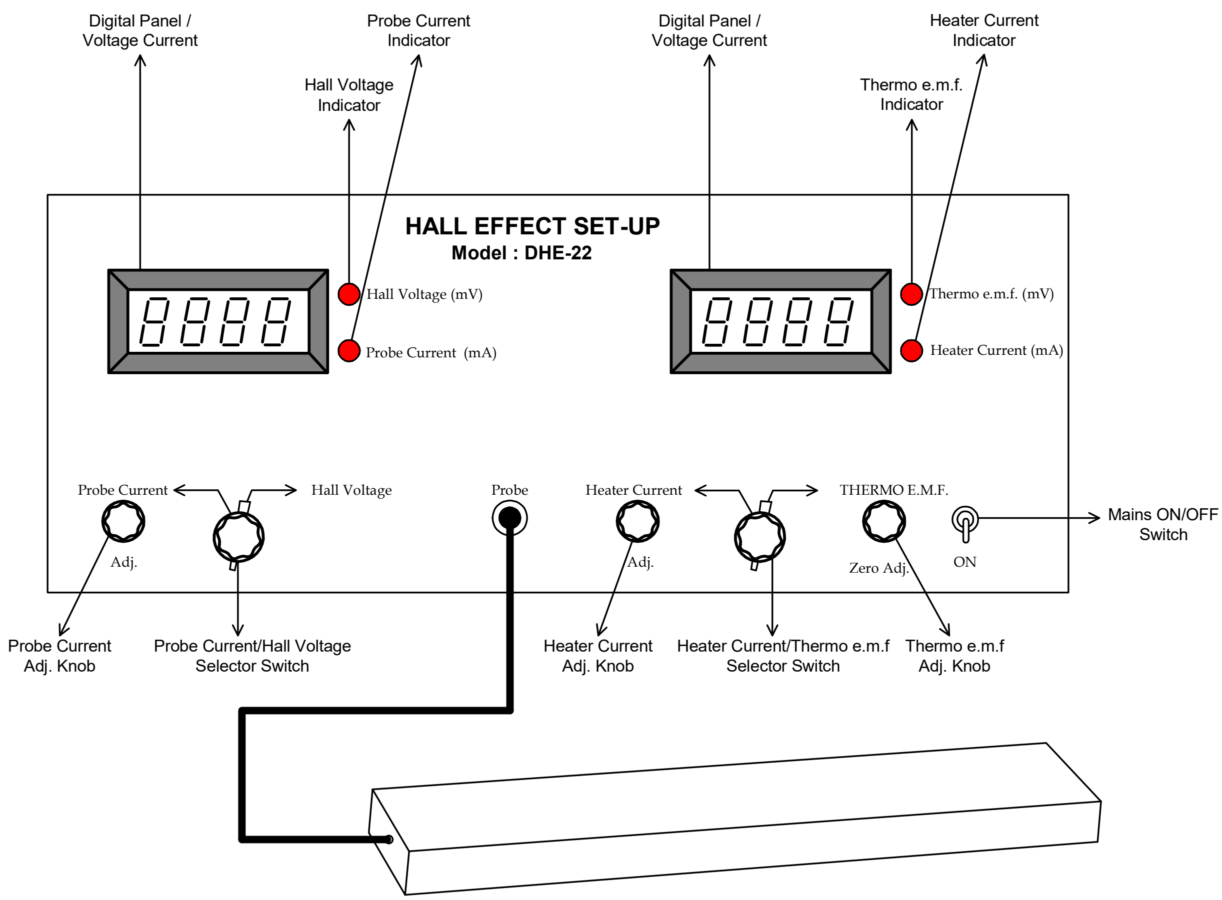

Fig. 5 : Panel Diagram of the Hall effect set up

Apparatus :

1. Hall probe (Ge:p type, n-type, Si, n-type)
2. Oven
3. Temperature sensor
4. Hall Effect Set-up, Model : DHE-22
5. Electromagnet, EMU-50V
6. Constant Current Power Supply, DPS-50
7. Digital Gaussmeter, DGM-102

1. HALL PROBE (GE : p-& n-TYPE, Si:n-type)

Ge/Si single crystal with four spring type pressure contact is mounted on a glass-epoxy strips. Four leads are provided for connections with the probe current and Hall voltage measuring devices.

2. OVEN

It is a small oven which could be easily mounted over the crystal or removed if required.

Specifications

Size : 35 x 25 x 5 mm (internal size)

Temperature Range : Ambient to 100°C

Power requirement : 12W

3. TEMPERATURE SENSOR

Temperature is measured with Cromel-Alumel thermocouple with its junction at a distance of 1 mm from the crystal

4. HALL EFFECT SET-UP, MODEL : DHE-22

The set-up, DHE-22 consists of two sub set-ups, each consisting of further two units.

(i) Measurement of Probe Current & Hall Voltage

This unit consists of a digital millivoltmeter and constant current power supply. The Hall voltage and probe current can be read on the same digital panel meter through a selector switch.

(a) Digital Millivoltmeter

Intersil 3½ digit single chip ICL 7107 have been used. Since the use of internal reference causes the degradation in performance due to internal heating an external reference have **been used. Digital voltmeter is much more convenient to use in Hall Experiment, because the input voltage of either polarity can be measured.**

Specifications

Range : 0-200mV (100μV minimum)

Accuracy : ±0.1% of reading ± 1 digit

(b) Constant Current Power Supply

This power supply, specially designed for Hall Probe, provides 100% protection against crystal burn-out due to excessive current. The supply is a highly regulated and practically ripple free dc source.

Specifications

Current : 0-20mA

Resolution : 10μA

Accuracy : ±0.2% of the reading ±1 digit

Load regulated : 0.03% for 0 to full load

Line regulation : 0.05% for 10% variation

Input Supply : 220VAC ±10%

(ii) Measurement of Thermo emf and Heater current

The unit consists of a digital millivoltmeter and constant current power supply. The thermo emf of thermocouple and heater current can be read on the same DPM through a selector switch.

(a) Digital Millivoltmeter

Intersil 3½ digit single chip ICL 7107 have been used. Since the use of internal reference causes the degradation in performance due to internal heating an external reference have been used. Digital Voltmeter is much more convenient to use, because the input voltage of either polarity can be measured.

Specification

Range: 0 - 20 mV

Resolution: 10 μV equivalent to 0.25ºC in terms of thermo emf

Accuracy: ±0.1% of reading ± 1 digit

(b) Constant Current Power Supply

The supply is highly regulated and practical ripple free source.

Specifications

Current: 0 - 1A

Accuracy: ±0.2% of the reading ± 1 digit

Line regulation: 0.1% for 10% variation

Load regulation: 0.1% for 0 to full load

Input Supply : 220VAC ±10%

CALIBRATION TABLE FOR CHROMEL-ALUMEL

ºC	0	1	2	3	4	5	6	7	8	9
0	0.00	0.04	0.08	0.12	0.16	0.20	0.24	0.28	0.32	0.36
10	0.40	0.44	0.48	0.52	0.56	0.60	0.64	0.68	0.72	0.76
20	0.80	0.84	0.88	0.92	0.96	1.00	1.04	1.08	1.12	1.16
30	1.20	1.24	1.28	1.32	1.36	1.40	1.44	1.49	1.53	1.57
40	1.61	1.65	1.69	1.73	1.77	1.81	1.85	1.90	1.94	1.98
50	2.02	2.06	2.10	2.14	2.18	2.23	2.27	2.31	2.35	2.39
60	2.43	2.47	2.51	2.56	2.60	2.64	2.68	2.72	2.76	2.80
70	2.85	2.89	2.93	2.97	3.01	3.05	3.10	3.14	3.18	3.22
80	3.26	3.30	3.35	3.39	3.43	3.47	3.51	3.56	3.60	3.64
90	3.68	3.72	3.76	3.81	3.85	3.89	3.93	3.97	4.01	4.06
100	4.10	4.14	4.18	4.22	4.26	4.31	4.35	4.39	4.43	4.47
110	4.51	4.55	4.60	4.64	4.68	4.72	4.76	4.80	4.84	4.88

PROCEDURE

1. **Calibration of applied magnetic field:** Place the gaussmeter in between electromagnets and arrange the set up as shown in Fig. 6. For no current in the coils, use the "ZERO ADJ." knob to bring the magnetic field to 0, if required. Switch ON the constant current power supply. Gradually increase the current to the coils in suitable steps and record the magnetic field as displayed by the gaussmeter. Plot a calibration curve for current ~ magnetic field. Use this plot later to determine magnetic field for any given current to the electromagnets.

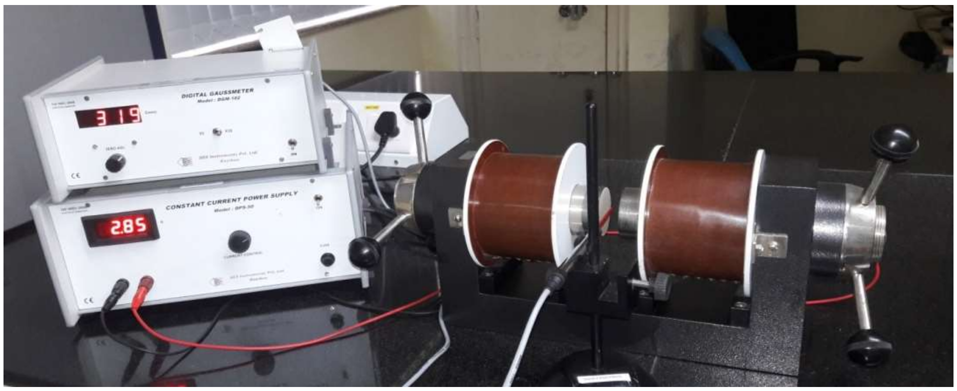

Fig. 6: Set up for calibration of applied magnetic field

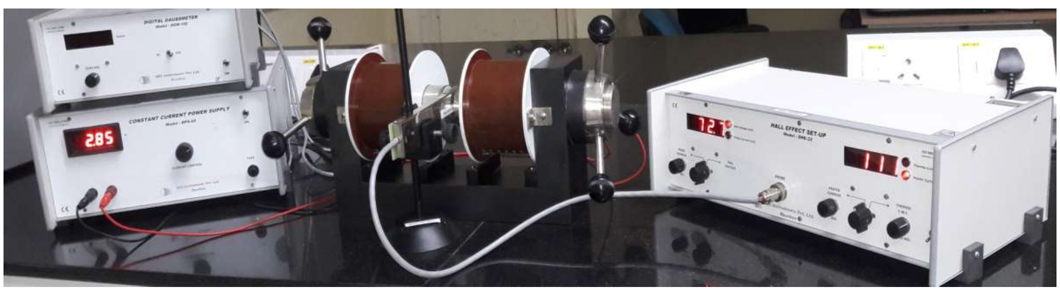

Fig. 7: Set up for Hall voltage measurement

2. Remove the gaussmeter carefully and replace it with the sample hall probe (p- or n-type Ge) connected to the Hall effect set up as shown in Fig. 7.
3. Switch 'ON' the Hall Effect set-up. Set the probe current at 0 and turn the display to voltage side. There may be some voltage reading due to imperfect alignment of the four contacts of the Hall Probe. This is generally known as the 'Zero field Potential'. It should be adjusted to a minimum possible value and later it should be subtracted from the observed Hall Voltage values.
4. **Measurement of Hall voltage ~ Probe current at room temperature (For both p- and n-type):** Note the ambient temperature. Switch on the electromagnet power supply and adjust the current to any desired value. Rotate the Hall probe till it become perpendicular to magnetic field. Hall voltage will be maximum in this adjustment.
5. Measure Hall voltage. Find the magnetic field corresponding to the current value using calibration plot. Calculate Hall coefficient at room temperature.

6. **Measurement of Hall voltage ~ Temperature for fixed probe current (For p-Ge):** Repeat step 4 keeping p-type Ge Hall probe in between the electromagnet. Determine the magnetic field.

7. Set the probe current at about 4 mA. Gradually vary the heater current up to say about 1A. After every new setting of heater current, wait for about 7-8 minutes for the temperature to stabilize. This would be indicated by a stable thermo e.m.f. also. Note down the temperature from calibration table.

9. Record the Hall voltage reading at the set temperature. Then switch off the constant current power supply of the electromagnet. Note down the off-set voltage at residual magnetic field and subtract it from the Hall voltage. This is very important.

10. There is no need to gradually increase/decrease the magnetic field. Just switch 'OFF' the supply for off-set voltage and switch 'ON' for the next reading.

11. Change of sign of Hall voltage on heating would occur for p-type sample only. This is explained in the Manual. There is no need to take further readings after the change of sign.

12. Allow about 10 minutes time for the thermal stabilization of the DHE-22 every time the experiment is to be performed.

13. Thermo emf (mV) reading if any at ambient temperature i.e. without heater current should be subtracted from the thermo emf reading to get the corresponding correct temperature from the calibration table provided with the set-up. It is assumed that the thermo-emf of the chromel-alumel thermocouple used with the heating arrangement varies linearly with the temperature difference between the two junctions of the thermocouple.

14. Calculate hall coefficient for each Hall voltage and plot it as a function of temperature.

Optional measurements:

15. Similarly, measurement of Hall voltage ~ Temperature can be performed for n-Ge at a fixed probe current.

16. Additionally, one can also vary magnetic field and record corresponding hall voltage at a given temperature. Hall coefficient can be calculated from a suitable plot.

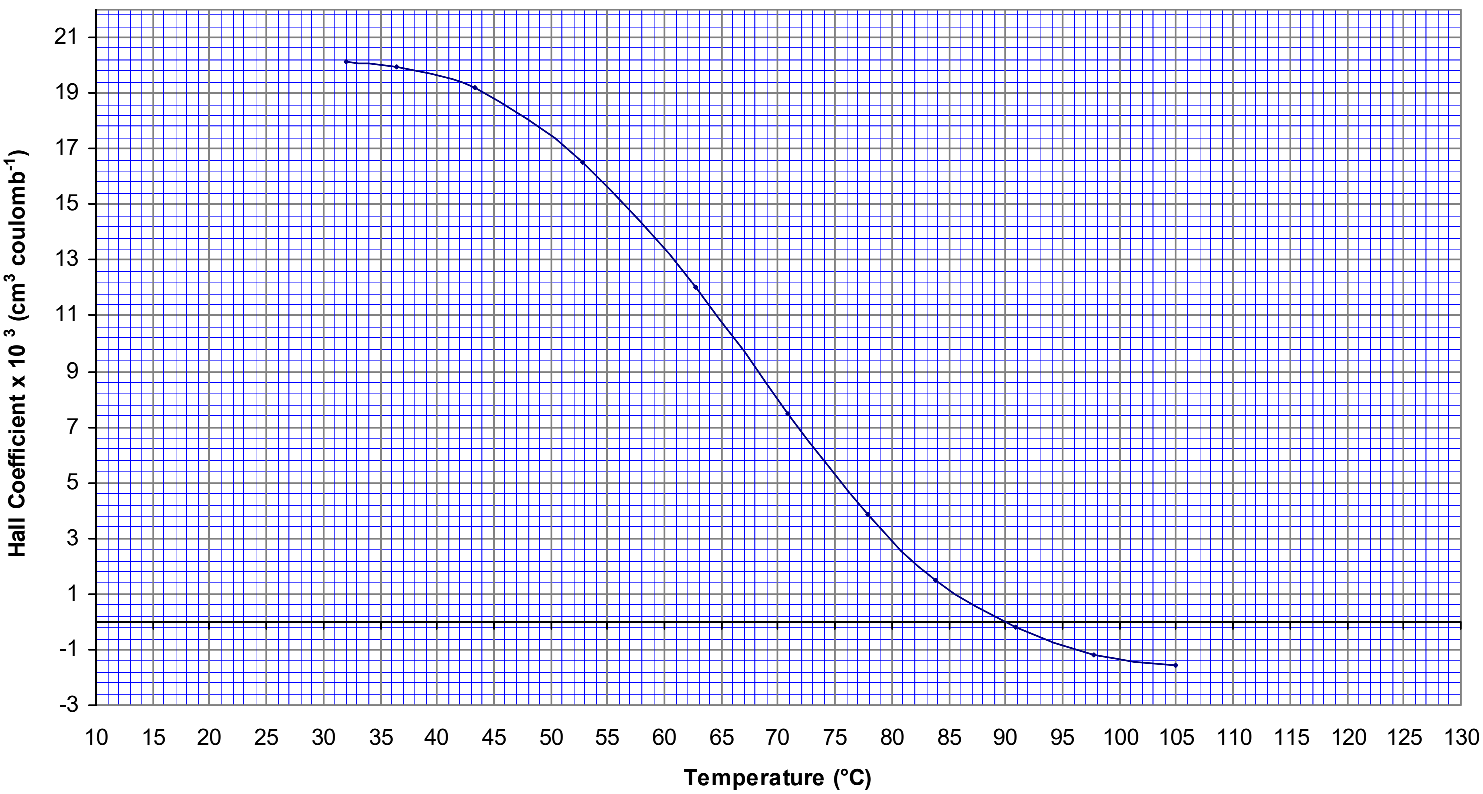

Fig. 8: Sample graph showing Hall coefficient ~ Temperature for p-Ge

Observations

(I) Ambient temperature :

Hall Coefficient for n-Ge:

Hall Coefficient for p-Ge:

(II) Sample : Ge (p-type) medium doping

Thickness : 0.50 mm

Sample data

Residual Magnetic Field: 130 Gauss Applied Mag. Field : 3.13 KGauss

Probe Current (I): 4.00 mA

S.No.	Heater current (mA)	Thermo. e.m.f. (mV)	Temp (°C)	Hall Voltage (mV)	Off-set voltage at residual (mV)	Corrected Hall Voltage (mV)	Hall Coefficient ($cm^3.coulomb^{-1}$)
1	0	0.00	17.0	54.6	-0.8	55.4	23.08
2	200	0.09	19.3	54.3	-0.9	55.2	23.00
3	300	0.29	24.3	54.8	0.29	54.5	22.71
4	400	0.59	31.8	53.1	-1.2	54.3	22.63
5	500	0.98	41.5	56.6	2.8	53.8	22.42
6	550	1.27	48.8	54.7	3.2	51.5	21.46
7	600	1.52	54.8	49.9	2.6	47.3	19.71
8	650	1.77	61.0	41.9	2.0	39.9	16.63
9	700	2.02	67.0	22.0	-8.7	30.7	12.79
10	750	2.25	72.0	14.4	-7.6	22.0	9.17
11	800	2.53	79.5	5.0	-7.4	12.4	5.17
12	850	2.82	86.5	-4.8	-8.6	3.8	1.58
13	900	3.05	92.0	-6.3	-6.7	-0.4	-0.17
14	950	3.54	100.8	-7.9	-5.2	-2.7	-1.13
15	1000	3.71	107.8	-7.8	-4.2	-3.6	-1.50

Note : Since Hall voltage at residual magnetic field form the part of Offset Voltage, the magnetic field for Hall Coefficient calculation would be = 3.13 - 0.13 = 3.00 KG

Graph: Variation of Hall Coefficient with temperature is shown in the sample graph

Formula used for calculation of Hall Coefficient (R)

$$R = \frac{V_y \; t}{I\,H}$$

where, V_y = Hall voltage
t = Thickness of the sample
I = Probe current
H = Magnetic field

CALCULATIONS

(a) Calculate charge carrier density from the relation

$$\mathbf{R} = \frac{\mathbf{1}}{\mathbf{ne}} \Rightarrow \mathbf{n} = \frac{\mathbf{1}}{\mathbf{Re}}$$

(b) Calculate carrier mobility, using, the formula

$$\mu_n \text{ (or } \mu_p) = R\sigma$$

using the specified value of resistivity ($1/\sigma$) given by the supplier or obtained by some other method (Four Probe Method).

QUESTIONS

1. What is Hall Effect?
2. What are n-type and p-type semiconductors?
3. What is the effect of temperature on Hall coefficient of a lightly doped semiconductor?
4. Do the holes actually move?
5. Why the resistance of the sample increases with the increase of magnetic field?
6. Why a high input impedance device is generally needed to measure the Hall voltage?

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