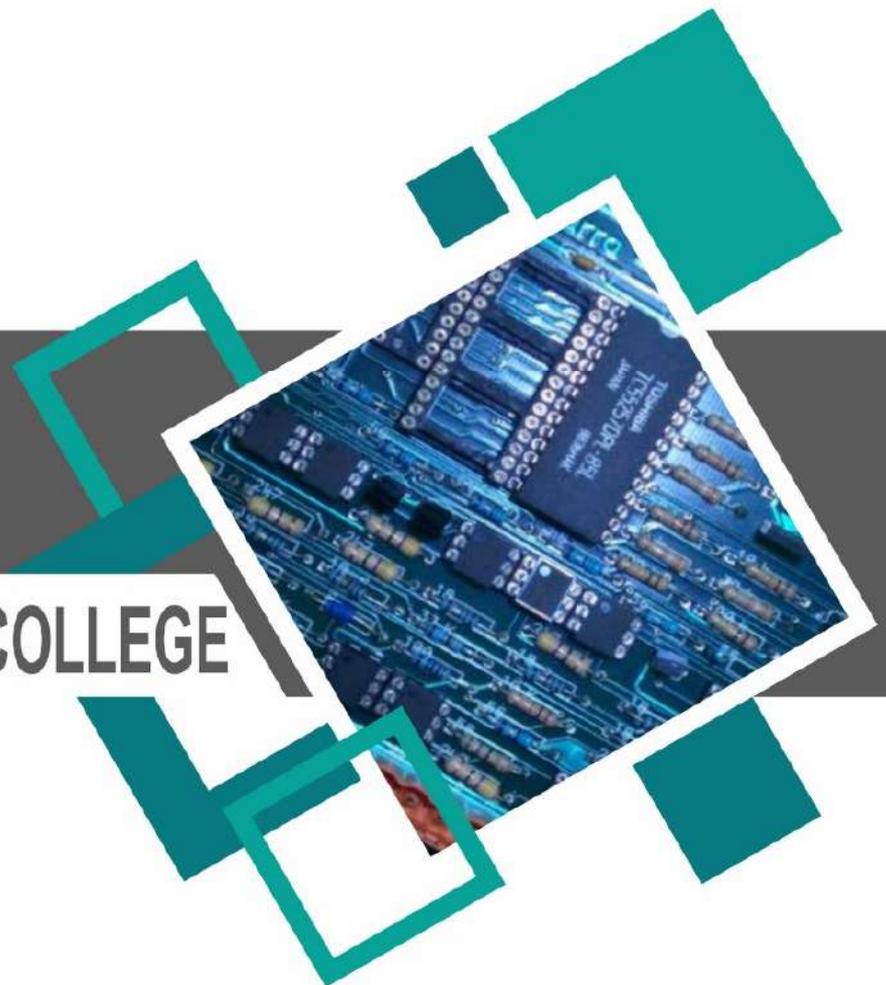


B.Sc. PHYSICS LAB MANUAL
5th Semester



Prepared By
Pure & Applied Sciences
Physics

MIDNAPORE CITY COLLEGE



Course No: C11P:
Quantum Mechanics and Applications Lab
Credit: 2.

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| 2 | Solve the s-wave radial Schrodinger equation for an atom | 7 |
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1. Solve the s-wave Schrodinger equation for the ground state and the first excited state of the hydrogen atom:

$$\frac{d^2y}{dr^2} = A(r)u(r), A(r) = \frac{2m}{\hbar^2} [V(r) - E] \text{ where } V(r) = -\frac{e^2}{r}$$

S wave Schrodinger equation for the ground state and the first excited state of the hydrogen atom : Here, m is the reduced mass of the electron. Obtain the energy eigenvalues and plot the corresponding wavefunctions. Remember that the ground state energy of the hydrogen atom is ≈ -13.6 eV. Take $e = 3.795$ (eVÅ)^{1/2} , $\hbar c = 1973$ (eVÅ) and $m = 0.511 \times 10^6$ eV/c² .

Program:

```
import numpy as np
from scipy import constants as const
from scipy import sparse as sparse
from scipy.sparse.linalg import eig
from matplotlib import pyplot as plt
hbar = const.hbar
e = const.e
m_e = const.m_e
pi = const.pi
epsilon_0 = const.epsilon_0
joule_to_eV = e

def calculate_potential_term(r):
    potential = e**2 / (4.0 * pi * epsilon_0) / r
    potential_term = sparse.diags((potential))
    return potential_term

def calculate_angular_term(r):
    angular = 1 * (1 + 1) / r**2
    angular_term = sparse.diags((angular))
    return angular_term

def calculate_laplace_three_point(r):
    h = r[1] - r[0]

    main_diag = -2.0 / h**2 * np.ones(N)
    off_diag = 1.0 / h**2 * np.ones(N - 1)
    laplace_term = sparse.diags([main_diag, off_diag, off_diag], (0, -1, 1))
    return laplace_term

def build_hamiltonian(r):
    laplace_term = calculate_laplace_three_point(r)
    angular_term = calculate_angular_term(r)
    potential_term = calculate_potential_term(r)

    hamiltonian = -hbar**2 / (2.0 * m_e) * (laplace_term - angular_term) - potential_term

    return hamiltonian
```

```

def plot(r, densities, eigenvalues):
    plt.xlabel('x ( $\mathbf{AA}$ )')
    plt.ylabel('probability density ( $\mathbf{AA}^{-1}$ )')

    energies = ['E = {>5.2f} eV'.format(eigenvalues[i].real / e) for i in range(3)]
    plt.plot(r * 1e+10, densities[0], color='blue', label=energies[0])
    plt.plot(r * 1e+10, densities[1], color='green', label=energies[1])
    plt.plot(r * 1e+10, densities[2], color='red', label=energies[2])

    plt.legend()
    plt.savefig('qm1.png', bbox_inches='tight', pad_inches = 0.3, dpi = 700)
    plt.show()
    return

""" set up horizontal axis and hamiltonian """
N = 2000
l = 0
r = np.linspace(2e-9, 0.0, N, endpoint=False)
hamiltonian = build_hamiltonian(r)

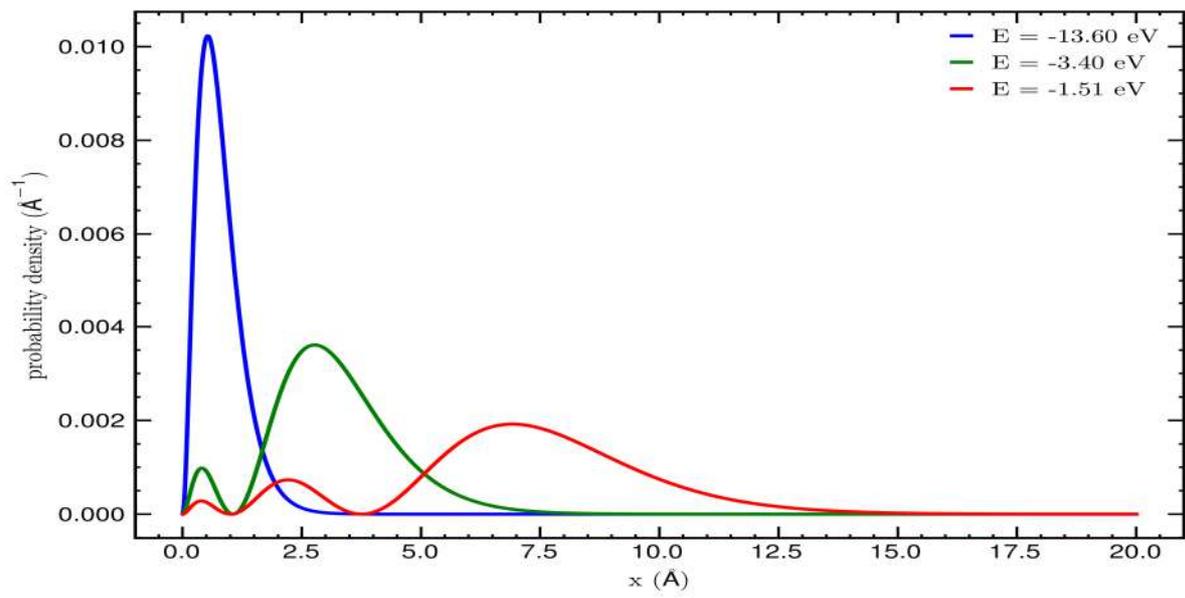
""" solve eigenproblem """
number_of_eigenvalues = 30
eigenvalues, eigenvectors = eigs(hamiltonian, k=number_of_eigenvalues, which='SM')

""" sort eigenvalue and eigenvectors """
eigenvectors = np.array([x for _, x in sorted(zip(eigenvalues, eigenvectors.T), key=lambda pair:
pair[0])])
eigenvalues = np.sort(eigenvalues)

""" compute probability density for each eigenvector """
densities = [np.absolute(eigenvectors[i, :])**2 for i in range(len(eigenvalues))]

""" plot results """
plot(r, densities, eigenvalues)

```



2. Solve the s-wave radial Schrodinger equation for an atom:

$$\frac{d^2y}{dr^2} = A(r)u(r), A(r) = \frac{2m}{\hbar^2} [V(r) - E]$$

where m is the reduced mass of the system (which can be chosen to be the mass of an electron), for the screened coulomb potential

$$V(r) = \frac{e^2}{r} e^{-r/a}$$

Find the energy (in eV) of the ground state of the atom to an accuracy of three significant digits. Also, plot the corresponding wavefunction. Take $e = 3.795 \text{ (eV}\text{\AA})^{1/2}$, $m = 0.511 \times 10^6 \text{ eV}/c^2$, and $a = 3 \text{ \AA}, 5 \text{ \AA}, 7 \text{ \AA}$. In these units $\hbar c = 1973 \text{ (eV}\text{\AA})$. The ground state energy is expected to be above -12 eV in all three cases.

Program:

```
import numpy as np
from scipy import constants as const
from scipy import sparse as sparse
from scipy.sparse.linalg import eigs
from matplotlib import pyplot as plt
hbar = const.hbar
e = const.e
m_e = const.m_e
pi = const.pi
epsilon_0 = const.epsilon_0
joul_to_eV = e
a = [3,5,7]
def calculate_potential_term(r):
    potential = (e**2 / r)*(e**(-r/a))
    potential_term = sparse.diags((potential))
    return potential_term

def calculate_angular_term(r):
    angular = 1 * (1 + 1) / r**2
    angular_term = sparse.diags((angular))
    return angular_term

def calculate_laplace_three_point(r):
    h = r[1] - r[0]

    main_diag = -2.0 / h**2 * np.ones(N)
    off_diag = 1.0 / h**2 * np.ones(N - 1)
    laplace_term = sparse.diags([main_diag, off_diag, off_diag], (0, -1, 1))
    return laplace_term

def build_hamiltonian(r):
    laplace_term = calculate_laplace_three_point(r)
    angular_term = calculate_angular_term(r)
    potential_term = calculate_potential_term(r)

    hamiltonian = -hbar**2 / (2.0 * m_e) * (laplace_term - angular_term) - potential_term

    return hamiltonian
```

```

""" set up horizontal axis and hamiltonian """
N = 2000
l = 0
r = np.linspace(2e-9, 0.0, N, endpoint=False)
hamiltonian = build_hamiltonian(r)

""" solve eigenproblem """
number_of_eigenvalues = 30
eigenvalues, eigenvectors = eigs(hamiltonian, k=number_of_eigenvalues, which='SM')

""" sort eigenvalue and eigenvectors """
eigenvectors = np.array([x for _, x in sorted(zip(eigenvalues, eigenvectors.T), key=lambda pair:
pair[0])])
eigenvalues = np.sort(eigenvalues)

""" compute probability density for each eigenvector """
densities = [np.absolute(eigenvectors[i, :])**2 for i in range(len(eigenvalues))]

```

3. Solve the s-wave radial Schrodinger equation for a particle of mass m:

$$\frac{d^2y}{dr^2} = A(r)u(r), A(r) = \frac{2m}{\hbar^2} [V(r) - E]$$

For the anharmonic oscillator potential

$$V(r) = \frac{1}{2}kr^2 + \frac{1}{3}br^3$$

for the ground state energy (in MeV) of particle to an accuracy of three significant digits. Also, plot the corresponding wave function. Choose $m = 940 \text{ MeV}/c^2$, $k = 100 \text{ MeV fm}^{-2}$, $b = 0, 10, 30 \text{ MeV fm}^{-3}$. In these units, $\hbar c = 197.3 \text{ MeV fm}$. The ground state energy I expected to lie between 90 and 110 MeV for all three cases.

Program:

```
import numpy as np
from scipy import constants as const
from scipy import sparse as sparse
from scipy.sparse.linalg import eigs
from matplotlib import pyplot as plt
hbar = const.hbar
e = const.e
m_e = const.m_e
pi = const.pi
epsilon_0 = const.epsilon_0
joule_to_eV = e
k=100 #mev
b = [0,10,30]
m= 940
ch = 197.3
def calculate_potential_term(r):
    potential = 0.5*k*(r**2) + (1/3)*b*r**3
    potential_term = sparse.diags((potential))
    return potential_term

def calculate_angular_term(r):
    angular = 1 * (1 + 1) / r**2
    angular_term = sparse.diags((angular))
    return angular_term

def calculate_laplace_three_point(r):
    h = r[1] - r[0]

    main_diag = -2.0 / h**2 * np.ones(N)
    off_diag = 1.0 / h**2 * np.ones(N - 1)
    laplace_term = sparse.diags([main_diag, off_diag, off_diag], (0, -1, 1))
    return laplace_term

def build_hamiltonian(r):
    laplace_term = calculate_laplace_three_point(r)
    angular_term = calculate_angular_term(r)
    potential_term = calculate_potential_term(r)

    hamiltonian = -hbar**2 / (2.0 * m_e) * (laplace_term - angular_term) - potential_term
```

```

return hamiltonian

""" set up horizontal axis and hamiltonian """
N = 2000
l = 0
r = np.linspace(2e-9, 0.0, N, endpoint=False)
hamiltonian = build_hamiltonian(r)

""" solve eigenproblem """
number_of_eigenvalues = 30
eigenvalues, eigenvectors = eigs(hamiltonian, k=number_of_eigenvalues, which='SM')

""" sort eigenvalue and eigenvectors """
eigenvectors = np.array([x for _, x in sorted(zip(eigenvalues, eigenvectors.T), key=lambda pair:
pair[0])])
eigenvalues = np.sort(eigenvalues)

""" compute probability density for each eigenvector """
densities = [np.absolute(eigenvectors[i, :])**2 for i in range(len(eigenvalues))]

```

Course No: C12P:
Solid State Physics Lab
Credit: 2.

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1. MAGNETIC SUSCEPTIBILITY OF A PARAMAGNETIC MATERIAL BY QUINCKE'S METHOD

❖ Objective

1. To determine the magnetic susceptibility χ of a given paramagnetic solution for a specific concentration.
2. Calculate mass susceptibility χ' , Molar susceptibility χ'' , Curie constant C and Magnetic dipole moment.

❖ Theory

When a material is placed within a magnetic field, the magnetic forces of the material's electrons will be affected. This effect is known as Faraday's Law of Magnetic Induction. However, materials can react quite differently to the presence of an external magnetic field. This reaction is dependent on a number of factors, such as the atomic and molecular structure of the material, and the net magnetic field associated with the atoms. The magnetic moments associated with atoms have three origins. These are the electron motion, the change in motion caused by an external magnetic field, and the spin of the electrons. In most atoms, electrons occur in pairs with spins in opposite directions. These opposite spins cause their magnetic fields to cancel each other. Therefore, no net magnetic field exists. Alternately, materials with some unpaired electrons will have a net magnetic field and will react more to an external field. Most materials can be classified as diamagnetic, paramagnetic or ferromagnetic.

Although you might expect the determination of electromagnetic quantities such as susceptibility to involve only electrical and magnetic measurements, this practical shows how very simple measurements of *mechanical* phenomena, such as the displacement of a liquid column can be used instead. Quincke devised a simple method to determine the magnetic susceptibility, χ , of a *paramagnetic* solution by observing how the liquid rises up between the two pole pieces of an electromagnet, when a direct current is passed through the electromagnet coil windings. A material's magnetic susceptibility tells us how "susceptible" it is to becoming temporarily magnetized by an applied magnetic field and defined as the magnetization (M) produced per unit magnetic field (H).

$$\chi = \frac{M}{H} \quad (1)$$

Consider a paramagnetic medium in the presence of a uniform applied flux density B_0 . Loosely speaking, paramagnets are materials which are attracted to magnets. They contain

microscopic magnetic dipoles of magnetic dipole moment \mathbf{m} which are randomly oriented. However, in the presence of a uniform field \mathbf{B} each dipole possesses a magnetic potential energy $U = -\mathbf{m} \cdot \mathbf{B}$ [1]. So they all tend to align up parallel to \mathbf{B} , which is the orientation in which their potential energy is minimum (i.e. most negative). Consequently, the liquid, which contains many such dipoles, will tend to be drawn into the region of maximum field since this will minimize its total magnetic potential energy. In other words, the liquid experiences an attractive magnetic force F_m pulling it into the region of strongest field. The dipoles in the liquid, FeCl_3 solution for this experiment are due to Fe^{3+} ions which are paramagnetic in their ground-state. The “spins” of several outer electrons are aligned parallel to each other to give rise to a net magnetic moment \mathbf{m} which is not compensated by other electrons. A region of empty space permeated by a magnetic field H possesses an energy whose density (energy per unit volume) is $u = \frac{1}{2}\mu_0 H^2$ [1], where μ_0 is the magnetic permeability of vacuum.

In presence of a medium, this magnetic energy density may be written:

$$u = \frac{1}{2}\mu H^2 \quad (2)$$

where μ is the magnetic permeability of the medium and $H = |\mathbf{H}|$. For fields which are not too large, the magnetic permeability μ of a paramagnet can be treated as independent of the applied field; i.e. it is a “constant”. Note that $\mu > \mu_0$ for a paramagnet. The \mathbf{H} vector has the very useful property that its tangential component is continuous across a boundary, so that the value of H in the air above the meniscus is equal to that in the liquid. This is in contrast to the flux density, where B_0 in air is different (less, in this case) from the value B in the liquid:

$$H = \frac{B_0}{\mu_0} = \frac{B}{\mu} = \frac{B}{\mu_0(1+\chi)} \quad (3)$$

Suppose that, when the field is turned on, the meniscus in the narrow tube rises by an amount h , relative to its zero-field position (see Fig. 1). A volume $\pi r^2 h$ of air in the narrow tube (with permeability μ_0) is, therefore, replaced by liquid. Hence, the magnetic potential energy of this volume of space increases by an amount:

$$\Delta U = \frac{1}{2}(\mu - \mu_0)H^2 \times (\pi r^2 h) \quad (4)$$

The work done by the upward magnetic force F_m in raising the liquid by an amount h is $F_m h =$

$$\frac{\Delta U}{h} = \frac{1}{2}(\mu - \mu_0)H^2 \pi r^2 \quad (5)$$

When the liquid in one arm of the tube rises by h , it falls on the other arm by h . It continues to rise till the upward magnetic force is balanced by the weight of the head of liquid. The downward gravitational force on the head of liquid, of mass m , is given by-

$$F_g = mg = 2\pi r^2 \rho hg \quad (6)$$

where ρ is the density of the liquid. However, there is also a very small additional upwards force on the liquid due to the buoyancy of the air, which, strictly, ought to be included (By the Principle of Archimedes, bodies immersed in any fluid, even air, experience this buoyancy; you are yourself very slightly lighter by virtue of the surrounding air, though this effect is extremely tiny compared to that which you experience when immersed in a much denser fluid, such as water). The liquid in the narrow column displaces a volume of air, while that in the wide column is replaced by air, and this leads to a net upwards buoyancy force on the narrow column given by

$$F_b = 2\pi r^2 \rho_a hg \quad (7)$$

where ρ_a is the density of the air. Combining all these forces, we have $F_m = F_g - F_b$, so that

$$\frac{1}{2}(\mu - \mu_a)H^2 \pi r^2 = 2\pi r^2 (\rho - \rho_a)hg \quad (8)$$

Using Eq.3 in Eq.8, we finally obtain the volume susceptibility, which is a dimensionless quantity:

$$\chi = [4g\mu_o(\rho - \rho_a)]\frac{h}{B^2} - \chi_a \quad (9)$$

Where χ_a is the susceptibility of air. In practice, the corrections due to air are negligible. There will also be a small but significant diamagnetic (i.e. Negative) contribution to the susceptibility mainly due to water. The total susceptibility of the solution is given by $\chi = \chi_{Fe^{+}} + \chi_{water}$. In the present work you will correct χ to yield the true value of χ_{Fe} . Some other parameters are defined in terms of volume susceptibility as follows:

Mass Susceptibility is given by: $\chi' = \chi/\rho$ (10)

Molar Susceptibility is given by: $\chi'' = \chi'M$ (11)

where M = Molecular weight

Curie constant is given by: $C = \chi''/T$ (12)

where T = Temperature of sample

Magnetic moment μ of dipole of the specimen by relation

$$\mu = 2.8241\sqrt{C} \quad (13)$$

where μ is expressed in Bohr magneton μ_B with a value of $9.272 \times 10^{-24} \text{A}\cdot\text{m}^2$

Literature value of molar susceptibility of FeCl_3 is $+1.69 \times 10^{-8} \text{m}^3/\text{mol}$ [2].

Since the thermal effects tend to destroy the alignment of magnetic dipoles, so the susceptibility of a paramagnet decreases as the temperature T is increased. Using statistical mechanics, it may be shown that at high temperatures ($kT \gg mB$) the contribution χ_{Fe} of the paramagnetic Fe^{3+} ions to the volume susceptibility of the solution is given by,

$$\chi = \frac{\mu_o M}{B} = \frac{Nm^2 \mu_o}{3kT} = \frac{Np^2 \mu_B^2 \mu_o}{3kT} \quad (14)$$

Where k is Boltzmann's constant and N is the number of Fe^{3+} ions per unit volume, p is the magneton number defined in Appendix A, μ_B is the Bohr magneton and $m = p\mu_B$. The $1/T$ dependence of χ_{Mn} is known as Curie's Law.

The above theory assumes that the magnetic field acting on each ion is just the applied field B ; field and contributions due to neighboring magnetic ions are neglected. For dilute paramagnetic materials these other contributions are very small and the approximation is valid. This is not so for concentrated magnetic materials and ferromagnets.

Apparatus:

1. Adjustable electromagnet with pole pieces
2. Constant power supply (0-16 V, 5A DC)
3. Digital Gauss meter
4. Hall probe for magnetic strength measurement
5. Traveling Microscope
6. Quincke's tube (a U tube)
7. Measuring cylinder (100 ml), Pipette (5 ml)/dropper, Wash bottle
8. Specific gravity bottle (25 cc)
9. FeCl_3 for making solutions
10. Electronic balance (Least count = 0.01gm)
11. Connecting cords

Experimental set-up

A schematic diagram of Quinck's method is shown in Fig.1. Quinck's tube is U shaped glass

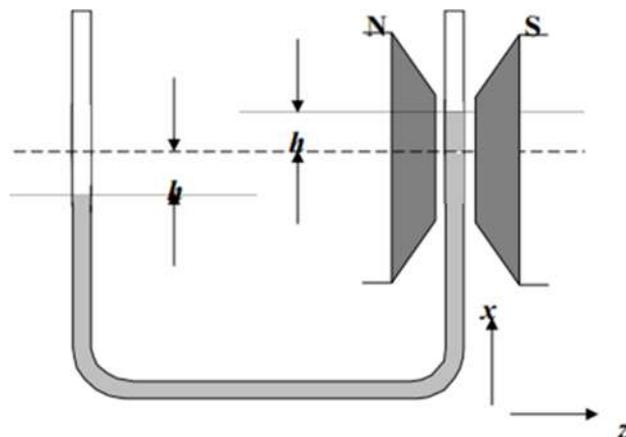


Fig. 1: Schematics of the set up

tube. One arm of the tube is placed between the pole-pieces of an electromagnet shown as N-S such that the meniscus of the liquid lies symmetrically between N-S. The length of the limb is sufficient as to keep the other lower extreme end of this limb well outside the field H of the magnet. The rise or fall h is measured by means of a traveling microscope of least count of the order of 10^{-3} cm. The picture of the actual set up is given in Fig. 2.



Fig. 2 Experimental set up for Quicke's method

Procedure

- 1) Prepare the FeCl_3 solution of known mass (10 or 20gm) in 100 ml water.
- 2) Calculate the number of moles of Fe^{3+} ions per unit volume of the solution. 1 mole of a substance has a weight in grams equal to its molar weight, W_m . The molecular weight is found by adding up the atomic weights of the constituent atoms of the molecule. If X grams of FeCl_3 were dissolved in $V \text{ m}^3$ of the solution, the number of moles is X/W_m . Each mole contains N_A (Avagadro's number) of molecules. Thus the number of molecules in $V \text{ m}^3$ is $N = N_A X/W_m$
- 3) Measure the density ρ of your solution using a specific gravity bottle. The method here is to
 - a. weigh the bottle + stopper when it is dry and empty
 - b. fill it with distilled water and weigh it again
 - c. dry it with a dryer and fill it with your solution and weigh it again. The density ρ may be found, knowing the density of water ρ_{water} , from the following equation

$$\rho = \rho_{\text{water}} \frac{c - a}{b - a} \quad (16)$$

- 4) Adjust the pole pieces so that the gap between them is about 10 mm (Diameter of the U-tube is about 8mm).
- 5) Connect the electromagnet coils in series to the power supply and ammeter. The field between the pole pieces must be calibrated as a function of current over an appropriate range (1- 4A). The magnet may run continuously with a current of 5A (for precautions, we would avoid prolonged use at 5A, hence the range up to 4A) and for short periods with 10A. The Hall probe will be used to measure the magnetic field B (how does this work?). Position the Hall probe using the stand provided so that the same position is maintained throughout the calibration. With the U-tube removed, insert the Hall probe into the field region between the flats of the pole pieces.
- 6) Switch on the Gauss meter and rotate the zero adjustment knob till you get zero reading on it. Now, switch on the power supply and adjust the current at 1A. Adjust the probe's position and orientation until it registers a maximum positive field. Clamp the probe handle firmly in place so that it cannot move. Measure the flux density B . Slowly increase the current (I) in small steps and record corresponding values of B .

- 7) If you record your calibration data with sufficiently small increments of current this will provide the best definition of the entire curve, which will be linear in a certain range for smaller values of current and then the slope will decrease as magnetic saturation occurs in the material of the pole pieces. Note there may also be some magnetic hysteresis present and for a given current, the field may be slightly different, depending on whether the current is increasing or decreasing. The magnetic saturation means that the highest values of current do not produce an equivalent increase in the values of the magnetic field.
- 8) Bring the current in the power supply back to zero and switch off supply after you finish calibration.
- 9) Transfer some of the prepared solution to the U- tube so that the meniscus is at the centre of the pole-pieces. Focus the travelling microscope on the meniscus and note down the initial reading for $B = 0$.
- 10) Switch on the supply and slowly vary the current upto 4A in steps of 0.5A. The solution in the tube rises up. Note down the corresponding height of the liquid column for each value of current.

Observations

Table 1: Data for calibration

| Sl# | I (A) | B (Gauss) |
|-----|-------|-----------|
| | | |
| | | |

Table 2: Measurement of ρ

Wt. of empty specific gravity bottle (a) = ..

Wt. of specific gravity bottle filled with test liquid (b) = ..

Wt. of specific gravity bottle filled with distilled water (c) = ..

$$\rho = \rho_{\text{water}} \frac{c - a}{b - a}$$

Use $\rho_{\text{water}} = 1000 \text{ kg/m}^3$

Table 2. Measurement of $h \sim B$

| SL No. | I | B | B2 | Meniscus Reading | | | | | | Difference h= (b-a) |
|--------|---|---|----|------------------|-----|-----|---------|-----|------|------------------------|
| | | | | B=0 (a) | | | B≠0 (b) | | | |
| | | | | M.S | V.S | T.R | M.S | V.S | T.R. | |
| | | | | | | | | | | |
| | | | | | | | | | | |

Graph:

Plot a graph $h \sim B^2$ and do straight line fitting to determine slope.

Calculations: Use $\chi_a \sim 0$ and $\rho_a = 1.29 \text{ kg/m}^3$

Volume susceptibility, $\chi_{\text{water}} = -9.04 \times 10^{-6}$

$\chi_{\text{Fe}} = \dots\dots$ $\chi_{\text{Fe}^2} = \dots\dots$ $\chi_{\text{Fe}^3} = \dots\dots$ $C = \dots\dots$ $\mu = \dots\dots$

Conclusion and discussion:

Precautions:

1. *Scrupulous cleanliness of the U-tube is essential. Thoroughly clean the tube and rinse it well with distilled water before starting and dry it.*
2. *Make several sets of measurements to ensure consistency; false readings can arise from liquid running down the tube or sticking to the sides.*
3. *Carefully swab down the inside of the U-tube with a cotton bud, to ensure that there are no droplets of liquid which might interfere with the plastic spacers on the rod which measures the height of the meniscus.*
4. *Do not use the U-tube for longer than one laboratory period without recleaning. After cleaning ask the laboratory technician to dry the tube for you with compressed air.*
5. *Try to avoid the backlash error of the travelling microscope. The small change of height may cause you more error in the calculation.*

References

- 1] S. Grant and W.R. Phillips, "Electromagnetism", (Wiley)
- 2] <http://www.agoenvironmental.com/sites/default/files/pdf/diamagnetic%20element%20list.pdf>

Appendix A: Magnetic moment values

The magnetic susceptibility of a substance is related to the magnetic dipole moments of its individual atoms or ions. The total angular momentum of an atom or ion arises from both the orbital motion and the spin of the electrons. The magnetic dipole moment can be expressed in the form- $m = p\mu_B$,

where p , the magneton number, is the dipole moment in units of the quantity μ_B , which is known as the Bohr magneton. The Bohr magneton is the atomic unit of magnetic moment defined by,

$$\mu_B = eh / 4\pi m_e$$

where, in this equation, e and m_e are the electronic charge and mass and h is Planck's constant. The dimensionless magneton number p is usually between 1 and 10 for atomic systems.

The rules for calculating p can be summarised as follows,

- (i) the unfilled electron shells for any atom or ion can be found in standard tables.
- (ii) the quantum numbers of the individual electrons can be added

$$L = \sum_i l_i \quad \text{and} \quad S = \sum_i s_i$$

to give the largest values of L and S consistent with the Pauli Exclusion Principle

- (iii) the total quantum number J can be found from

$$J = L - S \quad \text{first half of the electron shell}$$

$$J = L + S \quad \text{second half of the electron shell}$$

- (iv) the magneton number p is given by,

$$p = g \sqrt{J(J+1)} \quad \text{where } g \text{ the so called Landé splitting factor}$$

$$g = \left\{ \frac{3}{2} + \frac{S(S+1) - L(L+1)}{2J(J+1)} \right\}$$

takes into account that the spin effectively creates twice as much magnetic moment as the orbital motion.

- (v) the result of these calculations are tabulated in most textbooks on condensed matter physics, See the Table 1.

Table 1: Magneton numbers p for some transition metals (TM^{2+} free ions)

| No of electrons in 3d shell | Ion | S | L | J | P |
|-----------------------------|------------------|-----|---|-----|------|
| 0 | Ca ²⁺ | 0 | 0 | 0 | 0 |
| 1 | Sc ²⁺ | 1/2 | 2 | 3/2 | 1.55 |
| 2 | Ti ²⁺ | 1 | 3 | 2 | 1.63 |
| 3 | V ²⁺ | 3/2 | 3 | 3/2 | 0.77 |
| 4 | Cr ²⁺ | 2 | 2 | 0 | 0 |
| 5 | Mn ²⁺ | 5/2 | 0 | 5/2 | 5.92 |
| 6 | Fe ²⁺ | 2 | 2 | 4 | 6.71 |
| 7 | Fe ³⁺ | 5/2 | 0 | 5/2 | 5.92 |
| 8 | Co ²⁺ | 3/2 | 3 | 9/2 | 6.63 |
| 9 | Ni ²⁺ | 1 | 3 | 4 | 5.59 |
| 10 | Cu ²⁺ | 1/2 | 2 | 5/2 | 3.55 |
| 11 | Zn ²⁺ | 0 | 0 | 0 | 0 |

2. DETERMINE THE COUPLING CO-EFFICIENT OF PIEZOELECTRIC CRYSTAL

❖ Objective

To determine the coupling co-efficient of a piezoelectric crystal

❖ Apparatus require

- i) Piezoelectric crystal, 5 nos crystal value mounted inside the box and connections brought out the terminals.
- ii) Resistance box 10-100 ohm
- iii) Inductance box 10-100 mH
- iv) Capacitance box 1nF – 10 nF
- v) AC Voltmeter 0-10V
- vi) AC current Meter 0-5 mA
- vii) Frequency Source 1 Hz to 2 mHz

❖ Formula Used-

The coupling coefficient $K_C = 1/Q$

Where $Q = \frac{1}{R} \sqrt{\frac{L}{C}}$ Hz (Quality factor)

Series Resonance frequency $f_S = \frac{1}{2\pi} \sqrt{1/LC} = \frac{1}{2\pi\sqrt{LC}}$ Hz

Parallel Resonance frequency $f_P = \frac{1}{2\pi} \sqrt{1/LC_T} = \frac{1}{2\pi\sqrt{LC_T}}$ Hz

Where L = inductance in henry

C = Capacitance in farads

$$C_T = \frac{C \times C_m}{C + C_m}$$

Quality Factor, $Q = \frac{f_2}{f_2 - f_1}$

So, the coupling coefficient, $K_C = \frac{f_2 - f_1}{f_1}$

Theory-

A quartz crystal exhibits the property that when mechanical stress is applied across the faces of the crystal, a difference of Potential develops across opposite faces of the crystal. This property of a crystal called the piezoelectric effect. Similarly if a voltage applied across on set of faces of the crystal causes mechanical distortion in the crystal shape.

When alternative voltage is applied to crystal, mechanical vibrations are set up. These vibrations having a natural resonant frequency depend on the crystal.

Although crystal has electro mechanical resonance, we can represent the crystal action by an equivalent electrical resonant circuit as shown in fig.1. The inductor L and capacitor C electrical equivalents of the crystal mass and compliance. While resistance R is an electrical equivalent of the crystal structure is internal friction. The shunt capacitance C_m shows the capacitance due to mechanical mounting of the crystal. Because the crystal losses represented by RI are small, the equivalent crystal Q (Quality factor) is high typically 20,000 values of Q upto 10^6 can be achieved by using crystal.

Series and Parallel Resonance:- Crystal as represented by the equivalent electrical circuit can have two resonant frequencies-

- One resonant condition occurs when the reactance of the series RLC leg are equal (and opposite). For this the series resonant impedance is very low (equal to R)
- The other resonant condition occurs at a higher frequency when the reactance of the series resonant leg equal the reactive of the capacitor C_m . This is a parallel or anti resonance condition of the crystal. At this frequency offers very high impedance to the external circuit. The graph between current (I) or impedance (Z) as shown in fig.2.

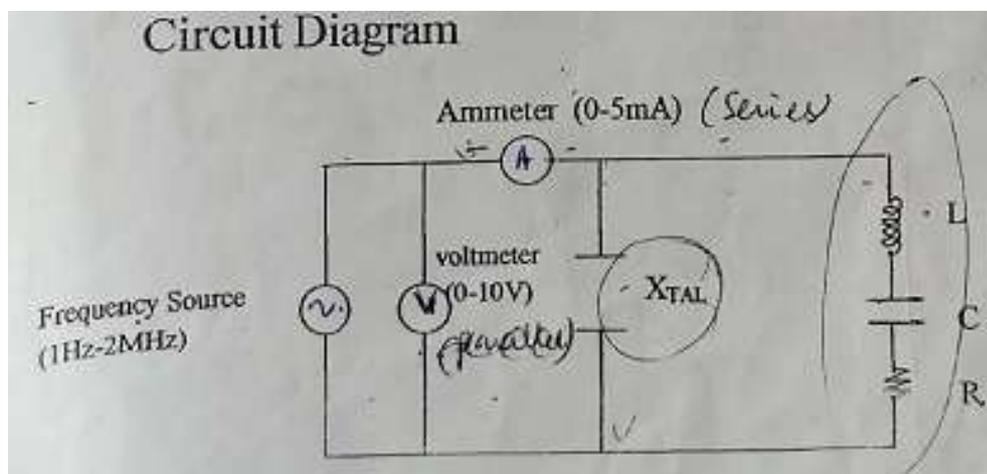


Table No. 2: V = Volt

| S. No. | Frequency Hz - MHz | Current (I) mA | Impedance- $Z = V/I$ |
|---------|-----------------------|-------------------|-------------------------|
| 1. | | | |
| 2. | | | |

Table No. 2

Capacitance of Piezoelectric crystals measured by the capacitance meter.

| X _{TAL} (MHz) | Capacitance, C _m (pF) |
|------------------------|----------------------------------|
| 4.096 | 12 |
| 4.433 | 13.5 |
| 6.144 | 14.5 |
| 8.0 | 15.2 |
| 11.059 | 12.9 |

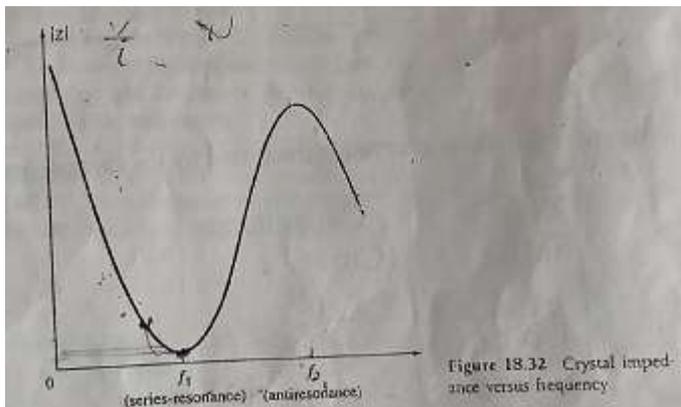
Calculations

Plot the graph between frequency and impedance, Z

Value of coupling Co-efficient $K_C = \frac{F_2 - F_1}{F_1}$ from the graph

Theoretical value of coupling coefficient $K_C = 1/Q$

Percentage of error =%



3. MEASUREMENT OF RESISTIVITY AND DETERMINATION OF BAND GAP USING FOUR-PROBE METHOD

Objective-

- (i) To measure resistivity of a semiconductor and a metal at room temperature.
- (ii) To measure resistivity of a semiconductor as a function of temperature (room temperature to 150 °C) and determination of energy band gap.

INTRODUCTION

Four Probe method is one of the standard & most commonly used method for the accurate measurement of resistivity. It overcomes the problem of contact resistance and also offer several other advantages. Accurate resistivity measurement in samples having a variety of shapes is possible by this method. The pressure contacts provided in the Four Point Arrangement are especially useful for quick measurement. This setup can measure samples of reasonably wide resistivity range (micro ohm to mega ohm).

BRIEF DESCRIPTION OF THE SET UP

1. PID-TZ Controlled Oven

The unit is a high quality PID (Proportional, Integral and Differential) controller wherein the temperatures can be set and controlled easily. The P, I and D parameters are factory set (P = 1.8, I = 300, D = 80) for immediate use, however, the user may adjust these for specific applications as well as auto-tune the oven whenever required. The steps for these are given in the user manual of the controller. A common controller may be used either for our small oven, up to 200°C or a larger oven up to 600°C. The two are switch selectable and use thermocouple as temperature sensors (see Fig.1).

General Specifications

The controller is designed around Autonics Temperature Controller Model TZN4S. Although this is a very versatile piece of equipment, below is a summary of the specifications that are relevant to the present application. For more details the reader may refer to the full catalog of the controller available at www.autonics.com

| | |
|-----------------------|---|
| Temperature Range | Ambient to 200°C/600°C |
| Power Supply | 100-240VAC; 50/60Hz |
| Display Method | 7 Segment LED display [Process value (PV):Red, Set value (SV):Green] |
| Input Sensor | Thermocouple (Chromel – Alumel) |
| Control Method | PID, PIDF, PIDS |
| Display Accuracy | ± 0.3% |
| Setting Type | Setting by front push buttons |
| Proportional Band (P) | 0 to 100.0% |
| Integral Time (I) | 0 to 3600 Sec |
| Derivative Time (D) | 0 to 3600 Sec |
| Control Time (T) | 1 to 120 Sec |
| Sampling Time | 0.5 Sec |
| Setting (P, I & D) | Manual / Auto-tuned |

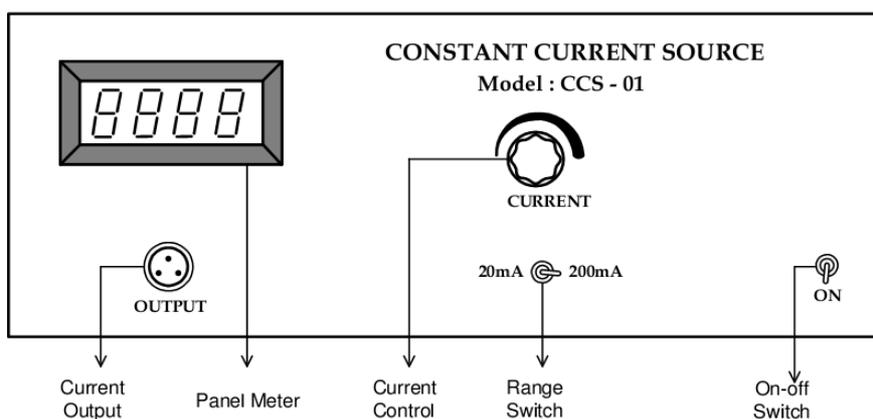


Fig. 3: Constant Current Source, CCS-01

Controls

- (1) OVEN SELECTOR Switch – to select between the smaller 200 °C or larger 600 °C ovens. Select 200°C for the small oven used in this experiment.
- (2) POWER CONNECTORS – a 3-pin round for small 200°C oven and two sockets for the large 600°C oven
- (3) SENSOR CONNECTOR – Common thermocouple input for both ovens
- (4) OVEN ON-OFF switches – for individual oven with its own indicator
- (5) PID TEMPERATURE CONTROLLER – for setting, displaying and controlling the temperature of the oven used. Details shown in Fig.2 above
- (6) MAINS SWITCH – for connecting the mains power to the unit

2. Constant Current Source, Model : CCS-01

(for low resistivity to medium resistivity samples)

It is an IC regulated current generator to provide a constant current to the outer probes irrespective of the changing resistance of the sample due to change in temperatures. The basic scheme is to use the feedback principle to limit the load current of the

supply to preset maximum value. Variations in the current are achieved by a potentiometer included for that purpose. The supply is a highly regulated and practically ripples free d.c. source. The constant current source is suitable for the resistivity measurement of thin films of metals/ alloys and semiconductors like germanium.

Specification

| | |
|----------------------|---|
| Open Circuit Voltage | : 10V |
| Current Range | : 0-20mA, 0-200mA |
| Resolution | : 10 μ A |
| Accuracy | : $\pm 0.25\%$ of the reading ± 1 digit |
| Display | : 3½ digit, 7 segment LED with auto polarity and decimal indication |
| Load Regulation | : 0.03% for 0 to full load |
| Line Regulation | : 0.05% for 10% changes |

Controls

- (1) **Range Switch** – The current meter can be switched between 20mA and 200mA range using this switch. Keep the range switch at the desired range and set the desired current using the current control knob. In case the meter shows over ranging (sign of 1 on the left and all other digits goes blank) range switch maybe shifted to higher range.
- (2) **Panel Meter** – Display the current in mA.
- (3) **Current Control** – This is to feed the desired current in the Sample.
- (4) **Current Output** – Connect suitable connector from Four probe Arrangement in this connector. This will enable the unit to feed desired current in the sample
- (5) **ON-OFF switch** – To power the unit ON/ OFF.

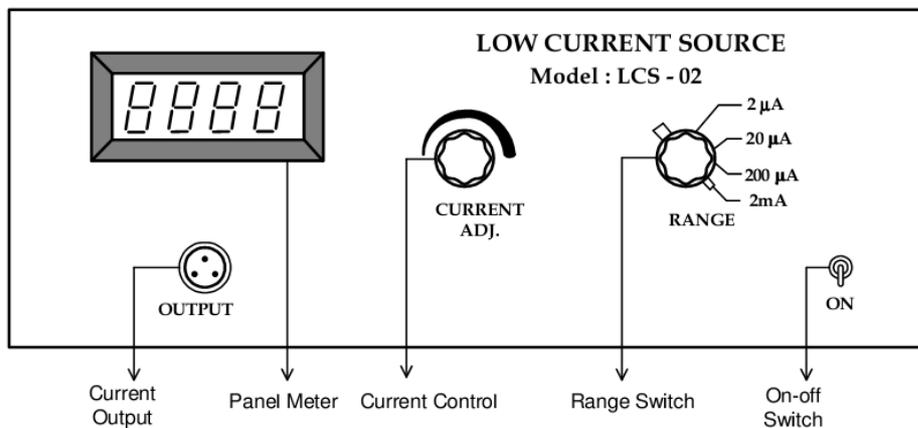


Fig. 4: Low Current Source, LCS-02

3. Low Current Source, Model : LCS-02

(for high resistivity samples)

Low Constant Current Sources are needed when the sample resistance, either inherently or due to contact resistances, is large. These include the resistivity measurement of silicon wafers or high resistivity film deposits. Large values of the sample resistance make the measurement prone to noise pick-up from the mains and elsewhere. This is one of the most significant problems of high resistance measurement.

In the present unit the problem of pick-up has been reduced to very low levels by having a battery operated source. Since the current requirement is small and the circuit being specially designed for this purpose, the batteries should have a reasonably long life. Further, a transistor circuit has been preferred over an Op-Amp based circuit as it offers a reduction of the battery count and is also simpler. An internal voltage reference of 2.5 volt ensures reliable operation even when the battery voltage falls and a ten turn potentiometer makes the current adjustment very easy. The actual current is read on a 3½ digit LCD display. There are two current ranges, which may be selected with the help of a switch on the panel.

Specification

| | |
|----------------------|---|
| Open Circuit Voltage | : 18V |
| Current Range | : 0-2 μ A, 0-20 μ A, 0-200 μ A, 0-2mA |
| Resolution | : 1nA at 0-2 μ A range |
| Accuracy | : $\pm 0.25\%$ of the reading ± 1 digit |
| Display | : 3½ digit, 7 segment LCD with auto polarity and decimal indication |
| Load Regulation | : 0.05% for 0 to full load |
| Power | : 3 x 9V batteries |

Controls

- (1) **Range Switch** – The current meter can be switched between 2 μ A, 20 μ A, 200 μ A and 2mA range using this switch. Keep the range switch at the desired range and set the desired current using the current control knob. In case the meter shows over ranging (sign of 1 on the left and all other digits goes blank) range switch maybe shifted to higher range.
- (2) **Panel Meter** – Display the current in μ A/ mA (as per setting of Range Switch)
- (3) **Current Control** – This is to feed the desired current in the Sample.

- (4) **Current Output** – Connect suitable connector from Four probe Arrangement in this connector. This will enable the unit to feed the desired current in the sample
- (5) **ON-OFF Switch** – To power the unit ON/ OFF.

Note: Please note that this unit is operated on 9V x 3 batteries. In case there is any problem in operation, please check the batteries also. Batteries are assessable after opening the Top Cover of the unit.

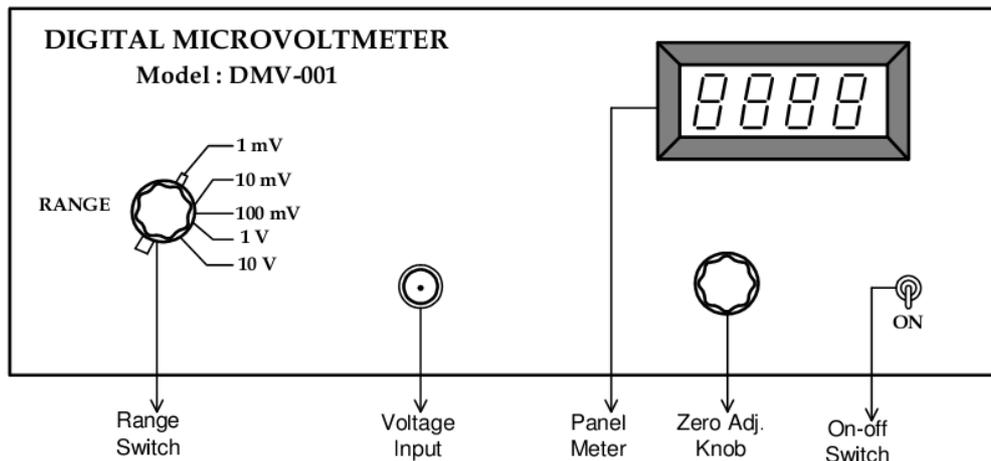


Fig. 5: Digital Microvoltmeter, DMV-001

4. D.C. Microvoltmeter, Model DMV-001

Digital Microvoltmeter, DMV-001 is a very versatile multipurpose instrument for the measurement of low dc voltage. It has 5 decade ranges from 1mV to 10V with 100% over-ranging. For better accuracy and convenience, readings are directly obtained on 3½ digit DPM.

This instrument uses a very well designed chopper stabilized IC amplifier. This amplifier offers exceptionally low offset voltage and input bias parameters, combined with excellent speed characteristics.

Filter circuit is provided to reduce the line pickups of 50 Hz. All internal power supplies are IC regulated.

Specification

| | |
|-----------------|--|
| Range | : 1mV, 10mV, 100mV, 1V & 10V with 100% over ranging |
| Resolution | : 1µV |
| Accuracy | : ± 0.2% |
| Stability | : Within ± 1 digit |
| Input Impedance | : >1000MΩ (10MΩ on 10V range) |
| Display | : 3½ digit, 7 segment LED with auto polarity and decimal |

indication

Controls

- (1) **Range Switch** – The voltmeter can be switched between 1mV, 10mV, 100mV, 1V & 10V range using this switch. Keep the range switch at lowest range for better accuracy. In case the meter shows over ranging (sign of 1 on the left and all other digits goes blank) range switch maybe shifted to higher range.
- (2) **Panel Meter** – Display the Voltage in mV/ V (as per setting of Range Switch)
- (3) **Zero Adj. Knob** – This is to adjust Zero of Microvoltmeter before starting the experiment.
- (4) **Voltage Input** – Connect suitable connector from Four probe Arrangement in this connector. This will enable the unit to measure the voltage output of the sample
- (5) **ON-OFF switch** – To power the unit ON/ OFF.

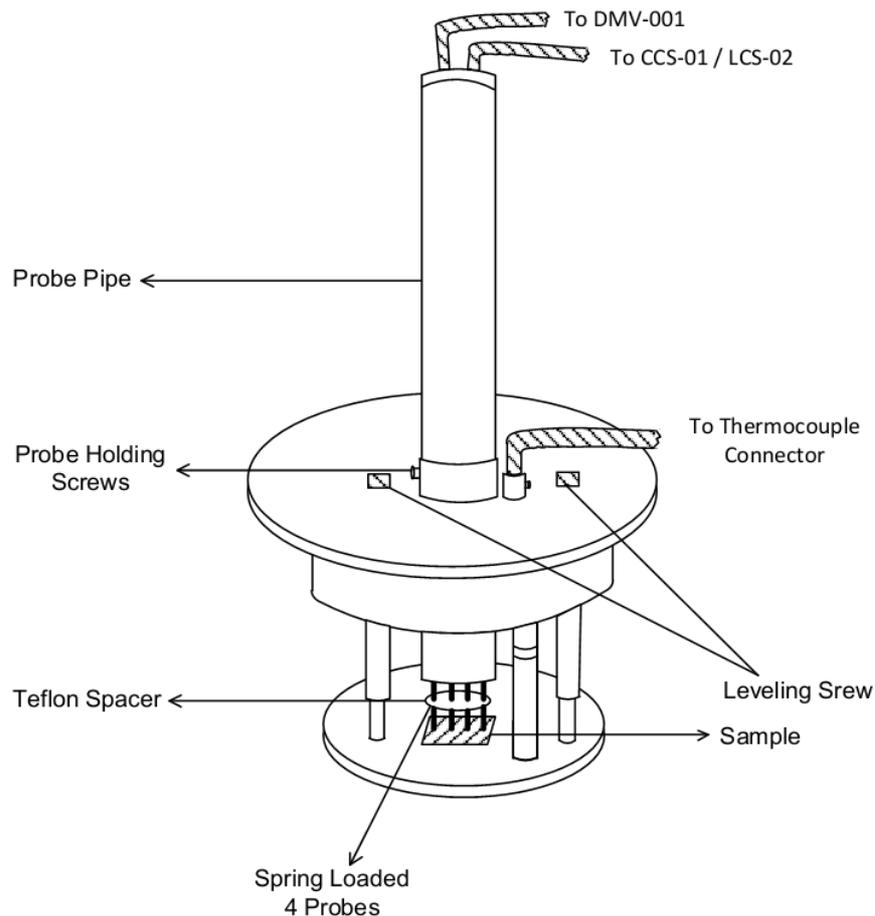


Fig. 6: Four Probe Arrangement

5. Four Probes Arrangement

It has four individually spring loaded probes. The probes are collinear and equally spaced. The probes are mounted in a teflon bush, which ensure a good electrical insulation between the probes. A teflon spacer near the tips is also provided to keep the probes at equal distance. The probe arrangement is mounted in a suitable stand, which also holds the sample plate and RTD sensor. This stand also serves as the lid of PID Controlled Oven. Proper leads are provided for current, Voltage & Temp. measurement with their universal connectors. For current measurement there is three pin connector which can be connected to the CCS-01/ LCS-02 as per requirement of sample. For voltage measurement BNC connector is used connected to DMV-001 unit. For temperature measurement, a two pin connector is provided for connection with PID- Controlled oven unit PID-200 at connector marked as Temperature Sensor.

Three leveling screws are provided in Four Probe arrangement by which we can adjust the level of platform to make it horizontal. A probe holding screw is provided at the collar of the arrangement. Initially it should be in loose position, to allow free movement of Probe Pipe. After placing the sample the Probe Pipe should be lowered so that all four pins touches the sample. Further Press the pipe very lightly so that the assured firm contact is made of all Four Pins with the sample. Tighten the Probe Holding Screw at this position. The Probe Arrangement is ready with the sample for the experiment.

APPARATUS

- (1). PID Controller with a Oven Unit, Model PID-TZ
- (2). Constant Current Sources:-
 - a) Constant Current Source, Model CCS-01
 - b) Low Current Source, Model LCS-02
- (3). D.C. Microvoltmeter, Model DMV-001
- (4). Four Probe Arrangement with Thermocouple sensor and suitable connectors for DMV and CCS/ LCS.
- (5). Set of test samples and emery powder.

BASIC THEORY

Four sharp probes are placed on a flat surface of the material to be measured (Fig.7). The current is passed through the two outer electrodes, and the floating potential is measured across the inner pair. If the flat surface on which the probes rest is adequately large, it may be considered to be a semi-infinite volume. To prevent minority carrier injection and make good contacts, the surface on which the probes rest, maybe mechanically lapped.

The experimental circuit used for measurement is illustrated schematically in Fig. 8. A nominal value of probe spacing, which has been found satisfactory, is an equal distance of 2.0 mm between adjacent probes.

In order to use the four-probe method, it is assumed that:

1. The resistivity of the material is uniform in the area of measurement.
2. If there is minority carrier injection into the semiconductor by the current - carrying electrodes, most of the carriers recombine near the electrodes so that their effect on the conductivity is negligible. (This means that the measurements should be made on surface, which has a high recombination rate, such as mechanical by lapped surfaces).
3. The surface on which the probes rest is flat with no surface leakage.
4. The four probes used for resistivity measurements are equally spaced and collinear.
5. The diameter of the contact between the metallic probes and the semiconductor should be small compared to the distance between probes.
6. The surfaces of the material may be either conducting or non-conducting. A conducting boundary (such as copper) is one on which the sample is plated or placed. A non-conducting boundary is produced when the surface of the sample is in contact with an insulator.

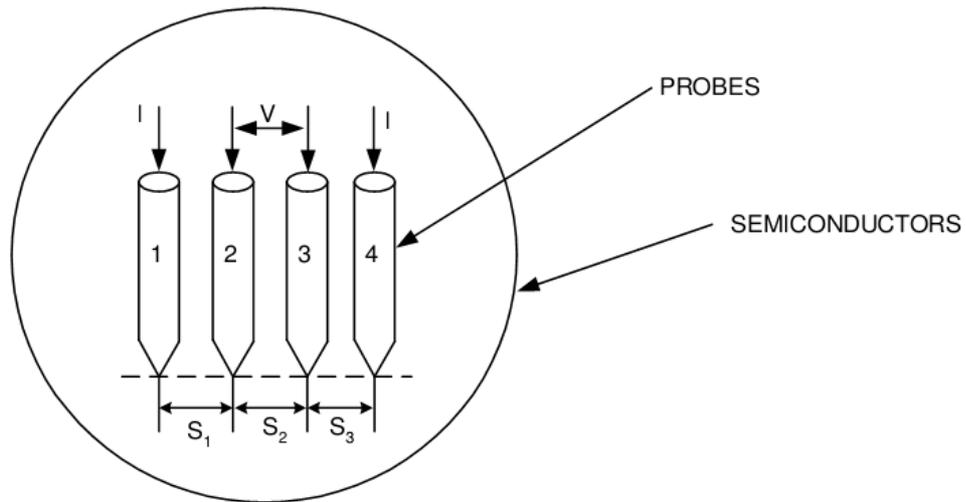


Fig. 7: Model for the four probe resistivity measurement

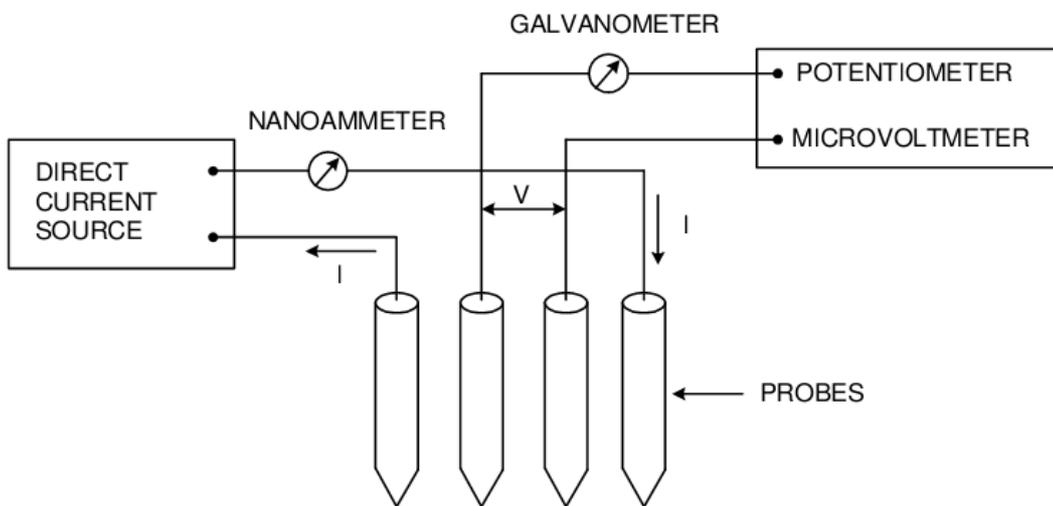


Fig. 8: Circuit used for resistivity measurement

CASE 1 - RESISTIVITY MEASUREMENTS ON A LARGE SAMPLE

One added boundary condition is required to treat this case namely, the probes are far from any of the other surfaces of the sample and the sample can thus be considered a semi- infinite volume of uniform resistivity material. Fig. 7 shows the geometry of this case. Four probes are spaced S_1 , S_2 and S_3 apart. Current I is passed through the outer probes (1 and 4) and the floating potential V is measured across the inner pair of probes 2 and 3.

The floating potential V_f a distance r from an electrode carrying a current I in a material of resistivity ρ_0 is given by

$$V_f = \frac{\rho_0 I}{2\pi r}$$

In the model shown in Fig. 7 there are two current-carrying electrodes, numbered 1 and 4, and the floating potential V_f , at any Y point in the semiconductor is the difference between the potential induced by each of the electrodes, since they carry currents of equal magnitude but in opposite directions Thus:

$$V_f = \frac{\rho_0 I}{2\pi} \left(\frac{1}{r_1} - \frac{1}{r_4} \right) \quad (1)$$

Where r_1 = distance from probe number 1 and r_4 = distance from probe number 4.

The floating potentials at probe 2, V_{f2} , and at probe 3, V_{f3} can be calculated from (1) by substituting the proper distances as follows:

$$V_{f2} = \frac{\rho_0 I}{2\pi} \left(\frac{1}{S_1} - \frac{1}{S_2 + S_3} \right)$$

$$V_{f3} = \frac{\rho_0 I}{2\pi} \left(\frac{1}{S_1 + S_2} - \frac{1}{S_3} \right)$$

and the resistivity ρ_0 is computable as

$$\rho_0 = \frac{V}{I} - \frac{2\pi}{\left(\frac{1}{S_1} + \frac{1}{S_3} - \frac{1}{S_1 + S_2} - \frac{1}{S_2 + S_3} \right)} \quad (2)$$

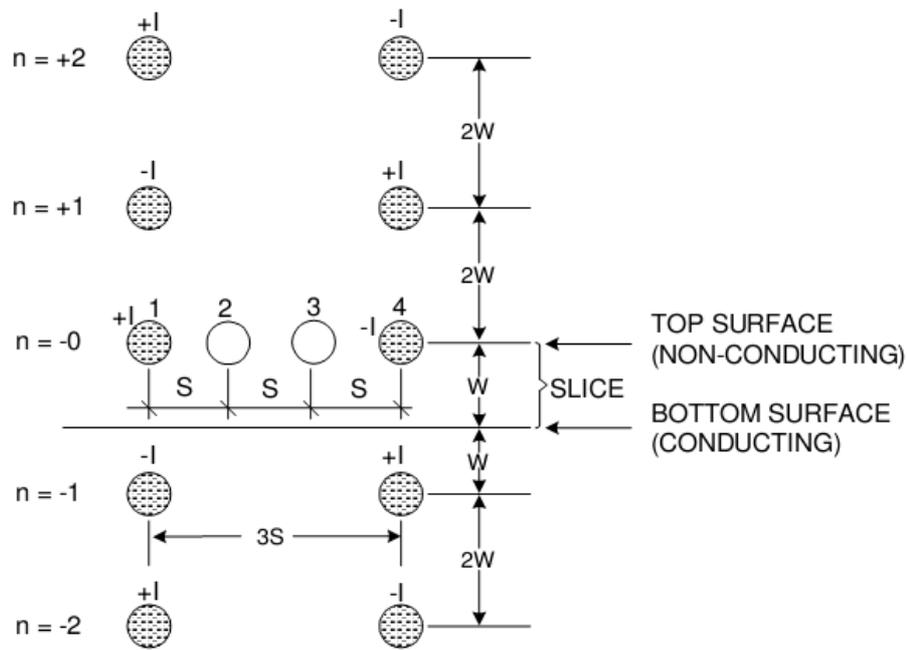


Fig. 9: Images for the case of the resistivity probes on a slice with conducting bottom surface

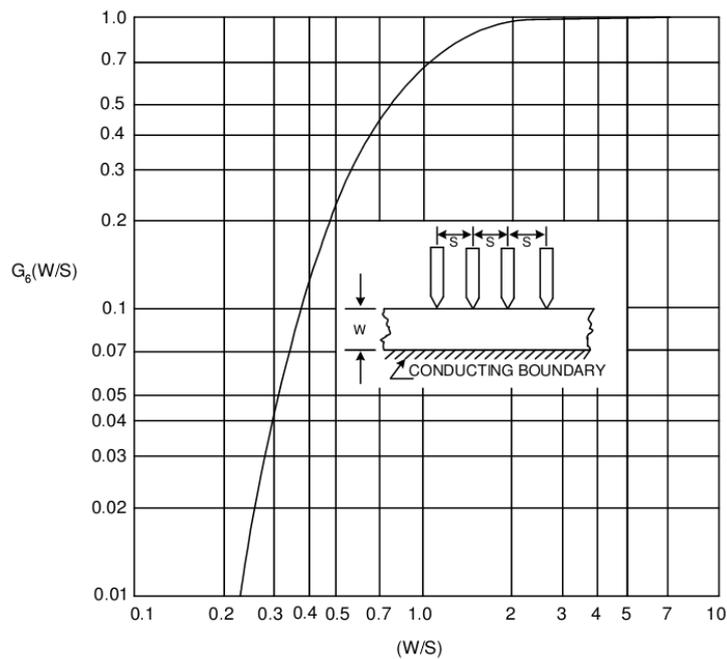


Fig. 10: G_6 (W/S) for probes on a thin slice with a conducting bottom surface

When the point spacings are equal, that is, $S_1 = S_2 = S_3 = S$ the above simplifies to:

$$\rho_0 = \frac{V}{I} \times 2\pi S \quad (3)$$

CASE 2- RESISTIVITY MEASUREMENTS ON A THIN SLICE- CONDUCTING BOTTOM SURFACE

Two boundary conditions must be met in this case; the top surface of the slice must be a reflecting (non-conducting) surface and the bottom surface must be an absorbing (conducting) surface. Since the two boundaries are parallel, a solution by the method of images requires for each current source an infinite series of images along a line normal to the plane and passing through the current source.

The model for this case is shown in Fig. 9. The side surface of the slice is assumed to be far from the area of measurement and, therefore, only the effect of the bottom surface needs to be considered. In this analysis equal probe spacing S shall be assumed. The width of the slice is W . The array of images needed is indicated in Fig. 9. where the polarity and spacing of the first few images are as shown.

The floating potential V_{f2} at electrodes 2 is

$$V_{f2} = \frac{rI}{2p} \left[\sum_{n=-\infty}^{n=\infty} (-1)^n \frac{1}{\sqrt{S^2 + (2nW)^2}} - \sum_{n=-\infty}^{n=\infty} (-1)^n \frac{1}{\sqrt{(2S)^2 + (2nW)^2}} \right] \quad (4)$$

Likewise, the floating potential at electrode (3) can be obtained and

$$V = \frac{\rho I}{2\pi} \left[\frac{1}{S} + \sum_{n=1}^{n=\infty} (-1)^n \frac{4}{\sqrt{S^2 + (2nW)^2}} - \sum_{n=1}^{n=\infty} (-1)^n \frac{4}{\sqrt{(2S)^2 + (2nW)^2}} \right] \quad (5)$$

The resistivity then becomes

$$\rho = \frac{\rho_0}{G_6 (W/S)} \quad (6)$$

Where resistivity ρ_0 is computable from (2 and 3) can be used if the point spacing are different, but approximately equal. The function $G_6 (W/S)$ is computed from

$$G_6\left(\frac{W}{S}\right) = 1 + 4 \frac{S}{W} \sum_{n=1}^{n=\infty} (-1)^n \left[\frac{1}{\sqrt{\left(\frac{S}{W}\right)^2 + (2n)^2}} - \frac{1}{\sqrt{\left(2\frac{S}{W}\right)^2 + (2n)^2}} \right] \quad (7)$$

which is tabulated in Table I and plotted in Fig. 10.

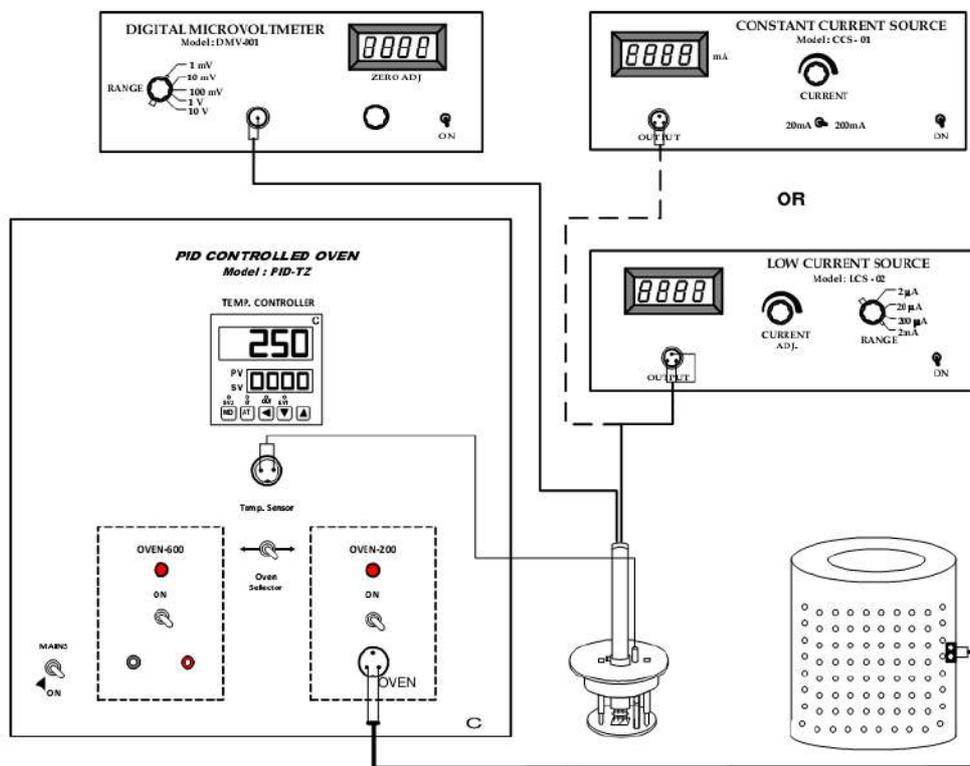


Fig. 12: Connection diagram for the set up



Fig. 13: Complete experimental set up

PROCEDURE

Before starting the experiment, make sure that the surface of your sample is clean and conducting. Particularly in case of Germanium and Silicon, a oxidation layer is formed which causes error in readings. Therefore for such samples, it is advisable to remove this oxidation layer by rubbing the sample in fine emery slurry on a glass surface for 2 – 3 minutes. The sample will be ready to use after washing it in plane water and subsequent drying.

(I) Measurement of resistivity of n-Si and Al at room temperature:

1. Put the sample (n-Si/Al) on the base plate of the four probe arrangement. Unscrew the pipe holding the four probes and slowly let the four probes rest at the middle of the sample. Apply a very gentle pressure on the probes and tighten the pipe in this position.

CAUTION: Use only the minimum pressure required for proper electrical contacts particularly for semiconductor wafers and thin films.

2. Connect the outer pair of probes to the constant current source through 3-pin socket and the inner pair to the D.C. Microvoltmeter through an BNC connector.
3. Place the Four Probe Arrangement in the oven.
4. Switch 'ON' D.C. Microvoltmeter and allow about 5 minutes time for thermal stability. Adjust the zero of D.C. Microvoltmeter with the knob provided for it.
5. Switch 'ON' the Constant Current Power Supply (For Ge and Al samples)/ Low Current Power Supply (For Si sample) and check the zero reading of D.C. Microvoltmeter at zero current reading again. Adjust it, if required. In case it can not be adjusted (this may happen in highly resistive samples), note it down and treat it as zero error.
6. Increase the current gradually and note the corresponding voltage readings. Subtract the zero reading if any and check for Ohm's Law ($\frac{V}{I} = R$). This would ensure that the system is working properly and the systematic readings could be taken.

(II) Measurement of resistivity of n-Ge at various temperatures:

7. Put n-Ge sample in the four probe arrangement following the procedure described in (I). The only difference here is that the current will be fixed (say at 5mA) and temperature is varied.
8. For different temperature settings, the PID Controlled Oven should be used. It stabilizes the temperature at the desired value while recording data.

The PID parameters are already set to a reasonable level ($P = 3.0$; $I = 350$; $D = 87$) for immediate operation of the unit in a range 80°C to 200°C . To operate the system one only needs to set the desired final temperature as described below. For other temperatures the parameters are to be set again.

Set the PID Controlled oven PID-TZ as follows :

- (i) Connect the Thermocouple sensor's 2-pin socket of Four Probe Arrangement and the oven socket to the PID Controller. Select the 200°C oven, switch the MAINS ON, and switch the oven ON. Now RUN the controller.
- (ii) Set a desired temperature for the first reading as described below.

- Step.1** Connect the controller and the sensor, switch ON the unit. The oven should be OFF.
- Step.2** The upper display would show the present oven temperature (PV or process value) and the lower display shows the current setting of the oven temperature (SV or set value).
- Step.3** Set the desired temperature by using the keys \blacktriangleleft , \blacktriangleup and \blacktriangledown , **taking care of the maximum temperature allowed for the oven connected.**
- Step.4** Press MD key to return to the RUN mode. The oven may now be switched ON and operated in the usual manner. The oven temperature at any instant would be seen on the upper display.
- (iii) Allow about 5 minutes time to stabilize the circuit. The Process Value (PV) will slowly rise and become steady.
- (iv) Record the voltage readings for the set temperature.
- (v) Set the temperature for the next reading and repeat (ii) and (iii) above. Continue till the highest temperature needed for the experiment is reached. **This must be $<200^{\circ}\text{C}$ for the safety of the four probe arrangement as well as the oven.**
- (vi) Plot a graph for $\text{Log}_{10}\rho \sim (1/T)$ and calculate the energy band gap.
- (vii) When completed switch the oven and MAINS OFF. Allow the oven to cool down for the next experiment.

OBSERVATIONS

Table 1: Data for resistivity of Al foil

No. of commercial Al foils: 16

Thickness of one foil: = 0.001 cm

Thickness of Stack: 0.16 ± 0.01 mm

Probe distance (S): $0.200 \pm 2\%$ cm (fixed)

| S.No. | Current (I) | Voltage (volts) | V/I |
|-------|-------------|-----------------|-----|
| | | | |

Table 2: Data for resistivity of n-Si

Thickness (W): $0.50 \pm 2\%$ mm

| S.No. | Current (I) | Voltage (volts) | V/I |
|-------|-------------|-----------------|-----|
| | | | |

Table 2: Data for resistivity ~ Temperature of n-Ge

Thickness (W): $0.50 \pm 2\%$ mm

Probe current (I) = 5 mA (fixed)

| S.No. | Temp (T in K) | Voltage (volts) | ρ (Ω .cm.) | $T^{-1} \times 10^{-3}$ (K^{-1}) | $\text{Log}_{10}\rho$ |
|-------|------------------|-----------------|----------------------------|---|-----------------------|
| | | | | | |

CALCULATIONS AND GRAPH

From Eq. (3)

$$\rho_0 = \frac{V}{I} \times 2\pi S$$

Correction Factor:

Since the thickness of the samples are small compared to the probe distance a correction factor for it has to be applied. Further the bottom surface is non-conducting in the present case, Eq. (9) will be applied.

$$\rho = \frac{\rho_0}{G_7(W/S)}$$

The function $G_7(W/S)$ may be obtained from Table-I or Fig. 5 for the appropriate value of (W/S) . For sample $W/S < 0.25$, correction factor may be obtained directly from Eqn. 10. Thus ρ may be calculated for various temperatures.

Energy Band Gap

We know, $E_g = 2k \frac{\text{Log}_e \rho}{\frac{1}{T}}$

Where k is the Boltzmann's constant = 8.6×10^{-5} eV/deg & T is temperature in kelvin. Use the graph to determine E_g .

Determination of the band gap of a Ge Sample

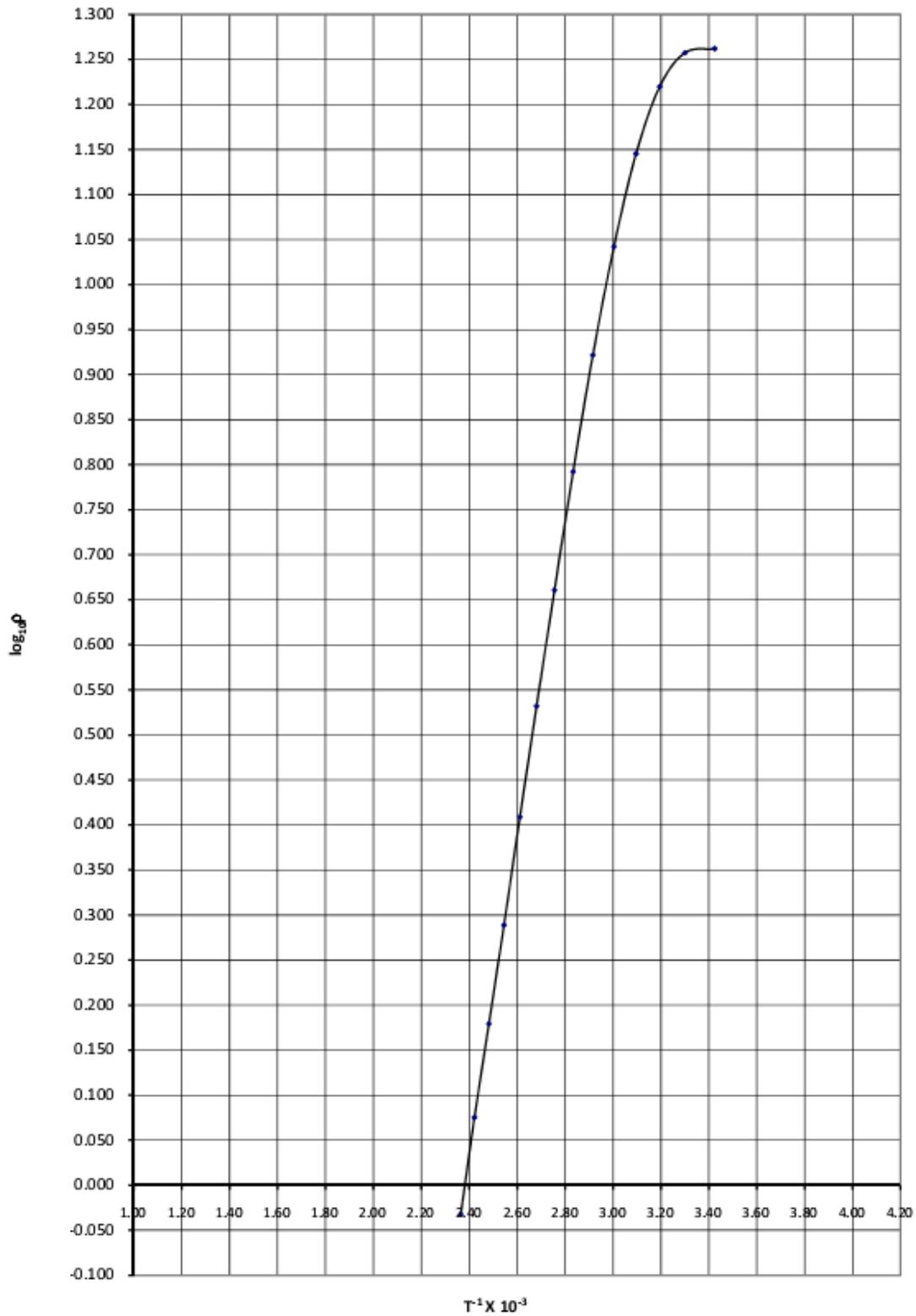


Fig. 14: Sample Graph of $\text{Log}_{10} \rho \sim (1/T)$ for n-Ge sample

Typical values of samples:

Standard value for pure Aluminium = 2.8×10^{-6} ohm.cm.

Typical value for n-Si (as supplied by manufacturer) = (6 ± 1) ohm.cm.

Typical value for n-Ge at 303K (as per datasheet of manufacturer) = 18.09 ohm.cm

Typical value of band gap for n-Ge at 303K (as per datasheet of manufacturer) = 0.68eV

The results given above are only for reference, exact values depend upon the sample and may not replicate.

SOME USEFUL POINTS

1. Very high resistance ($> 1M\Omega$) may cause high off-set in D.C. Microvoltmeter which can not be adjusted with the knob provided - Note it down and treat it zero error.
2. Unstable voltage reading may be due to improper contacts of probes with the sample.
 - (a) This may be due to insulating layer on the sample - Clean it.
 - (b) It may be due to loose contacts of probes with the sample - tighten the springs of 4-probes (1/2 thread only)
 - (c) Check the earth point and see that the whole system, constant current power supply, D.C. Microvoltmeter and Four Probe Arrangement are properly grounded.
3. In cases of semiconductor, like Si though the resistivity of sample may not be high but because of contact resistance, its effective resistance is usually very high.

Sources of Error

1. Material (Al) used in the foil is commercial grade, while standard resistance is for pure Al.
2. The thickness of Al foil is very small and there could be error of $\pm 7\%$ in measurement of thickness.
3. The formula for ρ is valid for semi-infinite /very large surface in comparison with the probe distance.
4. Variation of doping in the sample

REFERENCES

1. 'Introduction of Solid State Physics', by C. Kittel IVth edition.
2. 'Resistivity Measurements on Germanium for Transistor', by L.B. Valdes, Proceedings of the IRE, Vol. 42, p. 420 (1954).
3. Hand Book of Semiconductor Electronics, by L.P. Hunter (ed.) McGraw Hill Book Co, Inc. NY (1962).
4. 'Experiments in Modern Physics', by A.C. Melissions, Academic Press NY 1966.

4. MEASUREMENT OF DIELECTRIC CONSTANT OF A DIELECTRIC MATERIALS

Objective: To measure the dielectric constant of a dielectric material

Dielectric Materials

Dielectrics are non-conducting substances which are the insulating materials and are bad conductor of electric current. Dielectric materials can be made to hold an electrostatic charge while dissipating minimal energy in the form of heat. **Examples** of Dielectric are **Mica, Plastics, Glass, Porcelain and Various Metal Oxides** and even dry air is also example of dielectric.

Dielectric Constant

In parallel plate capacitor, when dielectric slab is placed between the two plates then the ratio of the applied electric field strength to the strength of the reduced value of electric field capacitor is called dielectric constant **k**.

The larger the dielectric constant, the more charge can be stored. Completely filling the space between capacitor plates with a dielectric increases the capacitance by a factor of the dielectric constant:

$C = kC_0$, where C_0 is the capacitance with no dielectric between the plates.

Dielectric constant, **k**, is given by

$$k = 1 + \frac{C_1 - C_2}{C_0}$$

C_0 = Capacity of test capacitor without dielectric (it is given)

C_1 = Capacity of variable air capacitor for maximum deflection in microammeter when test capacitor is without dielectric.

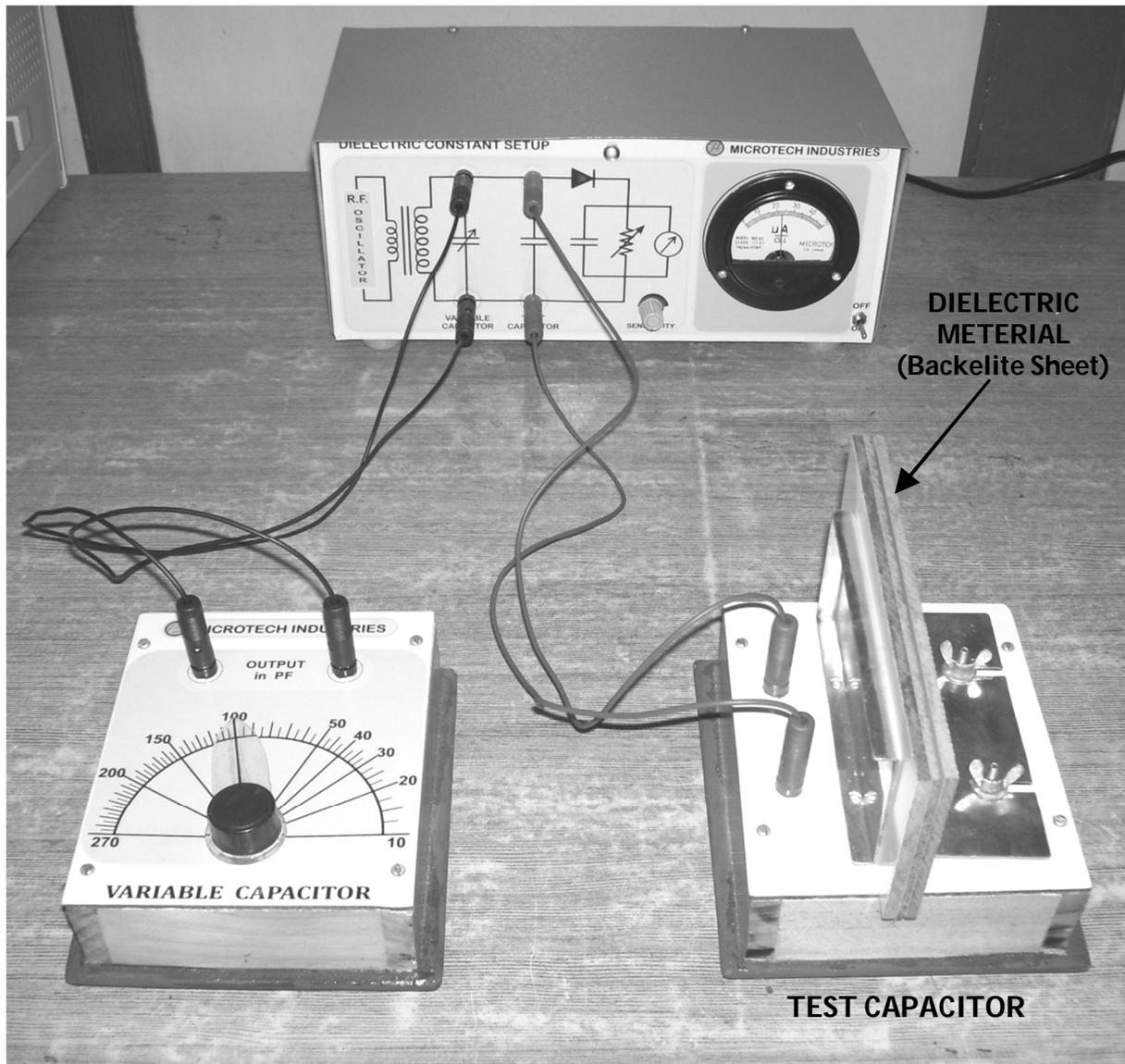
C_2 = Capacity of variable air capacitor for maximum deflection in microammeter when test capacitor is filled with dielectric.

| C ₀ | |
|-----------------------------|----------------------|
| Gap between plates in mm | Capacitance in PF |
| 3 | 38 |
| 4 | 28 |
| 7 | 23 |
| 8 | 20 |
| 11 | 18 |

Experimental Procedure

1. Connect the “Variable Capacitor” at the R.F.Oscillator terminals and set it at minimum position. Set the sensitivity of the meter at mid. position by adjusting the sensitivity knob.
2. Now connect the “Test Capacitor” to second terminals.
3. Keep test capacitor without dielectric and increase the variable capacitor C_1 at minimum position to the maximum position and observe where get maximum deflection at meter. Do it 2 or 3 times to get accurate result. Note the capacitance C_1 .
4. Now fill the dielectric to the test capacitor. Again vary the capacitance of the variable capacitor same way and Note the capacitance C_2 .

| Sl. No. | Gap between plates in mm | Capacitance C_0 in PF (From Chart) | Capacitance without dielectric C_1 in PF | Capacitance with dielectric C_2 in PF | Dielectric constant $k = 1 + \frac{C_1 - C_2}{C_0}$ |
|---------|--------------------------|--------------------------------------|--|---|--|
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |
| | | | | | |



Experimental setup for Measurement of the “Dielectric Constant” of a Substance by Resonance Method

Reference:

Microtech Industries 14a/1g, Ultadanga Road. Gopal Bhavan, Kolkata 700 004. Mobile no. 9831263293, E mail : microtekindustries90@gmail.com, microtechi@rediffmail.com, Website : www.microtekindustries.com

5. TO DETERMINE THE HALL COEFFICIENT OF A SEMICONDUCTOR SAMPLE

Objective:

- i) To determine the Hall coefficient (R)
- ii) To determine the carrier density (n) of charge carrier
- iii) To determine the carrier mobility (μ) of a given semiconductor

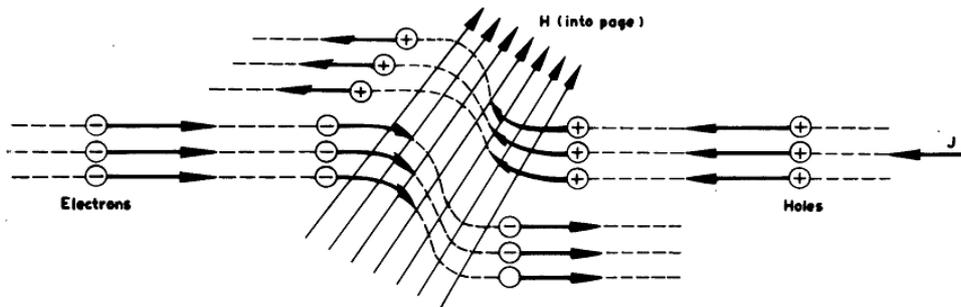


FIG.1 CARRIER SEPARATION DUE TO A MAGNETIC FIELD

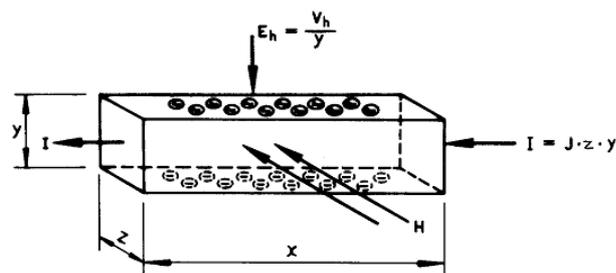


FIG.2 SAMPLE FOR STUDYING HALL EFFECT

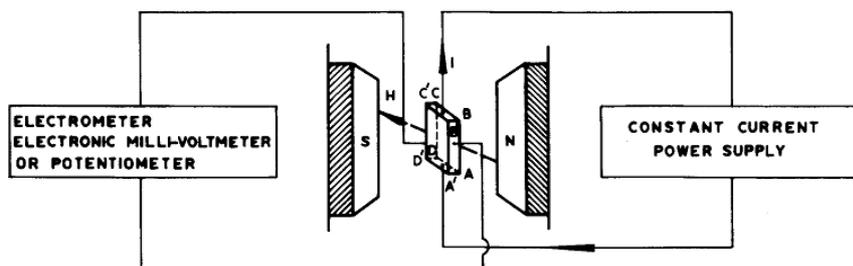


FIG. 3

www.sestechno.com

Introduction:

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

Theory:

As you are undoubtedly aware, 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. When this happens, electrons and holes will be separated by opposite forces. They will in turn produce an electric field (\mathbf{E}_h) which depends on the cross product of the magnetic intensity, \mathbf{H} , and the current density, \mathbf{J} . The situation is demonstrated in Fig. 1.

$$\bar{\mathbf{E}}_h = R \bar{\mathbf{J}} \times \bar{\mathbf{H}} \quad (1)$$

Where R is called the Hall coefficient.

Now, let us consider a bar of semiconductor, having dimension, x, y and z. Let \mathbf{J} is directed along X and H along Z then \mathbf{E}_h will be along Y, as in Fig. 2.

Then we could write,

$$R = \frac{V_h/y}{JH} = \frac{V_h \cdot z}{IH} \quad (2)$$

Where V_h is the Hall voltage appearing between the two surfaces perpendicular to y and $I = J_{yz}$

In general, the Hall voltage is not a linear function of magnetic field applied, i.e. the Hall coefficient is not generally a constant, but a function of the applied magnetic field. Consequently, interpretation of the Hall Voltage is not usually a simple matter. However, 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

Metals and degenerate (doped) semiconductors are the examples of this type where one carrier dominates.

The magnetic force on the carriers is $\vec{E}_m = e(\vec{v} \times \vec{H})$ and is compensated by the Hall field $\vec{E}_h = e\vec{E}_m$, where v is the drift velocity of the carriers. Assuming the direction of various vectors as before

$$\vec{v} \times \vec{H} = \vec{E}_h$$

From simple reasoning, the current density \vec{J} is the charge q multiplied by the number of carriers traversing unit area in unit time, which is equivalent to the carrier density multiplied by the drift velocity i.e. $\vec{J} = q n \vec{v}$

By putting these values in equation (2)

$$R = \frac{E_h}{JH} = \frac{v.H}{q n v H} = \frac{1}{n q} \quad (3)$$

From this equation, it is clear that the sign of Hall coefficient depend upon the sign of the q . This means, in a p-type specimen the R would be positive, while in n-type it would be negative. Also for a fixed magnetic field and input current, the Hall voltage is proportional to $1/n$ or its resistivity. When one carrier dominates, the conductivity of the material is $\sigma = nq\mu$.

where μ is the mobility of the charge carriers.

$$\text{Thus } \mu = R\sigma \quad (4)$$

Equation (4) provides an experimental measurement of mobility; R is expressed in $\text{cm}^3 \text{ coulomb}^{-1}$ thus μ is expressed in units, of $\text{cm}^2 \cdot \text{volt}^{-1} \text{ sec}^{-1}$.

(b) Two type of Carriers

Intrinsic and lightly doped semiconductors are the examples of this type. In such cases, the quantitative interpretation of Hall coefficient is more difficult since both type of carriers contribute to the Hall field. It is also clear that for the same electric field, the Hall voltage of p-carriers will be opposite sign from the n-carriers. As a result, both mobilities enter into any calculation of Hall coefficient and a weighted average is the result* i.e.

$$R = \frac{\mu_h^2 p - \mu_e^2 n}{2(\mu_h p + \mu_e n)^2} \quad (5)$$

Where μ_h and μ_n are the mobilities of holes and electrons; p and n are the carrier densities of holes and electrons. Eq. (5) correctly reduces to equation (3) when only one type of carrier is present**.

* From Experiments in Modern Physics by Adrian C. Melissions (Academic Press) p. 86.

** Both Eq. (3) and Eq. (5) have been derived on the assumption that all carriers have same velocity; this is not true, but the exact calculation modifies the results obtained here by a factor of only $3\pi/8$.

Since the mobilities μ_h and μ_n are not constants but function of temperature (T) the Hall coefficient given by Eq. (5), is also a function of T and it may become zero, even change sign. In general $\mu_n > \mu_h$ so that inversion may happen only if $p > n$; thus 'Hall coefficient inversion' is characteristic only of p-type semiconductors.

At the point of zero Hall coefficient, it is possible to determine the ratio of mobilities and their relative concentration.

Thus we see that the Hall coefficient, in conjunction with resistivity measurements, can provide information on carrier densities, mobilities, impurity concentration and other values. It must be noted, however, that mobilities obtained from Hall Effect measurements $\mu = R\sigma$ do not always agree with directly measured values. The reason being that carriers are distributed in energy, and those with higher velocities will be deviated to a greater extent for a given field. As μ we know varies with carrier velocity.

EXPERIMENTAL TECHNIQUE

(a) Experimental Consideration Relevant to all measurements on Semiconductors

1. In single crystal material the resistivity may vary smoothly from point to point. In fact this is generally the case. The question is the amount of this variation rather than its presence. Often however, It is conventionally stated that it is constant within some percentage and when the variation does in fact fall within this tolerance, it is ignored.
2. High resistance or rectification action appears fairly often in electrical contacts to semiconductors and in fact is one of the major problem.
3. 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 principle draw back of this type of contacts is that they may be noisy. This problem can, however, be managed by keeping the contacts clean and firm.
4. 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.

Since Hall coefficient is independent of current, it is possible to determine whether or not any of these effects are interfering by measuring the Hall coefficient at different values of current.

(b) Experimental Consideration with the Measurements of Hall Coefficient.

1. The voltage appearing between the Hall Probes is not generally, the Hall voltage alone. There are other galvanomagnetic and thermomagnetic effects (Nernst effect, Righi-Leduc effect and Ettingshausen effect) which can produce voltages between the Hall Probes. In addition, IR drop due to probe misalignment (zero magnetic field potential) and thermoelectric voltage due to transverse thermal gradient may be present. All these except, the Ettingshausen effect are eliminated by the method of averaging four readings.

The Ettingshausen effect is negligible in materials in which a high thermal conductivity is primarily due to lattice conductivity or in which the thermoelectric power is small.

When the voltage between the Hall Probes is measured for both directions of current, only the Hall voltage and IR drop reverse. Therefore, the average of these readings eliminates the influence of the other effects. Further, when Hall voltage is measured for both the directions of the magnetic field, the IR drop does not reverse and may therefore be eliminated.

2. 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.
3. The resistance of the sample changes when the magnetic field is turned on. This phenomena 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.

Therefore, while taking readings with a varying magnetic field at a particular current value, it is necessary that current value should be adjusted, every time. The

problem can be eliminated by using a constant current power supply, which would keep the current constant irrespective of the resistance of the sample.

4. 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 ($\cong 1M$) devices such as electrometer, electronic millivoltmeters or good potentiometers preferably with lamp and scale arrangements.
5. 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.

BRIEF DESCRIPTION OF THE APPARATUS

1. (a) Hall Probe (Ge Crystal)
(b) Hall Probe (InAs)
2. Hall Effect Set-up (Digital), DHE-21
3. Electromagnet, Model EMU-75 or EMU-50V
4. Constant Current Power Supply, DPS-175 or DPS-50
5. Digital Gaussmeter, DGM-102

1. (a) Hall Probe (Ge Crystal)

Ge single crystal with four spring type pressure contacts is mounted on a sunmica - decorated bakelite strip. Four leads are provided for connections with measuring devices.

| | |
|-------------------------|---------------------------------|
| Contacts | : Spring type (Solid Silver) |
| Hall Voltage | : 0.1 - 1 Volt/100 mA/KG |
| Thickness of Ge Crystal | : 0.4 - 0.5 m.m. |
| Resistivity | : $\cong 10 \Omega \text{ cm.}$ |

The exact value of thickness and resistivity is provided in the test report of the Hall Probe (Ge) supplied with the set-up. The student after calculating the Hall Coefficient from this experiment and using the given value of resistivity can also get valuable information about **carrier density and carrier mobilities**. A typical example is provided in the appendix. A further advantage of this type of probe is that the sample can be changed. A minor draw back of this arrangement is that it may require zero

adjustment from time to time. This type of probes are specially designed and recommended for Hall Effect experiment.

1 (b) Hall Probe (Indium Arsenide)

Indium Arsenide crystal (rectangular) is mounted on a phenolic strip with four soldered contacts for connections with measuring devices. The crystal is covered by a protective layer of paint. The whole system is mounted in a pen type case for further protection.

| | |
|--------------|-----------------------|
| Contacts | : Soldered |
| Hall Voltage | : 8 - 10 mV/100 mA/KG |

The value of the thickness and resistivity of the sample given for these probes are not very reliable as these are not given for a specific probe and may vary from probe to probe as is usually the case with all semiconductor devices. These are essentially meant to be used as transducers.

2. Hall Effect Set-up (Digital), DHE-21

It is a high performance instrument of outstanding flexibility. The set-up consists of an electronic digital millivoltmeter and a constant current power supply. The Hall Voltage and probe current can be read on the same digital panel meter through the selector switch.

(a) Digital Millivoltmeter

Intersil 3½ digit single chip A/D Converter ICL 7107 have been used. It has high accuracy like, auto zero to less than 10 μV , zero drift less than 1 $\mu\text{V}/^\circ\text{C}$, input bias current of 10 pA and roll over error of less than one count. Since the use of internal reference causes the degradation in performance due to internal heating, an external reference has been used. This voltmeter is much more convenient to use in Hall experiment, because the input of either polarity can be measured.

SPECIFICATIONS

| | |
|--------------------|---|
| Range | : 0 - 200.0 mV |
| Resolution | : 100 μV |
| Accuracy | : $\pm 0.1\%$ of reading ± 1 digit |
| Impedance | : 1 Mohm |
| Special Features | : Auto Zero & polarity indicator |
| Overload Indicator | : Sign of 1 on the left & blanking of other digits. |

(b) Constant Current Power Supply

This power supply specially designed for Hall Probe provides 100 percent protection against crystal burn-out due to excessive current. The basic scheme is to use the feed - back principle to limit the load current of the supply to a pre - set maximum value. Variations in the current are achieved by a potentiometer. The supply is a highly regulated and practically ripple free d.c. source. The current is measured by the digital panel meter.

SPECIFICATIONS

| | |
|-----------------|--|
| Current range | : (0 - 20 mA) or as required for the particular Hall Probe |
| Resolution | : 10 μ A |
| Accuracy | : $\pm 0.2\%$ of the reading ± 1 digit |
| Load regulation | : 0.03% for 0 to full load |
| Line regulation | : 0.05% for 10% changes. |

3. (a) Electromagnet, EMU-75

| | |
|-------------------|--|
| Field Intensity | : 11,000 $\pm 5\%$ gauss in an air-gap of 10 mm. Air-gap is continuously variable upto 100 mm with two way knobbed wheel screw adjusting system. |
| Pole Pieces | : 75 mm diameter. Normally flat faced pole pieces are supplied with the magnet. |
| Energising Coils | : Two. Each coil is wound on non-magnetic formers and has a resistance of 12 ohms approx. |
| Yoke material | : Mild steel |
| Power requirement | : 0 - 100 V @ 3.5 A if connected in series. 0 - 50 V @ 7.0 A if connected in parallel. |

3. (b) Electromagnet, EMU-50V

| | |
|-------------------|---|
| Field Intensity | : 7.5 K gauss at 10 mm. The air-gap is continuously variable with two way knobbed wheel screw adjusting system. |
| Pole Pieces | : 50 mm diameter. Normally flat faced pole pieces are supplied with the magnet. |
| Energising Coils | : Two, each coil is wound on non magnetic formers and has a resistance of about 3.0 ohm. |
| Yoke Material | : 'U' shaped soft iron |
| Power Requirement | : 0 - 30 V @ 4.0 A, if coils are connected in series. |

4. (a) Constant Current Power Supply, DPS-175

The present constant current power supply was designed to be used with the electromagnet, Model EMU-75. The current requirement of 3.5 amp/coil, i.e. a total of 7 Amp was met by connecting six closely matched constant current sources in parallel. In this arrangement the first unit works as the 'master' with current adjustment control. All others are 'slave' units, generating exactly the same current as the master. All the six constant current sources are individually IC controlled and hence result in the highest quality of performance. The supply is protected against transients caused by the load inductance.

SPECIFICATIONS

| | |
|----------------------|--|
| Current | : Smoothly adjustable from 0 to 3.5 A. per coil, i.e. 7A |
| Regulation (line) | : $\pm 0.1\%$ for 10% mains variation. |
| Regulation (load) | : + 0.1% for load resistance variation from 0 to full load |
| Open circuit voltage | : 50 volt |
| Metering | : 3½ digit, 7 segment panel meter. |

4. (b) Constant Current Power Supply, DPS-50

The present constant current source is an inexpensive and high performance unit suitable for small and medium sized electromagnets. Although the equipment was designed for the electromagnet, model EMU-50, it can be used satisfactorily with any other electromagnet provided the coil resistance does not exceed 6 ohm.

The current regulation circuit is IC controlled and hence result in the highest quality of performance. Matched power transistors are used to share the load current. The supply is protected against transients caused by the inductive load of the magnet.

SPECIFICATIONS

| | |
|-----------------|--|
| Current Range | : 0 - 4 A (or as desired) |
| Load Regulation | : 0.1% for load resistance variation from zero to maximum |
| Line Regulation | : 0.1% for $\pm 10\%$ mains variation |
| Protected | : Electronically protected against overload or short circuit |
| Display | : 3½ digit, 7 segment LCD DPM |

A calibration chart (current vs. magnetic field) is supplied, which eliminate the need of a Gaussmeter when supplied with EMU-50.

5. Digital Gaussmeter, Model DGM-102

The Gaussmeter operates on the principle of Hall Effect in semiconductors. A semiconductor material carrying current develops an electro-motive force, when placed in a magnetic field, in a direction perpendicular to the direction of both electric current

and magnetic field. The magnitude of this e.m.f. is proportional to the field intensity if the current is kept constant, this e.m.f. is called the Hall Voltage. This small Hall Voltage is amplified through a high stability amplifier so that a millivoltmeter connected at the output of the amplifier can be calibrated directly in magnetic field unit (gauss).

SPECIFICATIONS

| | |
|------------|--|
| Range | : 0 - 2 K gauss & 0 - 20 K gauss |
| Resolution | : 1 gauss at 0 - 2 K gauss range |
| Accuracy | : $\pm 0.5\%$ |
| Display | : 3½ digit, 7 segment LED |
| Detector | : Hall probe with an Imported Hall Element |
| Power | : 220V, 50 Hz |
| Special | : Indicates the direction of the magnetic field. |

PROCEDURE

1. Connect the widthwise contacts of the Hall Probe to the terminals marked 'Voltage' and lengthwise contacts to terminals marked 'Current'.
2. Switch 'ON' the Hall Effect set-up 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, this error should be subtracted from the Hall Voltage reading.
4. Now place the probe in the magnetic field as shown in fig. 3 and 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 for both the directions of the current and magnetic field (i.e. four observations for a particular value of current and magnetic field).
6. Measure the Hall voltage as a function of current keeping the magnetic field constant. Plot a graph.
7. Measure the Hall voltage as a function of magnetic field keeping a suitable value of current as constant. Plot graph.
8. Measure the magnetic field by the Gaussmeter.

CALCULATIONS

- (a) From the graph Hall voltage Vs. magnetic field calculate Hall coefficient.
- (b) Determine the type of majority charge carriers, i.e. whether the crystal is n type or p type.
- (c) Calculate charge carrier density from the relation

$$R = \frac{1}{nq} \Rightarrow n = \frac{1}{Rq}$$

- (d) 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). *Typical calculations are shown in appendix*

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?
7. Why the Hall voltage should be measured for both the directions of current as well as of magnetic field?

REFERENCES FOR SUPPLEMENTARY READING

1. Fundamentals of semiconductor Devices, J.Lindmayer and C.Y. Wrigley, Affiliated East-West Press Pvt. Ltd., New Delhi.
2. Introduction to Solid State Physics, C. Kittel; John Wiley and Sons Inc., N.Y. (1971), 4th edition.
3. Experiments in Modern Physics, A.C. Melissios, Academic Press, N.Y. (1966).
4. Electrons and Holes, W. Shockley, D. Van Nostrand ,N.Y. (1950).
5. Hall Effect and Related Phenomena, E.H. Putley, Butterworths, London (1960).
6. Handbook of Semiconductor Electronics, L.P. Hunter (e.d.) McGraw Hill Book Co. Inc., N.Y. (1962).

APPENDIX

Sample calculation for Hall Coefficient, Carrier Density and Mobility taking Hall Probe S.No. 500 as sample.

Sample Details

| | | |
|---------------------------|--|--|
| Sample | : Ge crystal n- type | $\left\{ \text{ohm} = \frac{V}{I} = \frac{V}{\frac{dQ}{dt}} = V \cdot \text{coulomb}^{-1} \cdot \text{sec} \right\}$ |
| Thickness (z) | : 5×10^{-2} cm. | |
| Resistivity (ρ) | : 10 ohm. cm. or 10 volt coulomb ⁻¹ sec cm | |
| Conductivity (σ) | : $0.1 \text{ coulomb volt}^{-1} \text{ sec}^{-1} \text{ cm}^{-1}$ | |

Experimental Data

| | |
|------------------------|-------------------------|
| Current (I) | : 8×10^{-3} A |
| Magnetic Field (H) | : 1000 G |
| Hall Voltage (V_h) | : 53×10^{-3} V |

(i) Hall Coefficient (R)

we know from equation 2 of the text

$$\begin{aligned} R &= \frac{V_h \cdot z}{I H} \\ &= \frac{53 \times 10^{-3} \times 5 \times 10^{-2}}{8 \times 10^{-3} \times 10^3} \\ &= 33 \times 10^{-5} \text{ volt cm amp.}^{-1} \text{ G}^{-1} \\ \text{or} &= 33 \times 10^{-5} \times 10^8 \text{ cm}^3 \text{ coulomb} \\ &= 33 \times 10^3 \text{ cm}^3 \text{ coulomb}^{-1} \end{aligned}$$

(ii) Carrier Density (n)

we know from equation 3 of the text

$$\begin{aligned} R &= \frac{1}{nq} \Rightarrow n = \frac{1}{Rq} \\ &= \frac{1}{33 \times 10^3 \times 1.6 \times 10^{-19}} \\ &= 1.9 \times 10^{14} \text{ cm}^{-3} \end{aligned}$$

(iii) Carrier Mobility

For degenerate semiconductor i.e. when one carrier dominates.

$$\begin{aligned}\text{Carrier Mobility } \mu &= R\sigma \\ &= 33 \times 10^{-3} \times 0.1 \\ &= 3300 \text{ cm}^2 \text{ volt}^{-1} \text{ sec}^{-1}\end{aligned}$$

Thus we see that Hall Coefficient in conjunction with resistivity measurement can provide valuable information on carrier density, mobilities and other values. It must be noted however, that mobilities obtained from Hall Effect measurement $\mu=R\sigma$ do not always agree with directly measured values. The reason is explained in the booklet.

REFERENCE

SES instruments pvt. Ltd. (www.sestechno.com)

6. STUDY OF MAGNETIC HYSTERESIS IN FERROMAGNETIC MATERIAL

Objective:

To study the magnetic hysteresis loop for a ring shaped massive iron core.

Theory:

Magnetism in matter: The magnetic state of a material can be described by a vector \vec{M} called magnetization, or dipolar magnetic moment per unit volume. In vacuum, the magnetic induction $B\vec{}$ and the applied magnetic field intensity, $H\vec{}$, are connected by the equation:

$$B\vec{=} \mu_0 H\vec{=} \quad (1)$$

where $\mu_0 = 4\pi \times 10^{-7} \text{ Hm}^{-1}$, is the absolute magnetic permeability of vacuum. However, in a matter, magnetic induction depends on magnetization $M\vec{}$ in the following way:

$$B\vec{=} \mu_0 (H\vec{=} + M\vec{=}) \quad (2)$$

There is another important parameter called the magnetic susceptibility, χ , which is a measure of the quality of the magnetic material and defined as the magnetization produced per unit applied magnetic field, i.e.,

$$\chi = M/H \quad (3)$$

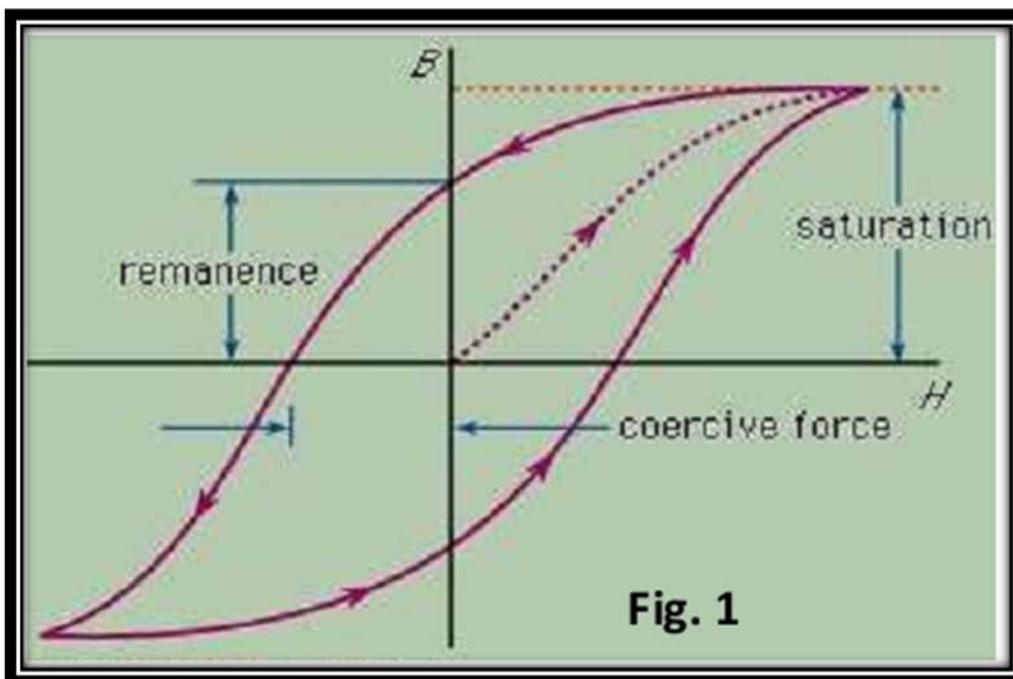
Magnetism in solids is broadly classified into 3 categories: diamagnetism, paramagnetism and ferromagnetism.

Diamagnetism: Diamagnetism is a very weak effect observed in solids having no permanent magnetic moments. It arises due to changes in the atomic orbital states induced by the applied magnetic field. It exists in all materials but usually suppressed by other stronger effects such as para- or ferromagnetism. For diamagnetic materials, magnetization $M\vec{}$ varies linearly with $H\vec{}$ in opposite direction. Hence $\chi < 0$. Diamagnetism is temperature independent.

Paramagnetism: Paramagnetism is also a weak effect, but unlike diamagnetism, the magnetic moment is aligned along the direction of applied magnetic field. Certain atoms and ions (oxygen, air, iron salts, etc.) have a permanent magnetic moment of their own. Without applied magnetic field, these are oriented randomly. Therefore they don't show any magnetization on a macroscopic scale. On applying an external magnetic field, a non-zero macroscopic magnetic moment $M\vec{}$ arises since all the magnetic momenta are aligned along

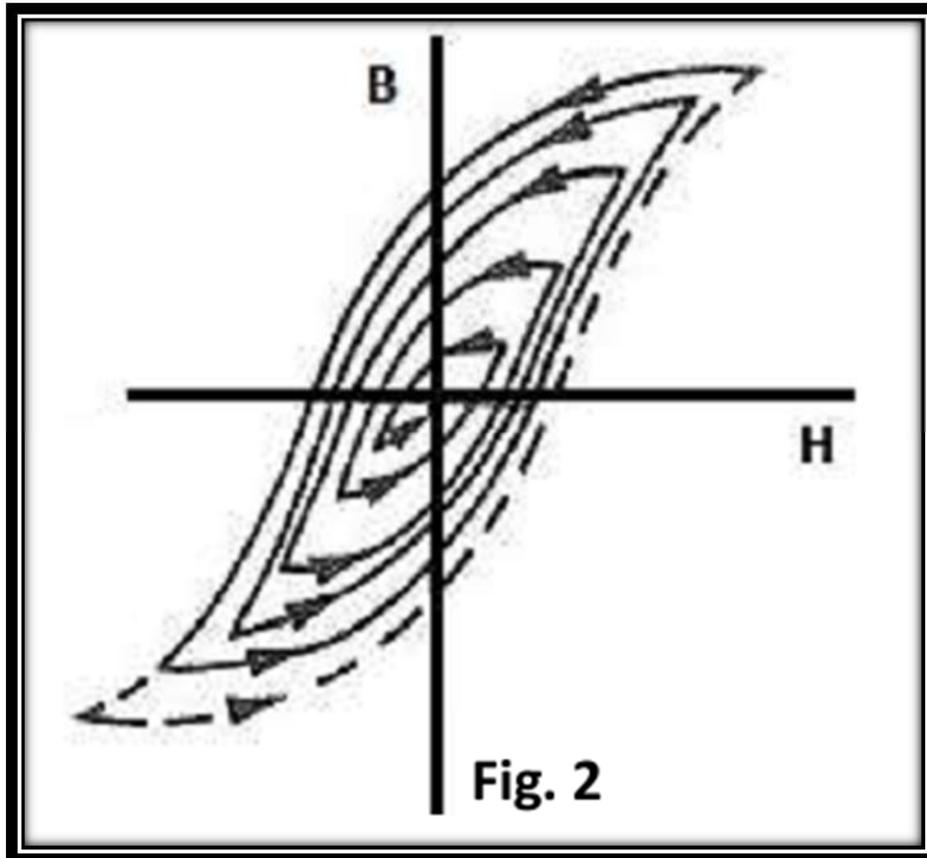
the applied field. The magnetization \vec{M} initially varies linearly with H and then saturates at a value M_s , called saturation magnetization. This saturation condition corresponds to the complete alignment of the magnetic dipoles along the applied field direction. However, once the applied field is removed, thermal agitation in the material is enough to disorient the atoms. Paramagnetic materials have a small, positive χ . Paramagnetism is temperature dependent.

Ferromagnetism: Ferromagnetism is associated with the presence of permanent magnetic dipoles where the magnetic momenta of adjacent atoms are aligned in a particular direction, even in the absence of an external magnetic field. This is known as spontaneous magnetization. A ferromagnetic material contains a number of small regions called domains, which are having spontaneous magnetization values of different magnitude. On application of an external magnetic field H , these domains align in the direction of H and develop a strong macroscopic magnetization M . The value of χ for a ferromagnetic material is large and positive. Ferromagnetism is temperature dependent as it exists below a certain temperature known as Curie temperature T_C . Some examples of ferromagnetic materials are iron, cobalt and nickel.



Hysteresis: Hysteresis loop (Fig. 1) shows the relation between the magnetization M or the magnetic induction B as a function of H . It is a characteristic property of any ferromagnetic material. The dotted line in Fig. 1 shows that as the applied field is increased the magnetization in the domains grows along the so-called easy direction of magnetization and

finally attains a saturation value at BS. At this point all the domains point along the direction of applied magnetic field. On decreasing the field, B is not reversible and possesses a non-zero value called remanent induction, B_r . It can be reduced to zero by applying a reverse magnetic field known as coercive magnetic field or coercivity, H_c . A similar variation is observed as the reverse field is varied resulting in a closed loop known as hysteresis loop.



Degaussing:

Degaussing is the process of decreasing or eliminating a remnant magnetic field present in a ferromagnetic material due to hysteresis. Annealing, hammering or applying a rapidly oscillating magnetic field (Fig. 2) are some of the methods of degaussing which tend to release the domain walls from their pinned state, and the domain boundaries tend to move back to a lower energy configuration.

Apparatus:

1. Iron core
2. Pair of coils (600 turns each, current limit 2A)
3. DC power supply

4. Digital gauss meter (DGM) with hall probe
5. Reversible switch
6. Connecting wires

Experimental set up:



Fig. 3: Experimental set up

Procedure:

1. Connect the power supply to the coils through the reversible switch and place the Gauss meter near to the magnet as shown in Fig. 3. The power supply should be in constant current (CC) mode.
2. Make sure that the sample is demagnetized. (How?)
3. Using zero adjustment knob, set the reading of the digital gauss meter at the best possible minimum value, B_{offset} .
4. With no current flowing in the circuit (power supply is OFF), note the reading of the DGM.
5. Switch on the power supply. Very slowly increase the current value (I) in steps of 0.1A up to 2A and record the corresponding readings from DGM after subtracting B_{offset} . DO NOT exceed the current value above 2A and AVOID 2A current flow in the coil for longer period to avoid damage to the coil.
6. Repeat the above step by varying the current from 2A to 0, 0 to -2A, -2A to 0 and

then again 0 – 2A to complete the loop. Use the reversible key for reversing the polarity of current.

- Calculate the value of H corresponding to each current using the formula

$$H = (n/L).I.$$

Where n= Number of turns in the coil = 600 L= Average field line length for the sample = 232 mm (as provided by manufacturer)

- Plot the hysteresis loop (B ~ H).
- To degauss the magnetized iron core, apply 2A current first and note down the value on DGM. Reduce the current to 0 and record the value (Remanence, Br) on DGM. Now, switch the polarity of current and set its value at less than 2A (say 1.7A). Record the corresponding value of B. Bring the current back to 0 and note the value of Br again.
- Repeat the above step by applying positive and negative field alternately to get gradually lower values of B. Record the value of Br each time. Continue this step till you get $Br \approx 0$ which means the iron core is demagnetized.

Table: 1 Data for Hysteresis curve

| Sl. # | Current I (A) | H (A/m) | B (Gauss) |
|-------|---------------|---------|-----------|
| | | | |
| | | | |
| | | | |
| | | | |

Table: 2 Degaussing

| Sl. # | Current (A) | B (Gauss) | Br (at I=0) |
|-------|-------------|-----------|-------------|
| | | | |
| | | | |
| | | | |

Observations:

Graph:

Plot B-H curve.

Plot B - |Br|

Results:

Determine values of coercivity, remanence, saturation magnetization and hysteresis loss from graph.

Conclusions:**Precautions:**

Avoid flow of large current in the coils for prolonged time.

Reference:

1. C. Kittel, Introduction to Solid State Physics
2. Manual by supplier