

Physics Practical Laboratory Manual

M.Sc. Physics IIIrd Semester

Laboratory Name: Condensed Matter Physics



Experiment List

- ❖ Study of the temperature dependence of Resistivity of a Semiconductor using Four Probe method and to determine the band gap of experimental material (Ge).
- ❖ To Study the Phase Diagram of Pb-Sn Alloy using Cooling Curve and Determine its composition.
- ❖ To Determine the Mass Susceptibility of Paramagnetic Solution Using Quincke's Method.
- ❖ To Determine the *Lande g* factor Using Electron Spin Resonance.
- ❖ To Determine Hall coefficient (R_H), Hall voltage (V_H), types of charge carriers and Hall angle (θ_H) using Hall Effect experiment.

Study of the temperature dependence of Resistivity of a Semiconductor using Four Probe method and to determine the band gap of experimental material (Ge)

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Department of Pure & Applied Physics

Condensed Matter Physics Practical Experiment Manual



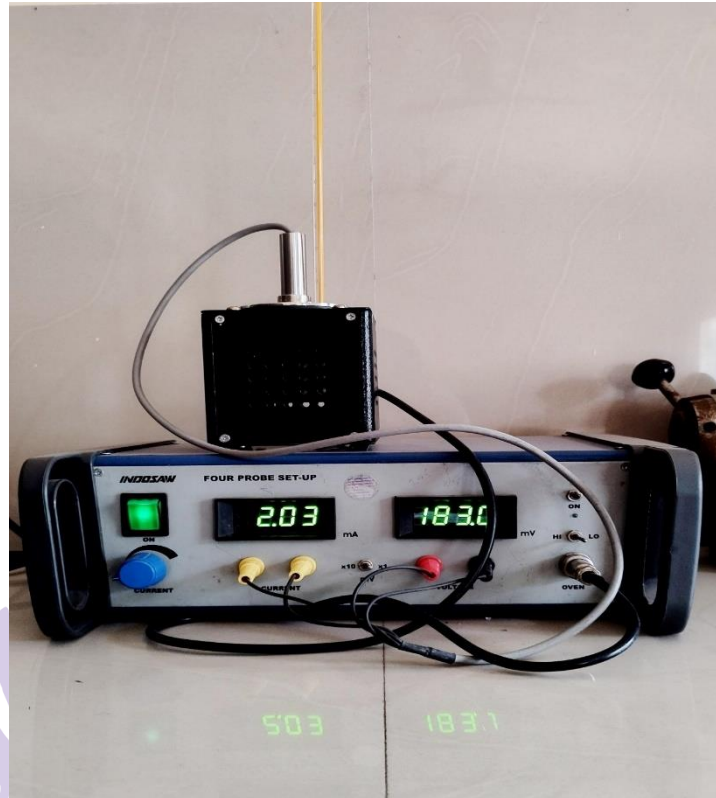
**Study of the temperature dependence of Resistivity of a
Semiconductor using Four Probe method and to determine
the band gap of experimental material (Ge)**

1. Historical Background

The four-probe method has its origins in the early 20th century and has been widely used in materials science and semiconductor physics. It was developed to address the limitations of traditional two-probe methods, especially when measuring the resistivity of small and thin samples. The concept of using multiple probes for electrical measurements can be traced back to the work of Walter Kohn and Lu Jeu Sham in the 1950s. They proposed a theoretical framework for understanding the electronic properties of materials, and this laid the groundwork for advanced experimental techniques.

2. Experimental Set up

Four probe apparatus, sample (a Ge crystal in form of a chip), oven, thermometer (260°C) constant power supply, oven power supply, panel meters for measurement of current and voltage.



Experimental Setup of Four Probe method

3. Basic Theory

The 4-point probe set up as shown in Figure 1 is consists of four equally spaced tungsten metal tips with finite radius. Each tip is supported by springs on the end to minimize sample damage during probing. The four metal tips are part of an auto-mechanical stage which travels up and down during measurements. A high impedance current source is used to supply current through the outer two probes; a voltmeter measures the voltage across the inner two probes to determine the sample resistivity. These inner probes draw no current because of the high input impedance voltmeter in the circuit. Thus, unwanted voltage drops (IR drop) at point B and point C caused by contact resistance between probes and the sample is eliminated from the potential measurements. Since these contact resistances are very sensitive to pressure and to surface condition (such as oxidation of either surface).

Study of the temperature dependence of Resistivity of a Semiconductor using Four Probe method and to determine the band gap of experimental material (Ge)

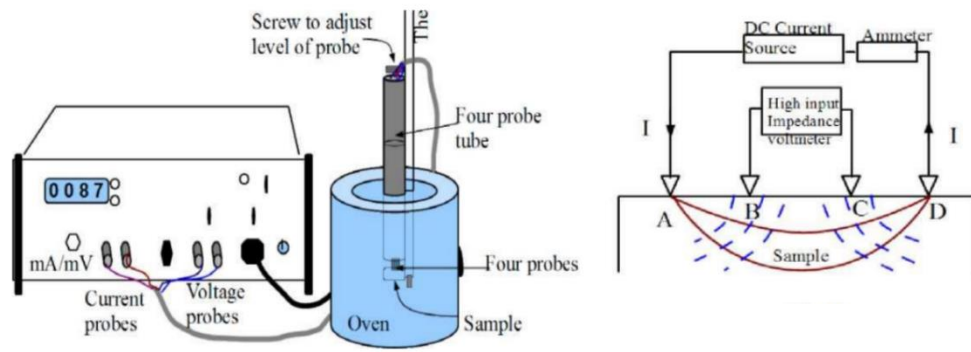


Figure 1. Schematic Illustration of Four Probe set up

Intrinsic semi-conduction is the process, in which thermally or optically excited electrons contribute to the conduction. In the absence of photonic excitation, intrinsic semiconduction takes place at temperatures above 0 K as sufficient thermal agitation is required to transfer electrons from the valence band to the conduction band. The temperature dependence resistivity of a semiconductor sample is inverse of conductivity which is the sum of the sum of the conductivities of the valence and conduction band carriers, which are holes and electrons, respectively. For a semiconductor material conductivity given by the expression,

$$\sigma = \sigma_e + \sigma_h \dots\dots\dots (1)$$

$$\sigma = e(n_e\mu_e + n_h\mu_h) \dots\dots\dots (2)$$

Where, e is the electronic charge, n_e and μ_e are the electron's concentration and mobility; similarly, n_h and μ_h are the hole's concentration and mobility. Here, mobility determines the average drift velocity in the presence of an applied external field. It also depends on the temperature. The mobility is a quantity that directly relates the drift velocity v_d of charge carriers to the applied electric field E across the material, i.e.,

$$\mu = \frac{v_d}{E} \dots\dots\dots (3)$$

In the intrinsic region the number of electrons is equal to the number of holes, $n_e = n_h = n_i$, so equation (2) implies as $\sigma = en_i(\mu_e + \mu_h) \dots\dots\dots (4)$

The electron density (electrons/volume) in the conduction band is obtained by integrating (density of states times probability of occupancy of states) from the bottom to top of the conduction band. The detailed calculations reveal that,

$$n_i = NT^{\frac{3}{2}} \exp\left(-\frac{E_g}{2K_B T}\right) \dots\dots\dots (5)$$

Substituting the value of n_i in equation (4), we get

$$\sigma = e(\mu_e + \mu_h)NT^{\frac{3}{2}} \exp\left(-\frac{E_g}{2K_B T}\right) \dots\dots\dots (6)$$

Whereas for a p-type semiconductor, $\sigma = en_h\mu_h \dots\dots\dots (7)$

Then equation (6) becomes $\sigma = e\mu_h NT^{\frac{3}{2}} \exp\left(-\frac{E_g}{2K_B T}\right) \dots\dots\dots (8)$

Also, $\mu_h = \beta T^{-\frac{3}{2}}$ and substituting this value we get,

$$\sigma = eN\beta \exp\left(-\frac{E_g}{2K_B T}\right) \dots\dots\dots (9)$$

This shows that conductivity depends on temperature it decreases exponentially with decrease in temperature.

So, the temperature dependency of resistivity can be given by the equation,

$$\rho = \frac{\exp\left(\frac{E_g}{2K_B T}\right)}{eN\beta} = A \exp\left(\frac{E_g}{2K_B T}\right) \dots\dots\dots (10), \text{ where } A \text{ is constant.}$$

Taking log in both sides, we get $\log \rho = \log A + \frac{1}{2.3026} * \frac{E_g}{2K_B T} \dots\dots\dots (11)$

Rewriting equation (11), $\log \rho = C + \frac{1}{2.3026 \times 10^3} * \left(\frac{E_g}{2K_B}\right) \left(\frac{1000}{T}\right) \dots\dots\dots (12)$

Therefore, if a graph is plotted in between $\log \rho$ vs $\left(\frac{1000}{T}\right)$, it should be a straight line and the band gap will be determined using the slope of it.

Study of the temperature dependence of Resistivity of a Semiconductor using Four Probe method and to determine the band gap of experimental material (Ge)

$$\text{Slope} = \frac{AC}{BC} = \frac{1}{2.3026 \times 10^3} * \left(\frac{E_g}{2K_B} \right)$$

$$K_B = 8.61733 \times 10^{-5} \text{ eVK}^{-1}$$

By putting the values

$$\begin{aligned} E_g &= 2 \times 8.61733 \times 10^{-5} \times 2.3026 \times 10^3 \times \text{slope} \\ &= 0.396845 \times \text{slope (eV)} \end{aligned}$$

4. Experimental Procedure

1. The setting of 4-point probes on the semiconductor chip is a delicate process. So first understand well the working of the apparatus. The semiconductor chip and probe set is costly.
2. Note the values of probe spacing (S) and the thickness (W) of the semiconductor chip. Note the type of semiconductor (germanium or something else).
3. Make the circuit as shown in Figure 1. Put the sample in the oven (normally already placed by lab instructor at room temperature).
4. Pass a milliamperere range current (say 5 mA) in the sample using constant current power supply.
5. The reading of the current through the sample is measured using milliammeter provided for this purpose. The voltage is measured by a high impedance millivoltmeter connected to the inner probes. The readings can be taken alternately on digital meter provided for this purpose.
6. Note temperature of sample (oven) using thermometer inserted in the oven for this purpose.
7. The oven temperature is increased a little, and its temperature noted after reaching steady state. Again, the constant current reading (advised to be kept the same) and the corresponding voltage readings are taken.
8. Repeat the procedure for different temperatures. Note the data in the observation table

5. Observation Table

Least count of thermometer = 1°C

Least count of milliammeter = 0.01 mA

Least count of digital voltmeter = $0.1 \times 10\text{ mV}$

Applied Current = _____ mA

Distance between the probes (s) = 0.24 cm

Thickness of the sample (w) = 0.05 cm

W/S value = _____ $F(w/s) = \frac{1}{2\pi s} \ln \frac{4s}{w}$ $2\pi s = \frac{4s}{w}$

Tabulation:1 (for heating)

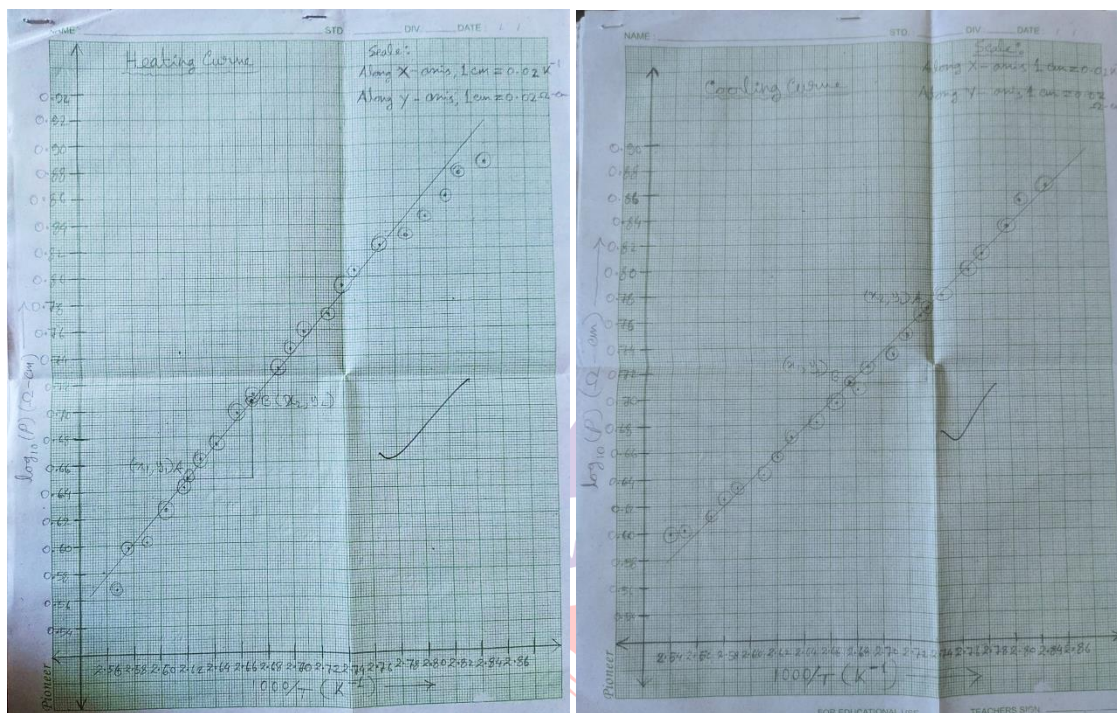
$T^{\circ}\text{C}$	T(k)	V(m,v)	$\rho_0 = \frac{V}{I} \times \frac{2\pi s}{w}$ $\Omega\text{-cm}$	$\rho = \rho_0 / F(w/s)$ $\Omega\text{-cm}$	$\log_{10} \rho$ $\Omega\text{-cm}$	$T^{-1} \times 10^{-3}$ k
80						
82						
84						
86						
118						
120						

Tabulation:2 (for cooling)

$T^{\circ}\text{C}$	T(k)	V(m,v)	$\rho_0 = \frac{V}{I} \times \frac{2\pi s}{w}$ $\Omega\text{-cm}$	$\rho = \rho_0 / F(w/s)$ $\Omega\text{-cm}$	$\log_{10} \rho$ $\Omega\text{-cm}$	$T^{-1} \times 10^{-3}$ k
120						
118						
116						
82						
80						

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Model graph:



6. Calculation

For heating

Slope = AC/BC = (Y₂ - Y₁) / (X₂ - X₁) = _____

E_g = _____ eV

For cooling

Slope = AC/BC = (Y₂ - Y₁) / (X₂ - X₁) = _____

E_g = _____ eV

7. Results

1) We obtain the energy band gap of p-type Ge sample as

For heating E_g = _____

For cooling E_g = _____

2) Resistivity decreases with increase in the temperature

8. Percentage error

$$\text{Percentage (\%)error} = \frac{(\text{Experimental value} - \text{Standard value}) \times 100}{\text{Standard Value}}$$

9. Precautions

1. Current should be constant while performing the experiment
2. The sample should be heated to a temperature near 160⁰C



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**To Study the Phase Diagram of Pb-Sn Alloy using
Cooling Curve and Determine its composition**

1. Basic Theory

PHASE DIAGRAM:

Phase diagram is a type of chart used to show conditions (pressure, temperature, volume, etc.) at which thermodynamically distinct phases (such as solid, liquid or gaseous states) occurs and co-exist at equilibrium. Phase diagram is classified on the basis of number of components in the system like single component systems have unitary diagram and two component systems have binary diagram and so on. The separation boundary between the phase in case of binary phase and multicomponent system is called a phase diagram. In case of binary phase, the atomic pressure is held at constant and a plot between concentration and temperature for a system having mass for more than one phase exhibits the existence of phase equilibrium. It is reflected by a constancy with time in the phase characteristics of a system.

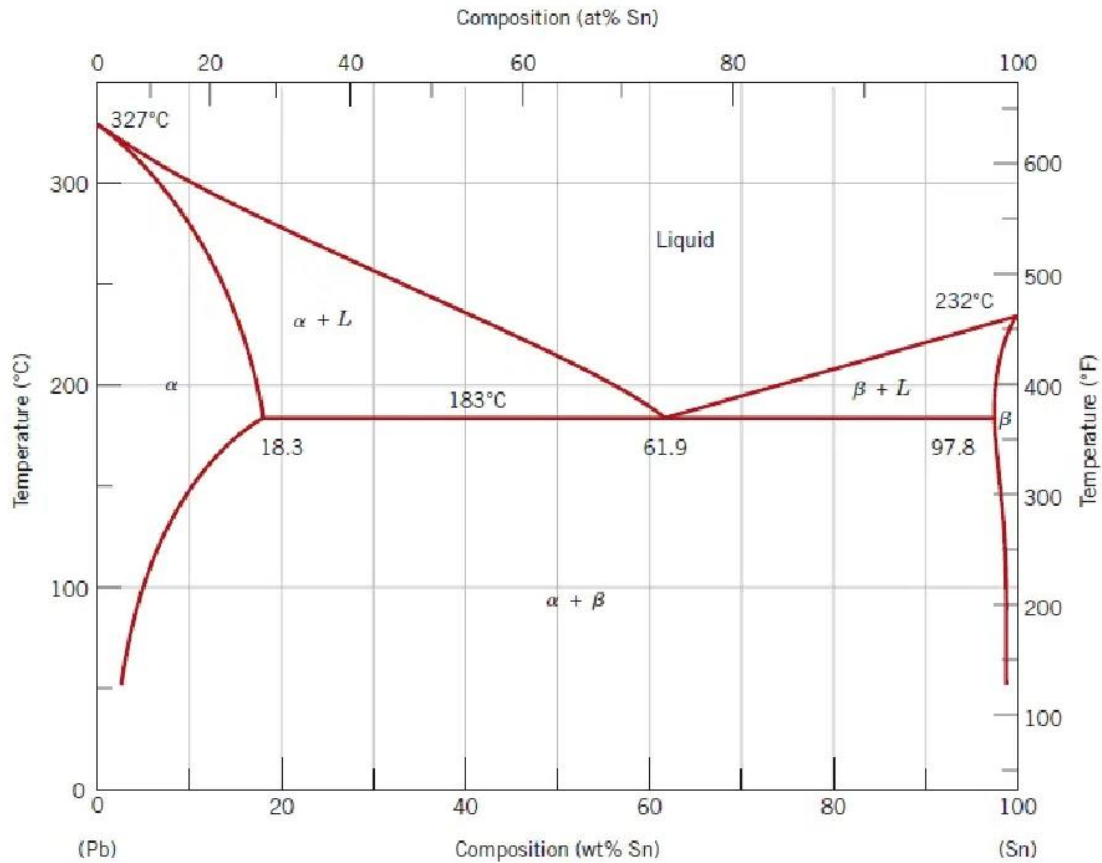


Figure 1: Phase diagram corresponding to Pb-Sn Alloy

COOLING CURVE:

A cooling curve is a line graph that represents the change of phase of matter typically from a gas to solid or a liquid to a solid. The independent variable (on x-axis) is time and the dependent variable (on y-axis) is temperature. The initial point of the graph is the starting temperature of matter noted as powering temperature. When a phase change occurs, there is a thermal arrest i.e., temperature stays constant. This is because matter has more internal energy as light or gas than in the solid state i.e., cooling to the amount of energy required for the phase change is known as latent heat. The cooling rate is the slope of the cooling curve at any point.

Due to the release of internal energy difference of two phase (latent heat), the temperature does not fall during solidification and a horizontal part in the thermal curve is obtained. When one of the constituents of the alloy undergoes a first order thermodynamic

transition (freezing) remain as such, the temperature of the alloy will exhibit a change from original slope depending on the relative percentage of the two constituents.

When temperature of the alloy falls to a value at which second constituents is also undergoing first order thermodynamical changes, then thermal curve will again exhibit horizontal slope or change in slope depending upon whether in the meanwhile first component has or has not transformed its structure completely. Hence study of thermal curve will reflect the phase transformation of different constituents.

All Phase transitions in alloys follows the Gibbs Phase rule. For a binary alloy system, the degree of freedom = $4-p$. Where “p” denotes the number of phases. Degree of freedom is equal to the number of the variable parameters externally controllable, such as temperature, pressure and composition. Usually one degree of freedom namely pressure is fixed during the cooling experiment and the experiment occurs at the atmospheric pressure. The balance of degree of freedom is $3-p$. So, at a point in phase diagram where three phases co-exist the degree freedom becomes zero which signifies its unique composition and temperature. Two phases co-exist over a range of temperature. The temperatures corresponding to the points at which changes in slope occur in the cooling curve known as “thermal arrest points” and depend on the composition of the alloy.

2. Experimental Set up

PID Oven and stop watch



Experimental Setup of Cooling curve experiment

3. Experimental Procedure

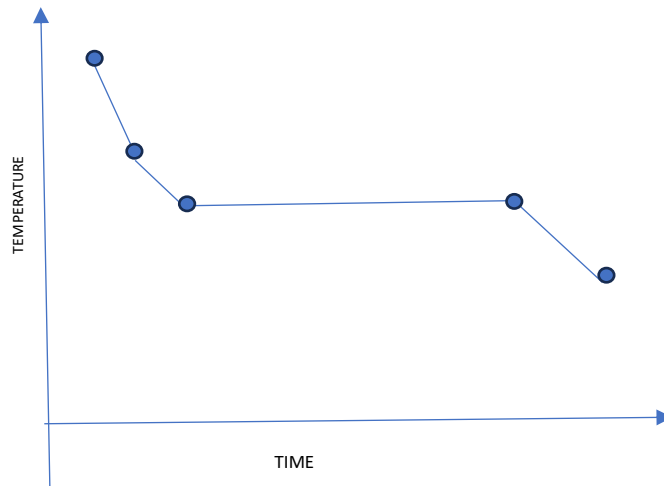
1. Switch on the main power supply.
2. Switch on the PID Oven supply and the dip the thermometer.
3. Then the Oven starts heating from the room temperature upto 100-130°C.
Then switch of the PID Oven supply.
4. Gradually the sample will be heated up to 210-235°C and after few minutes the samples starts to cool down.
5. Then start the stop watch and take the readings with some equivalent time intervals.
6. Plot the graph in between time and temperature and study the characteristics of the Pb-Sn alloy.

4. Observation Table

Time Interval = ----- sec

Si. NO.	Time (Minutes)	Temperature (°C)
1.		
2.		
3.		
4.		
5.		
6.		

Model graph:



5. Results

1. Plot the direct cooling curve and note down the arrect points at which changes in slope occurred.
2. From the Pb-Sn phase diagram find out the composition percentage of the Pb and Sn element in the Alloy.

We observe that when a phase change occurs there is a thermal arrest i.e. temperature becomes constant, in our experiment it is at °C.

6. Precautions

1. Carefully take the readings.
2. Make sure to turn off the PID Oven after heating upto 100-130⁰ C to avoid the overheating of the sample.
3. Start heating from room temperature.

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**To Determine the Mass Susceptibility of
Paramagnetic Solution Using Quincke's Method**

1. Introduction

Faraday divided the magnetic materials into three classes:

[a] Diamagnetic Substances:

These substances when placed in a magnetic field are feebly magnetized in a direction opposite to that of the magnetizing field. All closed shell materials are diamagnetic.

[b] Paramagnetic Substances:

These substances when placed in a magnetic field are feebly magnetized in the direction of the magnetizing field. Platinum, Aluminium, manganese, copper sulfate, solution of iron and nickel salts etc are some of the examples of such substances.

[c] Ferromagnetic Substances:

These substances when placed in a magnetic field are strongly magnetized in the direction of the magnetizing field iron, nickel, cobalt and their alloys are some of the examples of such substances.

❖ Magnetic Susceptibility:

The magnetic susceptibility ' χ ' (read as "chi") of a material is a measure of the ease with which a specimen of that material can be magnetized by a given magnetic intensity. It is defined as the ratio of the magnetization ' M ' produced due to the magnetic intensity ' H ' i.e.

$$\chi_v = \frac{M}{H} \dots\dots\dots (1)$$

Here magnetization M is the magnetic moment per unit volume and the, χ_v is known as the "Volume susceptibility ". Note that the volume susceptibility is a dimensionless quantity (irrespective of the system of units used). Let us denote it as χ_v for specifying it as the volume susceptibility. Equation (1) may also be expressed as

$$\chi_v = \frac{\mu_0 M}{B} \dots\dots\dots (2)$$

Where $B = \mu_0 H$ is the magnetic induction corresponding to the magnetic intensity H in vacuum.

If N be the number of atoms/volume and μ as the effective magnetic moment of each of these along B , then

$$M = N\mu \dots\dots\dots(3)$$

2. Experimental Set up

Quincke's tube fitted on stand, Electromagnet capable of producing magnetic field of about 10 K gauss with power supply, Gaussmeter, Travelling microscope and experimental solution.



Experimental Setup of the Quincke's Method

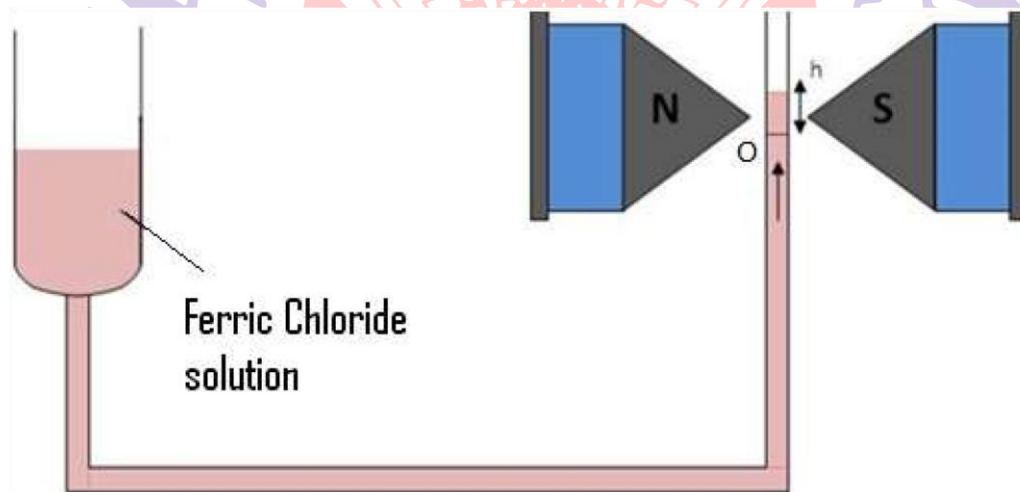


Figure 1. Level of Paramagnetic Liquid rises as we apply external magnetic field.

3. Basic Theory

MEASUREMENT OF SUSCEPTIBILITY:

When a solution of paramagnetic substance or ferromagnetic substance taken in a tube is placed between the poles of a magnet, there is a rise of liquid level. A

measurement of this rise in level of the solution in the tube enables us to determine the susceptibility of the substances. We know that the potential energy E_i of an atom of magnetic moment μ_i , when placed in a magnetic field of strength B (in weber/m² or tesla), is given by

$$E_i = \mu_i B = \mu B \dots\dots\dots (4)$$

Where μ is the effective magnetic moment along the direction of the magnetic field B i.e., Energy of unit volume of a substance with N atoms per unit volume will be $E = (N\mu)B = MB$ (energy/volume) and the force F on the unit volume of the substance, placed in an inhomogeneous magnetic field is

$$F = -\frac{dE}{dx} = -M \left(\frac{dB}{dx} \right) \dots\dots\dots (5)$$

And using equation (2) we get the force per unit volume

$$F = \left(\frac{\chi_v B}{\mu_0} \right) \frac{dB}{dx} = \left(\frac{\chi_v}{2\mu_0} \right) \frac{d}{dx} (B^2) \dots\dots\dots (6)$$

i.e., force on the volume V of the substance is

$$F = \left(\frac{\chi_v}{2\mu_0} \right) V \frac{d}{dx} (B^2) \dots\dots\dots (7)$$

From, Figure 1; let O be a section where the field is negligible and let ' x ' be the vertical coordinate of O . The force on the element dx of volume $a_c dx$ on the liquid at O is from equation (6)

$$dF = \left(\frac{\chi_v}{2\mu_0} \right) \frac{dB^2}{dx} (a_c dx) \dots\dots\dots (8)$$

Where ' a_c ' is the area of cross-section of the narrow limb. The force on the entire liquid above the point O is therefore

$$F = \int_0^{B_1} \left(\frac{\chi_v}{2\mu_0} \right) \frac{dB^2}{dx} (a_c dx) = \left(\frac{\chi_v a_c}{2\mu_0} \right) \int_0^{B_1} dB^2 = \left(\frac{1}{2\mu_0} \right) \chi_v a_c B_1^2 \dots\dots\dots (9)$$

Where B_1 is the field intensity at the upper level and the force F on the liquid above the point O due to the gravitational field is

$$F = mg = (a_c h) \rho g \dots\dots\dots (10)$$

where ρ is the density of the liquid. In equilibrium the two forces are equal and opposite thus from equation (7) and (8)

$$F = \left(\frac{1}{2\mu_0}\right) \chi_v a_c B_1^2 = (a_c h) \rho g \dots\dots\dots (11)$$

$$\chi_v = 2\mu_0 g \frac{h\rho}{B_1^2} \dots\dots\dots (12)$$

This is the volume susceptibility and is dimensionless. This volume susceptibility divided by density ρ gives the mass susceptibility of the solution

$$\chi_m = \frac{\chi_v}{\rho} = 2\mu_0 g \frac{h}{B_1^2} (m^3 kg^{-2}) \dots\dots\dots (13)$$

Where, $\mu_0 = 4\pi \times 10^{-7} \text{ V.S/Amp}$, g is in m/s^2 , B_1 is in Wb/m^2

4. Experimental Procedure

The experimental solution is placed in a Quincke's tube consisting of a wide and narrow limb. The wide limb is placed outside the field and the narrow limb inside the magnetic field provided by an electromagnet as shown in Fig. [1]. The field varies rapidly along the vertical direction due to the wedging of the pole pieces. Thus, the force given by eqn. (5) below on the specimen will be vertical.

1. Put the tube on stand and fix it with clamp.
2. Insert (the narrow limb of the Quincke's tube vertically between the pole pieces of (the electromagnet such that the meniscus is in the central region of the uniform magnetic field or in the centre of the poles and the wide limb is placed outside the field as shown in Figure 1.

3. Illuminate the meniscus level with an ordinary bulb and view it with a travelling microscope. Adjust the horizontal cross wire of the eye piece of microscope on the meniscus and note this reading of the microscope. It will be the initial position of the meniscus. Record this reading in table as shown below.
4. Switch ON the electromagnet power supply and adjust the current say at 0 amp, Bring the cross wire again on the meniscus and also record this reading in table by moving the microscope downwards.
5. Increase the power supply current in steps of 0.5 amp i.e. say 0.5, 1.0, 1.53.0 and note the corresponding position of the level of the liquid. Note all these readings in table.
6. Repeat the experiment for different concentration of the solution.
7. Finally put the magnetic field sensor b/w pole pieces. Switch on gauss meter and read the magnetic field corresponding to each value of current & note it in the table.

5. Observation Table

Table:1

S.No	Power supply current I (Amp)	Initial position of the meniscus $h_1(\text{cm})$	Final position of the meniscus $h_2(\text{cm})$	Change in height $h = (h_1-h_2)$ cm	Mag.Field B_1 (k gauss)	B_1^2 (k gauss) ²
1.						
2.						
3.						
4.						
..						
..						
..						

6. Calculation

Plot a graph (see Figure 2) each for different concentrations between B_1^2 magnetic field in kilo gauss along X-axis and 'h' change in height in cm along Y-axis, which gives a straight line with slope,

$$\frac{\Delta h}{\Delta B_1^2} = \frac{AB}{OB} \text{ cm/kgauss}^2 \text{ and convert it in } m/T^2$$

Now put above in equation (13) and calculate the mass susceptibility as

$$\chi_m = 2\mu_0 g \frac{\Delta h}{\Delta B_1^2}$$

Similarly calculate the value of mass susceptibility for other concentration of the solution and make table as shown below in Table 2 for the results.

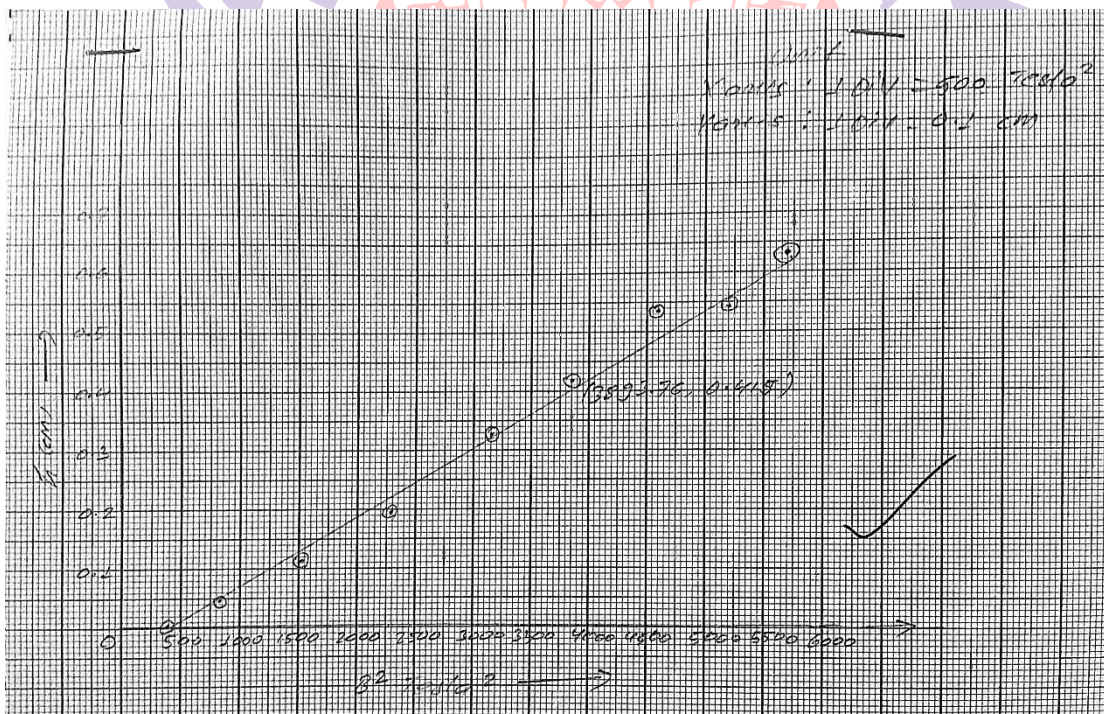


Figure 2. Graph plotted between B_1^2 magnetic field in kilo gauss along X-axis and 'h' change in height in cm along Y-axis to determine mass susceptibility.

7. Results

Table:2

The table shows the mass susceptibility of the given solution for different concentration.

Sl. No.	Concentration of the solution	Mass susceptibility χ_m
1.	50%	
2.	100%	
...

8. Precautions

1. Adjust the microscope to get clearer picture of meniscus. **B**
2. Use lamp and magnifying glass while taking readings.
3. Let the liquid rise and become steady before taking readings of meniscus.
4. Draw best fit straight line while plotting rise in liquid level 'h' vs B_1^2 .

9. Some constants and conversion factors:

Boltzmann constant, $k = 1.381 \times 10^{-23}$ Joule/K

Avogadro's number, $N_A = 6.0225 \times 10^{26}$ per kg mole

Bohr magneton, $\mu_B = 9.272 \times 10^{-24}$ Am² or 9.272×10^{-21} erg/gauss

Permeability of free space, $\mu_0 = 4\pi \times 10^{-7}$ 1 amp.turn/m

Mass susceptibility of water = 9.0×10^{-9} m³/kg

Molecular weight of FeCl₃ = 162.2 g/mole

Density of FeCl₃ = 2.9 g/cm³

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To Determine the *Lande g* factor Using Electron Spin Resonance

1. Background

Suppose a particle having a magnetic moment μ is placed in a uniform magnetic field of intensity B , then the Hamiltonian can be written as

$$\hat{H} = g \left(\frac{e}{2mc} \right) B \hat{J} \quad \text{----- (1)}$$

where g is the *Lande g* factor. Which is 1 for orbital angular momentum, and 2 for spin angular momentum. The factor $\frac{e\hbar}{2mc}$, is known as Bohr magneton (μ_B), when the particle is an electron. If the particle is a nucleon, then the factor is called the nuclear magneton. If the angular momentum, J results from a combination of an orbital angular momentum and a spin, then g would be given by the *Lande* formula

$$g = 1 + \frac{j(j+1)+s(s+1)-l(l+1)}{2j(j+1)} \quad \text{----- (2)}$$

where l, s and j represent the magnitude of the orbital, the spin and the total angular momenta, respectively and j only have the values from $l - s$ to $l + s$.

Conventionally, the static magnetic field is assumed to be pointing along the z -axis, then above equation (1) into

$$\hat{H} = g \left(\frac{e}{2mc} \right) B \hat{J}_z \quad \text{----- (3)}$$

Let us now consider an atom which has an electronic ground state with total angular momentum $j = 1/2$ and an excited state with $j = 3/2$ (see Figure 1).

This is a single transition which were induced by the absorption of radiation of frequency $\omega_{12} = \frac{(E_2 - E_1)}{\hbar}$. As the energy does not depend on the angular momentum states, the ground state is doubly degenerate corresponding to eigenvalues $\pm 1/2$ of \hat{J}_z and the excited state is quadruply degenerate corresponding to eigenvalues $+3/2, 1/2, -1/2, -3/2$ of \hat{J}_z .

If now an If one now a magnetic field B along the z-axis is acted upon, then each of the angular momentum states acquires a different energy. The ground state energy level thus splits into two sublevels and the excited state level into four sublevels. This is called **Zeeman splitting**. Now instead of a single transition of frequency $\omega_{12} = \frac{(E_2 - E_1)}{\hbar}$, many transitions of frequencies close to ω_{12} are possible. Experimentally this is seen as a splitting a single absorption or emission line into several closely spaced lines. This is called **Zeeman effect**.

Here, transition should also be possible between the sublevels of the same energy level. It is indeed possible and this phenomenon is known as electron spin resonance (ESR).

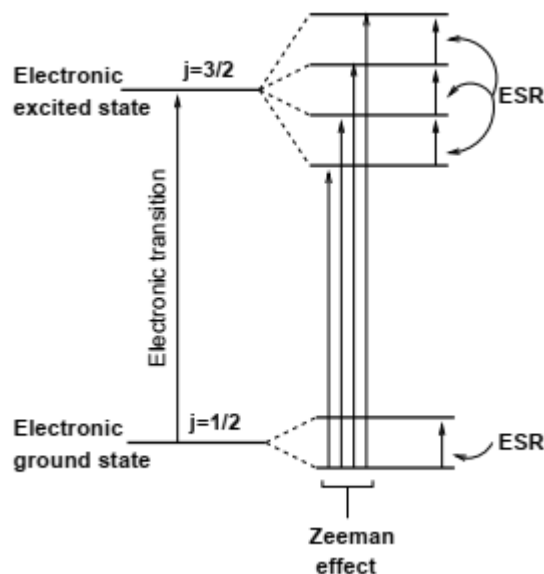


Figure 1. Electronic transition corresponding to the Zeeman splitting and ESR.

2. Experimental Set up

ESR setup which includes Helmholtz coils, R.F. oscillator and the test sample, and in addition, a cathode ray oscilloscope (CRO).

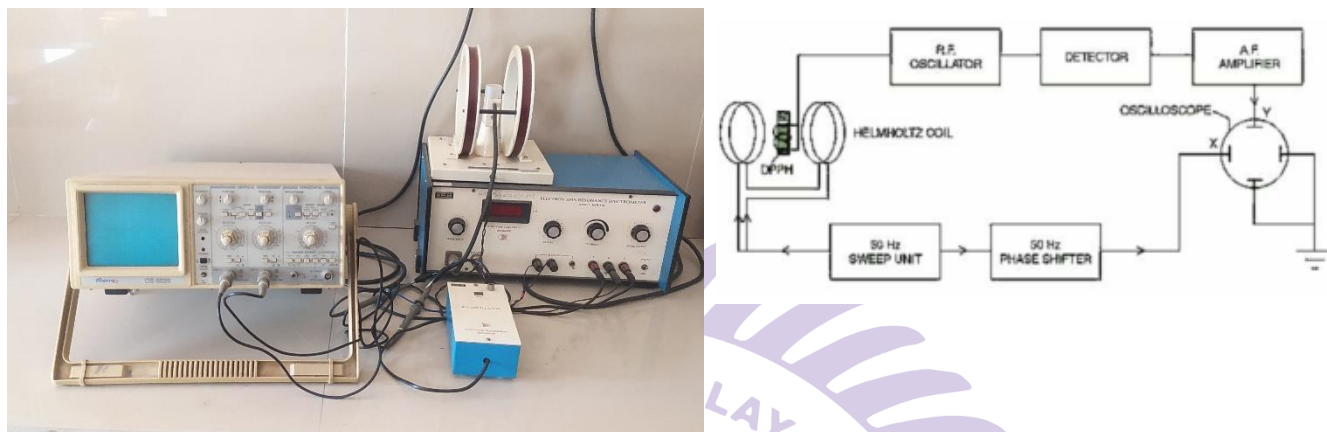


Figure 2. ESR experimental set up with its circuit components.

Basic circuit:

The first stage of the ESR circuit consists of a critically adjusted radio frequency oscillator. This type of oscillator is required here, so that the slightest increase in its load decreases the amplitude of oscillation to an appreciable extent. The sample is kept inside the tank coil of the oscillator, which in turn, is placed in the 50 Hz magnetic field generated by the Helmholtz coils. At resonance, i.e. when the frequency of oscillation becomes equal to frequency corresponding to the energy splitting of the sublevels, the oscillator amplitude registers a dip due to the absorption of power by the sample. This obviously, occurs periodically four times in each complete cycle of the supply voltage of the magnetic field. The result is an amplitude modulated carrier which is then detected using a diode detector and amplified by a chain of three low noise, high gain audio-frequency amplifiers to suit the input requirement of any oscilloscope. Highly stabilized and almost ripple free power supply for the above circuit is obtained using an integrated circuit regulator.

Phase shifter:

This can compensate the undermined phase difference which may be introduced in the amplification stages of the spectrometer and oscilloscope.

50 Hz sweep unit:

A 50 Hz current flows through Helmholtz coils which provides a low frequency magnetic field to the sample. As the resonance is observed at a few gauss only, no static magnetic field is applied.

R.F. Oscillator:

It is a transistorised radio frequency oscillator suitable for the determination of resonance frequency.

Sample Specification:

The sample used in our ESR setup is diphenyl-picryl-hydrazyl (DPPH). It is a widely used standard in ESR experiments. The structure of this organic molecule, shown in the Figure 3, contains three benzene rings.

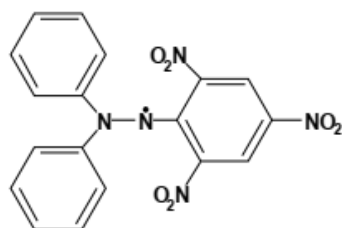


Figure 2. Chemical structure of DPPH

It's important feature is that it contains a single unpaired electron, whose orbital angular momentum is zero. So, the electron has only the spin angular momentum, and the material gives a g-factor which is close to 2.0038. One thus has to deal with the simple situation where $j = \frac{1}{2}$, and only two sublevels are involved.

Fact to be Remember:

In conventional spectroscopy, absorption intensity is plotted against the frequency of radiation to get the absorption spectrum. In the present case, one should obtain a single absorption peak at frequency $\omega = \frac{(\epsilon_j - \epsilon_i)}{\hbar}$, which is nothing but $\omega = \frac{geB}{2mc}$. However, in this setup it is difficult to vary the frequency of radiation. So, what is done is that the frequency of radiation is fixed at some ω_0 , and the normally static, magnetic field is swept between the positive and negative extremes of a maximum field value. This is done by supplying an alternating current to the Helmholtz coils which are supposed to generate the magnetic field. During the AC cycle, whenever the strength of the magnetic field (+ve or -ve) becomes equal to $B_0 = \frac{\omega_0 2mc}{ge}$, there is a resonance condition, and radiation is absorbed.

3. Basic Theory

Electron Spin Resonance:

Let us consider one electron with angular momentum j , in a magnetic field B . In addition we have an electromagnetic field of frequency ω in the direction perpendicular to B . The time-dependent Hamiltonian can thus be written as

$$\hat{H} = g \left(\frac{e}{2mc} \right) B \hat{J}_z + \hat{V}_0 e^{i\omega t} + \hat{V}_0^\dagger e^{-i\omega t} \quad (4)$$

Where, \hat{V}_0 represent the interaction of the electromagnetic field with the electron.

The electromagnetic field is supposed to be very weak compared to the applied static field B , and so we can use time-dependent perturbation theory to study this problem. The states that we will use are the eigenstates of \hat{J}_z , such that

$$\hat{J}_z |m\rangle = \hbar m |m\rangle \quad (5)$$

Where m will take the $2j + 1$ values, from $-j$ to $+j$. The energy of these levels

$$\text{is given by; } g \left(\frac{eB}{2mc} \right) \hat{J}_z |n\rangle = \epsilon_n |n\rangle \quad (6)$$

Where $\varepsilon_n = \frac{geBn\hbar}{2mc} = gBn\mu_B$.

In time-dependent perturbation theory, we know that the time-dependent interaction can cause transition between various $|m\rangle$ states. The transition rate per unit time, from i^{th} level to j^{th} level is given by:

$$W_{i \rightarrow j} = \frac{2\pi}{\hbar} |\langle j | \widehat{V}_0 | i \rangle|^2 \delta(\varepsilon_j - \varepsilon_i - \hbar\omega) \text{ ----- (7)}$$

Where we consider $\varepsilon_j > \varepsilon_i$. This expression says that transition from state $|i\rangle$ to $|j\rangle$ is possible when the frequency of radiation is

$$\omega = \frac{(\varepsilon_j - \varepsilon_i)}{\hbar} \text{ ----- (8)}$$

This is the **condition for Electron spin resonance**.

The form of \widehat{V}_0 will be such that, $\langle j | \widehat{V}_0 | i \rangle$ is nonzero only when $j = i \pm 1$.

This means that transition is possible between, $|-\frac{3}{2}\rangle$ and $|-\frac{1}{2}\rangle$, but not between, $|-\frac{3}{2}\rangle$ and $|\frac{1}{2}\rangle$. Such restrictions, imposed by the kind of interaction and the nature of states, are called **selection rules**.

4. Experimental Procedure

1. Connect the coaxial cable of the induction coil to the oscillator through the socket marked
2. Connect the Helmholtz coils to the power supply terminal marked.
3. Connect the "Out-put" terminal marked X, Y, E on the ESR spectrometer to the X plate and Y plate input and ground of the oscilloscope respectively and switch on the oscilloscope.
4. Connect the power supply with AC mains.
5. Adjust the current in the Helmholtz coils at 150 mA. The front panel controls of the ESR. ESR spectrometer are adjusted as follows: frequency, detector and phase, all centered.
6. The X plate of the CRO is calibrated in terms of magnetic field as follows:
 - X amplifier of the CRO is adjusted to obtain the maximum X deflection (e.g. P divisions). And, note the current flowing in the Helmholtz coils. The

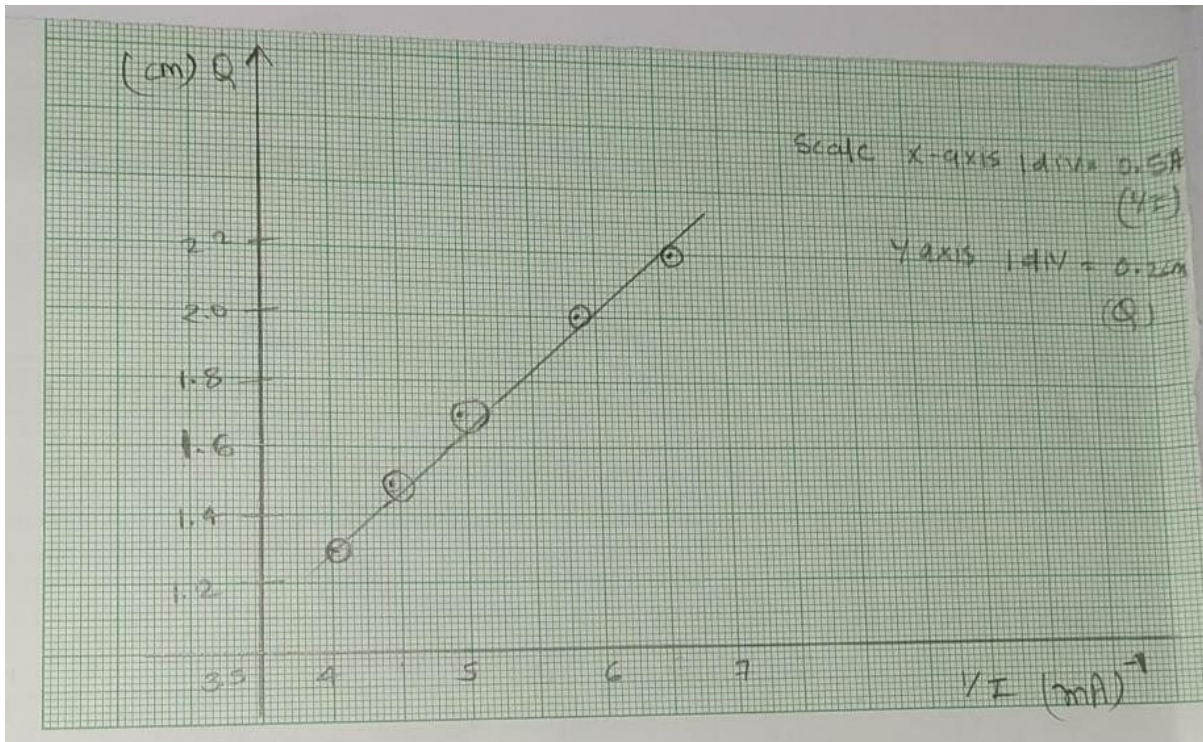
magnetic field can then be calculated from the formula for B given. Number of turn in the coils $N = 500$ and the radius $r = 7.7$ cm.

- ❖ The positions of the two peaks of the ESR signal at resonance is measured. Let this be Q divisions from the centre. The best possible resonance peaks are obtained by varying the frequency in the range of 12 to 14 MHz and the Y sensitivity of the oscilloscope. The phase knob is adjusted to coincide one pair of peaks with the other. The current through the coils is then varied, keeping the frequency fixed, and the corresponding position of the peaks from the centre noted. Otherwise use a trace paper to trace the spectra for the determination of the position. A graph between $1/I$ and Q is then plotted and can be used in calculating the g-factor.

5. Observation Table

Si.No.	I(mA)	I(A)	1/I	Distance of peaks from center (Q)			
				10 MHz	13 MHz	15 MHz	17 MHz
1.	150	0.150	6.667	2.4	1.9	1.9	1.9
2.							
3.							
4.							
5.							
6.							
7.							
8.							
9.							
10.							
11.							

Model graph:



6. Calculation

First, Let us calculate the magnetic field through the Helmholtz coils. This can be

done using the Biot-Savart law: $B = \mu_0 \left(\frac{4}{5}\right)^{\frac{3}{2}} N \frac{I}{r}$ ----- (9)

Where:

$\mu_0 = 4\pi \times 10^{-1}$ (cgs units)

N = number of turns in each coil

R = the radius of the Helmholtz coils in cm, which is equal to their separation when they are properly arranged

I = current passing through the coils

We will get B in gauss. Also, as the current is in AC ammeter, thus the field will be the r.m.s value. The peak value of the field is given by:

$$B_{max} = \sqrt{2}B = \mu_0 \frac{8\sqrt{2}}{\sqrt{125}} N \frac{1}{r} \text{ ----- (10)}$$

Suppose the peak value of the field (= B_{max}) corresponds to P divisions from the centre on the x-axis of the CRO screen. Then if Q be the distance of the observed resonances from the centre (in the units of divisions), the field corresponding to the resonance will be given by: $B_0 = Q \frac{B_{max}}{P} = \frac{\hbar\omega_0}{g\mu_B}$ (at resonance condition)

Now, for a fixed ω_0 , B_0 is fixed, although one can vary the current I and get various position of the absorption peaks. Then,

$$B_0 = \left(\frac{N\mu_0 8\sqrt{2}}{rP\sqrt{125}} \right) I \cdot Q \text{ ----- (11)}$$

The ESR spectrometer is such that P does not vary as one varies I. So, the best way to evaluate the above expression will be to plot a graph between $1/I$ and Q, and find out the slope, which will give the average value of $I \cdot Q$. The field at the absorption peaks can be calculated as:

$$B_0 = \left(\frac{N\mu_0 8\sqrt{2}}{rP\sqrt{125}} \right) \times \text{slope of the plot between } \frac{1}{I} \text{ and } Q \text{ ----- (12)}$$

7. Results

Here given: $N = 500$, $r = 7.7 \text{ cm}$, $\mu_0 = 0.1 \times 4\pi$, $\mu_B = 9.2741 \times 10^{-21}$, $h = 6.626 \times 10^{-27}$

Now we get the slope of the $1/I$ and Q plot = -----

Using the equation (12), we get the value of $B_0 = \text{----- gauss}$

Then, $g = \left(\frac{h\nu_0}{\mu_B B_0} \right) = \text{-----}$

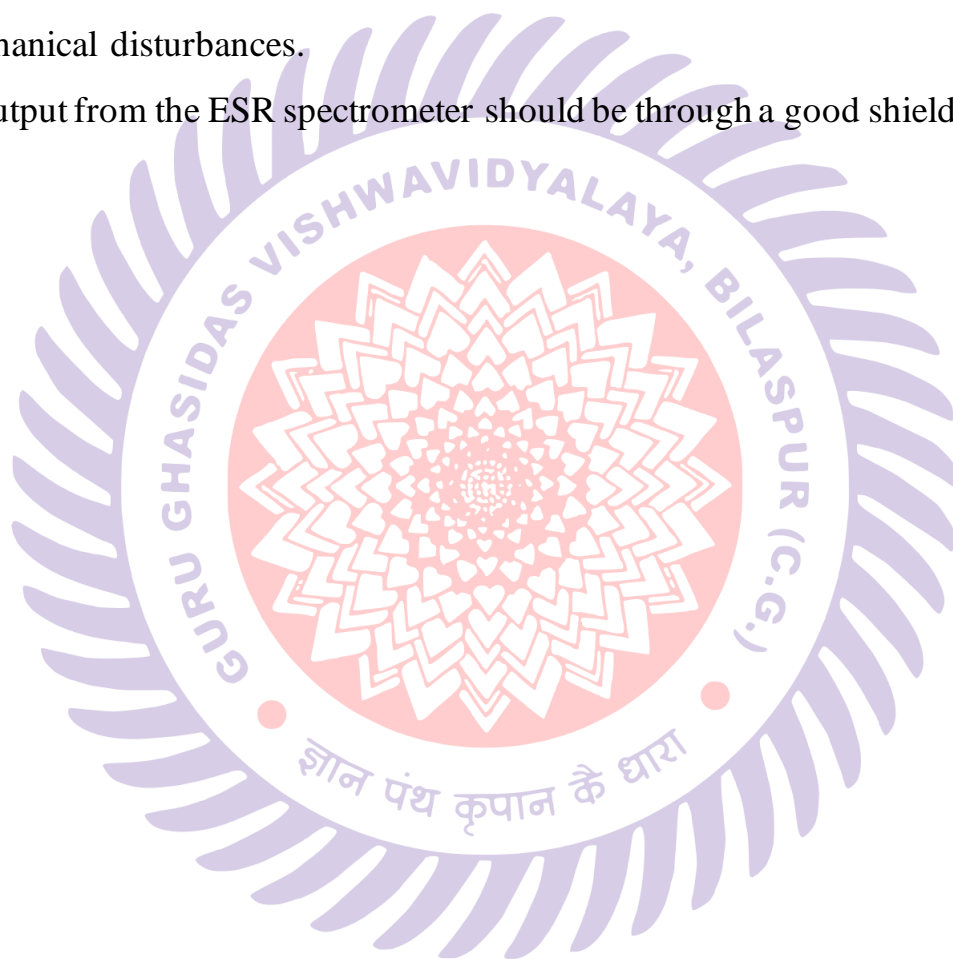
8. Percentage error

Percentage (%)error

$$= \frac{[\text{Experimental value} - \text{Standard value (2.0038)}] \times 100}{\text{Standard Value}}$$

9. Precautions

1. The direction of the Helmholtz coils should be preferable adjusted so that the field is perpendicular to earth's magnetic field, which is about 0.3 Gauss.
2. Setup the experiment at a place free from electric and magnetic fields and mechanical disturbances.
3. Y-output from the ESR spectrometer should be through a good shielded cable.



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Department of Pure & Applied Physics

Condensed Matter Physics Practical Experiment Manual



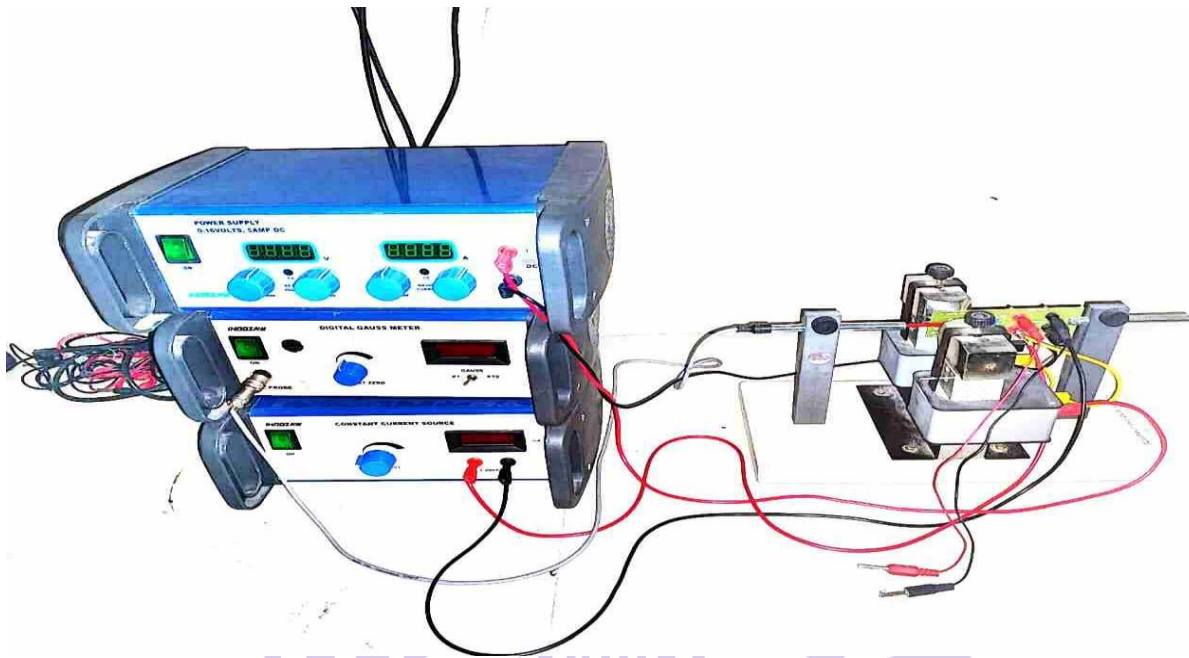
**To Determine Hall coefficient (R_H), Hall voltage (V_H), types of
charge carriers and Hall angle (θ_H) using Hall Effect experiment**

1. Historical Background

In 1879, E.H. Hall discovered this hall effect while working on his doctoral degree at Johns Hopkins University in Baltimore, Maryland. He observed that on placing a current carrying conductor perpendicular to a magnetic field, a voltage is observed perpendicular to both the magnetic field and the current. It was observed that the charge carriers, which were assumed to be electrons experienced a sideways force opposite to what was expected. This was later explained on the basis of band theory. The number of conducting charges and the sign of charge carriers cannot be determined by the measurement of conductivity of a specimen. In metals/conductors, the current carriers are only electrons whereas in semiconductors, both electrons and holes act as current carriers. Therefore, in semiconductor, it is quite necessary to determine whether a material is of n-type or p-type. The Hall effect can be used to distinguish the two types of charge carriers and also to determine the density of charge carriers.

2. Experimental Set up

Gauss meter, supply voltage, current power supply, hall effect experiment apparatus, hall probe, electromagnet, PCB with semiconductor, multimeter.



Experimental Setup of Hall Effect Experiment

3. Basic Theory

When a magnetic field is applied perpendicular to a current carrying specimen (metal or semiconductor), a voltage is developed in the specimen in a direction perpendicular to both the current and the magnetic field. This phenomenon is called Hall effect. The voltage so generated is called Hall voltage. We know that a static magnetic field has no effect on charges unless they are in motion. When the charges flow, a magnetic field directed perpendicular to the direction of flow produces a mutually perpendicular force on the charges. Consequently, electrons and holes get separated by opposite forces and produce an electric field E_H , thereby setting up a potential difference between the ends of a specimen. This is called Hall potential V_H .

Consider a semiconductor slab in the form of a flat strip with width 'b' and thickness 't'. Let a current, I flows through the strip along X- axis. P and P' are two points on the opposite faces of a b c d and a' b' c' d' respectively. If a millivoltmeter is connected between points P and P', it does not show any reading, indicating that there is no potential difference setup between these points. But, when a magnetic field is applied along Y-axis, i.e., perpendicular to the direction

of current, a deflection is produced in the millivoltmeter indicating that a potential difference is set up between P and P'. This potential difference is known as Hall voltage or Hall potential V_H . If a current is passed along x-axis, then the electrons move along negative direction of x-axis. The force on electron due to the applied magnetic field B along Y axis is given by;

$$\vec{F}_B = -e(\vec{v}_d \times \vec{B})\hat{z} \text{ ----- (1)}$$

$$\vec{F}_B = -ev_d B \hat{z} \text{ ----- (2)}$$

Where, v_d is the drift velocity of electron and e is the charge of electron.

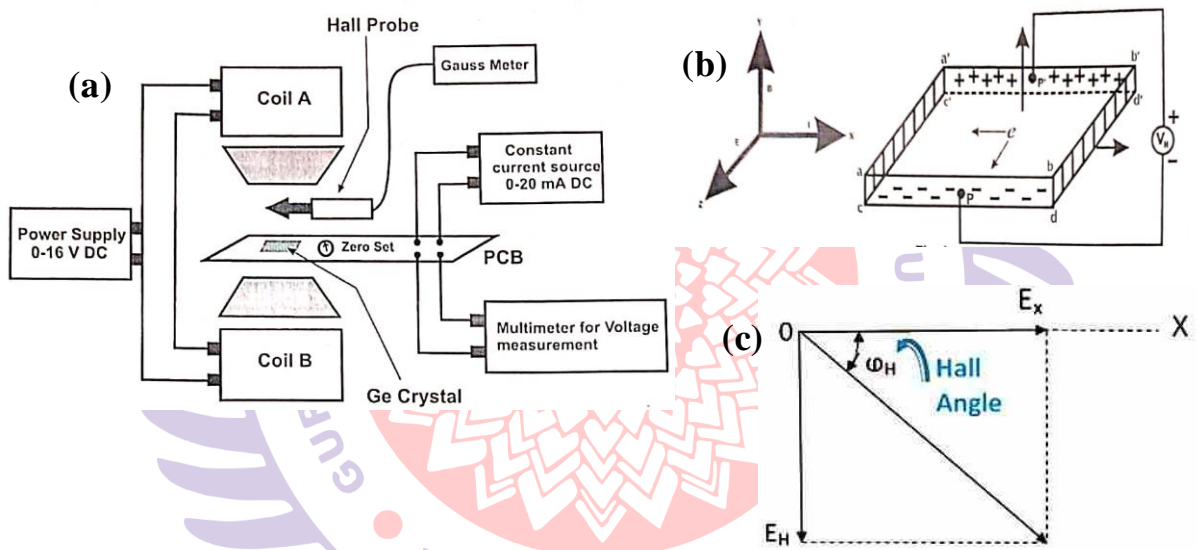


Figure 1. (a) Schematic representation of Hall effect experimental set up, (b) charge carrier motion dynamics under applied magnetic field in a semiconductor material and (c) graphical definition of Hall Angle

This force along \hat{z} direction deflects the positive charge carriers towards the 'a' 'b' 'd' 'c' surface of the semiconducting strip. This makes the that surface positively charged while leaving the opposite 'a c d b' surface negatively charged. This accumulation of charges near these two surfaces of the sample leads to the development of a transverse electric field $\vec{E} = E_z \hat{z}$ along the z-direction. Force due to this electric field $e\vec{E}$ opposed the Lorentz force \vec{F}_B and further prevents the charge accumulation. In the steady state condition, these two forces balance out each other and we get,

$$eE_z = ev_d B \quad \text{----- (3)}$$

Now, the cross-sectional area $A = bt$, and the current density

$$J_x = \frac{I_x}{A} = \frac{I}{bt} \quad \text{----- (4)}$$

Hall coefficient is defined as the ratio of the electric E_z to the current density J_x multiplied by magnetic field B , that is

$$R_H = \frac{E_z}{J_x B} \quad \text{----- (5)}$$

Now, if n is the charge carrier density i.e., number of charge carriers per unit volume (m^3), then $J_x = nev_d$ ----- (6)

Using this expression and multiplying both sides of equation (3) by 'bt' we get,

$$E_z bt = \frac{J_x bt B}{ne} \quad \text{----- (7)}$$

But, $E_z t = V_H$, the voltage across the opposite surfaces known as Hall voltage and $J_x bt = I_H$, then

$$V_H = \left(\frac{R_H B}{b} \right) I_H \quad \text{----- (8)}$$

$$\text{With, } \frac{1}{ne} = \left(\frac{V_H b}{BI} \right) \quad \text{----- (9)}$$

The hall coefficient is given by

$$R_H = \left(\frac{V_H b}{BI} \right) \text{-----(10)}$$

And charge carrier density is given by

$$n = \left(\frac{1}{eR_H} \right) \text{-----(11)}$$

If the condition is primarily due to one type of charge carriers, then conductivity is related to mobility μ_m as

$$\mu_m = \sigma R_H \text{-----(12)}$$

$$\text{therefore } \mu_m = \left(\frac{R_H}{\rho} \right) \text{-----(13)}$$

where, ρ is the resistivity.

There is another interesting quantity called the Hall angle (θ_H), defined by

$$\text{equation, } \tan\theta_H = \left(\frac{E_H}{E_x} \right) \text{-----(14)}$$

$$\text{but } E_H = V_x B, \text{ hence, } \tan\theta_H = \left(\frac{V_x B}{E_x} \right) = \mu_m B \text{-----(15)}$$

4. Experimental Procedure

1. Connect the width wise contacts of the Hall probe to the terminals marked 'voltage' and Length wise contacts to terminals marked 'current'.
2. Switch 'ON' the Hall effect setup and adjustment current (say few mA).
3. Switch over the display to voltage side. There may be some voltage reading even outside the magnetic field. This is due to imperfect alignment of the four contacts of the Hall probe and is generally known as the 'Zero field potential'. In case its value is comparable to the Hall voltage it should be adjusted to a minimum possible (for Hall probe (Ge) only). In all cases the error should be subtracted from the Hall voltage reading.
4. Switch on the constant current power supply at any desired value.

5. Measure the magnetic field between the pole pieces of the electromagnet using digital Gaussmeter and also measure the distance between two pole pieces.
6. The Hall probe is placed in between the pole pieces of the electromagnet and rotate the Hall probe till it becomes perpendicular to the magnetic field so that the Hall voltage will be minimum in this adjustment.
7. Measure the Hall voltage as a function of current in the Hall effect setup keeping the magnetic field constant and plot a graph.

5. Observation Table

Table:1

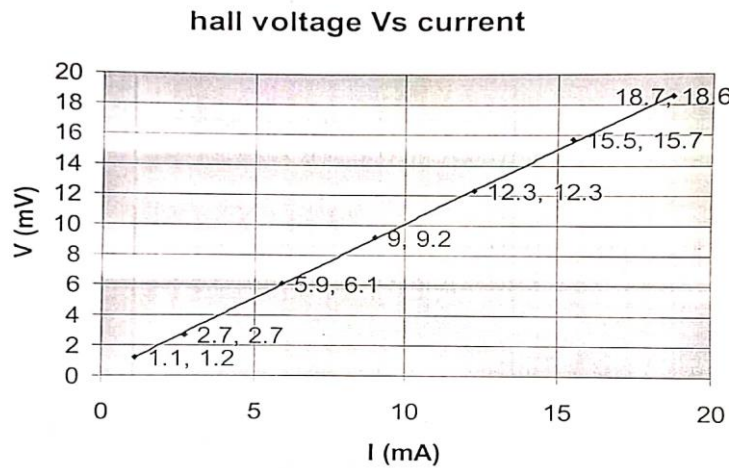
S.no	Current	Reading of millivoltmeter (mV)		Mean value of V_H (mV)	V_H/I (ohms)
		B and I in one direction	B and I in reversed direction		
1					
2					
3					
4					
5					
6					
7					

Table:2

S.No	Current I (mA)	Distance between two points between which potential difference is measured, l (m)	V_l (mV)	$\rho = V_l b t / I l$ (Ωm)
1				
2				
3				
4				

5				
6				
7				

Model graph:



6. Calculation

1. Mean value of $\frac{V_H}{I} = \underline{\hspace{2cm}} \Omega$
2. $R_H = \frac{V_H}{I} \times \frac{b}{B} = \text{Slope} \times \underline{\hspace{2cm}} = \underline{\hspace{2cm}} \text{m}^3\text{c}^{-1}$
3. $n = \frac{1}{R_H e} = \underline{\hspace{2cm}} \text{carriers.m}^{-3}$
4. $\rho = \underline{\hspace{2cm}} \Omega\text{m}$
5. $\mu_m = \frac{R_H}{\rho} = \underline{\hspace{2cm}} \text{m}^3\text{V}^{-1}\text{s}^{-1}$
6. $\theta_H = \tan^{-1}(\mu_m B) = \underline{\hspace{2cm}}^\circ$

7. Results

Thus, we obtain the following values through hall experiment,

1. $\frac{V_H}{I} = \underline{\hspace{2cm}} \Omega$
2. $R_H = \underline{\hspace{2cm}} \text{m}^{-3}$
3. $n = \underline{\hspace{2cm}} \text{m}^{-3}$

4. $\rho = \underline{\hspace{2cm}} \Omega\text{m}$
5. $\mu_m = \underline{\hspace{2cm}} \text{m}^3\text{v}^{-1}\text{s}^{-1}$
6. $\theta_H = \underline{\hspace{2cm}}^\circ$

8. Precautions

1. Before starting the experiment, check that the gauss meter is showing zero value. For this put the probe away from electromagnet and switch on the gauss meter, adjust its zero-adjustment knob.
2. Ensure that the specimen is located at the centre between the pole pieces and exactly perpendicular to the magnetic field.
3. To measure the magnetic flux the hall probe should be placed at the centre between the pole pieces, parallel to semiconductor sample.
4. For carrying out the experiment, the magnetic flux density should be maximum.
5. The deflection of the hall angle will be within 5° from the ideal value 90° .