

$$P(x)dx = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma}\right)^2\right] dx \quad (1)$$

where  $P(x)dx$  is the probability that the observation lies in an interval  $dx$  around  $x$ ,  $\bar{x}$  is the mean (average) given by

$$\bar{x} = \int_{-\infty}^{\infty} x P(x)dx \quad (2)$$

and  $\sigma$  is the standard deviation given by

$$\sigma = \left( \int_{-\infty}^{\infty} (x - \bar{x})^2 P(x)dx \right)^{\frac{1}{2}} \quad (3)$$

The quantity  $\sigma$  is a measure of the spread of the observations around  $\bar{x}$ . Specifically, 68% of all data is within the range  $\bar{x} - \sigma$  to  $\bar{x} + \sigma$ . For a discrete set of data,

$$\bar{x} = \left( \frac{1}{N} \right) \sum_i x_i \quad (4)$$

$$\sigma = \left[ \left( \frac{1}{N} \right) \sum_i (x_i - \bar{x})^2 \right]^{\frac{1}{2}} \quad (5)$$

For a small set of data, the best estimate of the standard deviation is given by

$$\sigma^2 = \left[ \left( \frac{1}{N-1} \right) \sum_i (x_i - \bar{x})^2 \right] \quad (6)$$

where  $\sigma^2$  is known as the variance.

### Maximum possible error

In the above discussion, we have only considered the measurement of one quantity. Most of the experiments involve measurement of several different quantities. Measurement of each of these quantities is limited in accuracy by the least count of the instrument and error arising because of this is termed as maximum possible error. The maximum possible error can be estimated in the following manner.

Suppose a physical quantity  $y$  is a function of two independent (measurable) variables  $x_1$  and  $x_2$  given by

$$y = f(x_1, x_2)$$

Then maximum possible error in  $y$  is given by

(7)

$$\frac{\Delta y}{y} = \frac{1}{f} \left[ \left( \frac{\partial f}{\partial x_1} \right) \Delta x_1 + \left( \frac{\partial f}{\partial x_2} \right) \Delta x_2 \right]$$

where  $\Delta x_1$  and  $\Delta x_2$  are the errors in quantities  $x_1$  and  $x_2$  respectively. If  $x_1$  and  $x_2$  are the measurable quantities, then  $\Delta x_1$  and  $\Delta x_2$  respectively are the least counts of the instrument used to measure them.

In all the experiments you are about to perform in this course, you are expected to estimate the maximum possible error from Eq. (7). Recall how the errors propagate in expressions containing powers!

### Least squares fit:

Suppose you are measuring two quantities  $x$  and  $y$  linearly related by  $y = bx + c$  (8)

The best estimates for the slope  $a$  and intercept  $b$  of the straight line are obtained as follows. Suppose that  $(y_i, x_i)$  be the measured value. If  $y(x_i)$  is the value defined by Eq. (8), then one should minimize the quantity,  $\sum_i (y(x_i) - y_i)^2 = \sum_i (y_i - ax_i - b)^2$  with respect to  $a$  and  $b$ . Setting the differentials to zero and solving the two simultaneous equations, gives the best estimates of  $a$  and  $b$  as

$$b = \frac{N \sum x_i y_i - \sum x_i \sum y_i}{N \sum x_i^2 - \left( \sum x_i \right)^2} \quad \text{ln NN} \quad \text{Ansia (701012)} \quad (9)$$

$$a = \left( \frac{\sum x_i^2 \sum y_i - \sum x_i \sum x_i y_i}{N \sum x_i^2 - \left( \sum x_i \right)^2} \right) \quad (10)$$

After obtaining the values of  $a$  and  $b$ , plot the straight line  $y = ax + b$  using values of  $a$  and  $b$  obtained by Eqs. (9) and (10). Plot the measured points  $(y_i, x_i)$  too on the same graph. See how well the experimental data points are clustered around this straight line!

Quite often you may be able to reduce the equation containing exponents to the linear form by suitable rearrangements. For example,  $y = ce^x$  can be rewritten as  $\ln y = \ln c + x$ , so a plot of  $\ln y$  versus  $x$  would be a straight line.

\*\*\*\*\*

## Experiment #1: Electron Spin Resonance

### Objective:

To measure the Lande's g-factor in a free radical using an electron spin resonance spectrometer.

### Theory:

When a particle with a magnetic moment  $\mu$  is placed in a uniform magnetic field of intensity  $H_0$ , (Fig 1.1a) then the moment will precess around  $H_0$  with a Larmor frequency of

$$\omega_0 = g [c/(2mc)] H_0 \quad (1)$$

where  $g$  is the Lande's g-factor ( $g = 1$  for pure orbital momentum and  $g = 2$  for a free electron). In the case of an anion in a crystal, the Lande's g-factor deviates from the Lande's g-factor and is known as the spectroscopic splitting factor.

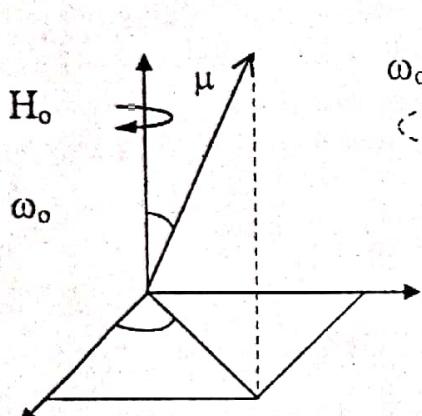


Fig. 1.1(a)

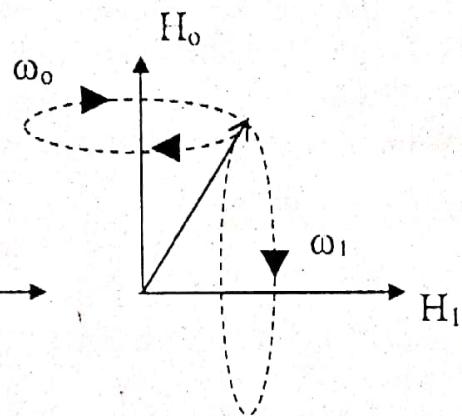


Fig. 1.1(b)

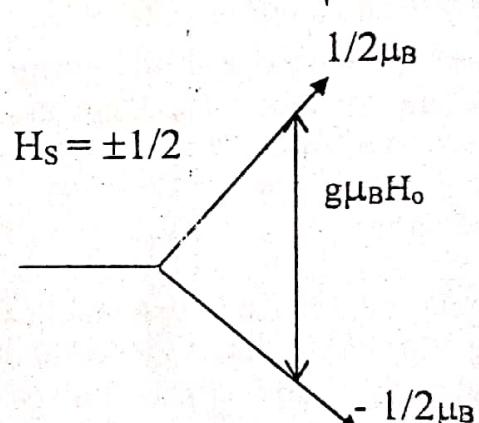


Fig. 1.1(c)

Now consider applying a weak magnetic field  $H_1$  oriented in the XY plane and rotating about Z-axis (Fig. 1.1b) in the same direction as the Larmor precession. If the angular frequency  $\omega_1$  of the magnetic field is not equal to  $\omega_0$ , then the angle  $\theta$  between  $\mu$  and  $H_1$  will continuously change and hence the net interaction would become zero. If on the other hand if  $\omega_1 = \omega_0$ , then the net interaction will not be zero. If one looks at this spin system from a reference frame rotating about the z-axis with angular velocity  $\omega_0$ , then it would appear that the spin is making an angle  $\Psi = 90^\circ - \theta$  with  $H_1$  (and would precess about  $H_1$ ). The change in  $\theta$  is the classical analogy to a transition between magnetic sublevels. Let us consider the quantum picture of magnetic resonance. Let the intrinsic angular momentum of the electron  $S$  couples with the orbital angular momentum of electron  $L$  to give the resultant  $J$ . The energy difference  $\Delta E$  between adjacent magnetic sublevels is  $\Delta E = g\mu_B H_0$ , where  $\mu_B$  is the Bohr magneton and the quantum mechanical value of  $g$  is

$$g = 1 + [J(J+1) + S(S+1) - L(L+1)] / 2J(J+1) \quad (2)$$

$$f = 13, 14.5, 16$$

Now consider the particle perturbed by an alternating magnetic field with frequency  $\nu_1$ . If the energy difference between two magnetic sublevels is  $\Delta E$  exactly equals  $h\nu_1$  and if the direction of the perturbing magnetic field is perpendicular to the direction of the static magnetic field, then there will be an induced transition between neighboring sublevels (as permitted by the selection rule  $\Delta m = \pm 1$ ). Therefore the condition for resonance is

$$\Delta E = g\mu_B H_0 = h\nu_0 = h\nu_1 \quad (3)$$

where  $\nu_1$  is the resonance frequency. The above condition is identical to the classical case of  $\omega_1 = \omega_0$ . For a free electron  $g = 2.00$ ,  $\mu_B = 0.927 \times 10^{-20}$  erg/Gauss and  $h = 6.625 \times 10^{-27}$  erg-sec. Substituting these values in Eq. (3) we get  $\nu_0/H_0 = 2.8$  MHz/Gauss. This implies that electron spin resonance (ESR) can be observed in RF range with magnetic field of a few gauss or in a microwave region with a few kilogauss. The latter give a better results but the instrumentation becomes highly sophisticated and costly. Here ESR is observed in RF range, for this, the sample under study is placed between a pair of Helmholtz coils (which is the part of a tank circuit of an oscillator). Whenever the sample absorbs power (usually at resonance), the power load on the oscillator circuit decreases. The change in the power  $\Delta W$  is measured by measuring the change in the current through the oscillator. The block diagram of the ESR spectrometer is shown below. Understand the function of each module.

#### Procedure:

1. Connect the X and Y terminals to the corresponding terminals of the CRO by connecting leads, Helmholtz Coil leads to terminal marked "H-Coils".
2. Adjust the "current" knob fully anticlockwise (minimum).
3. Set FREQUENCY knob to "center", sensitivity to "maximum" and phase KNOB to "centre" Position.
4. Switch on "H-Coil" power and set the current to (say) 150mA.
5. Four peaks would be observed on the screen (Understand the origin of the four peaks). Adjust the PHASE knob to coincide two peaks over the other two.
6. Adjust FREQUENCY and SENSITIVITY knobs of the spectrometer and the SENSITIVITY knob of the CRO such that sharp peaks are obtained.
7. Adjust PHASE knob to merge the four into two (as far as possible).
8. Pick-up the RF signal with the help of copper strip wrapped around the RF coil and feed the signal on to digital storage Oscilloscope (DSO, 100 MHz) for the measurement of the resonance frequency.

#### Measurements:

##### Resonance Field:

Let the position between the peaks is  $2Q$  division (mm) and the horizontal deflection is  $P$  division (mm) (Fig. 1.2a). Then the corresponding peak-to-peak magnetic field  $H_{pp} = 165.25$  Gauss/amp (assuming radius of coil as 7.7 cm and number of turns in the coil as 500). The resonance field  $H_0$  is given by

$$H_0 = 165.25 * I * Q / P \quad (4)$$

Calculate the g-factor using Eq.3. Repeat the measurement for several values of I and calculate the average value of g.

Plot  $I/I$  vs Q and determine the slope. The slope will give  $Q^*I$ . Using this value of  $Q^*I$ , calculate the Lande's factor again.

If you are unable to merge the four peaks into two very precisely, make the peaks to cross near baseline as shown in Fig 1.2(b). Mark the points  $P_1$ ,  $P_2$ ,  $Q_1$  and  $Q_2$  on a tracing paper and measure and  $2Q$  with the help of graph paper. Change the frequency using the frequency knob and repeat the measurement for three different frequencies.

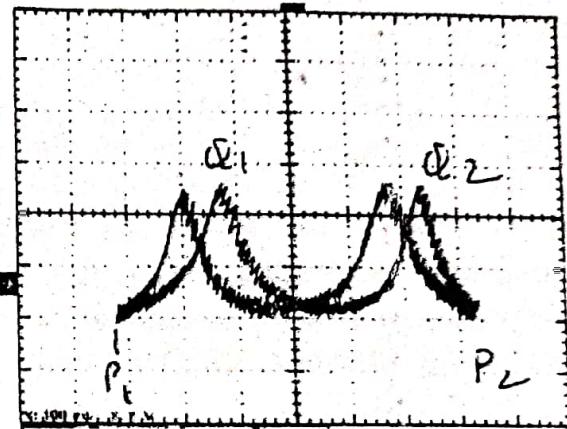
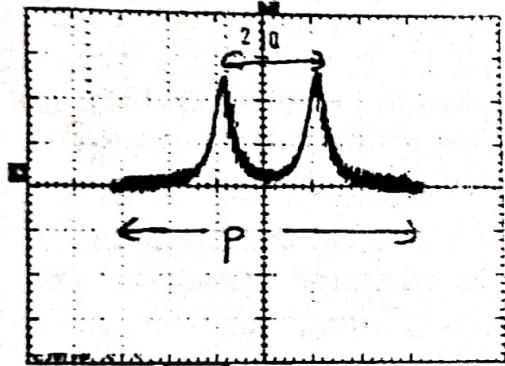


Fig. 1.2 (a) and (b)

### Questions?

1. What is the sample used? Do your results agree with those expected for the given sample?
2. What are the major sources of error in this experiment?

## Experiment # 2: Electrical Resistivity of a semiconductor

### Objective:

To study the temperature variation of the electrical resistivity of a semiconducting material using four-probe technique and to estimate its band gap energy.

### Theory:

Electrical resistivity of a semiconductor plays an important role in determining the characteristics of the complete device viz. transistor made out of it. The temperature dependence of the resistivity can be described by  $\rho = \rho_0 \exp(E_g/2k_B T)$ , where  $E_g$ ,  $k_B$  and  $T$  are band gap energy, Boltzmann's constant and absolute temperature, respectively. In order to determine the parameters of a semiconductor device in a given environment, its resistivity has to be measured accurately. The Ohm's law in terms of the electric field and current density given by the relation,

$$\vec{E} = \rho \vec{J} \quad (1)$$

where,  $\rho$  is the electrical resistivity of the material. For a long thin wire-like geometry of uniform cross-section or for a long parallelepiped shaped sample of uniform cross-section, the resistivity  $\rho$  can be measured by measuring the voltage drop  $V$  across the sample due to passage of a constant current  $I$  through the sample as shown in Fig. 2.1

This simple (two-probe) method has following drawbacks:

- 1) Error due to contact resistance of measuring leads.
- 2) Cannot be used for materials having random shapes.
- 3) For some materials, soldering the test leads is difficult.
- 4) In case of semiconductors, soldering results in injection of impurities into the materials, thereby affecting the intrinsic electrical resistivity.
- 5) Certain metallic contacts form Schottky barrier on semiconductors.

To overcome the first two problems, a collinear equidistant four-probe method is used. This method is appropriate for the measurement of resistivity of specimen having wide variety of shapes. Usage of pressure contacts instead of soldered contacts eliminates the rest of the problems discussed above.

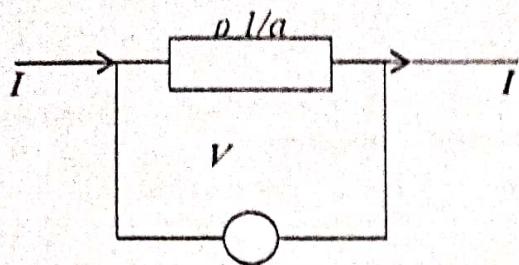


Fig. 2.1

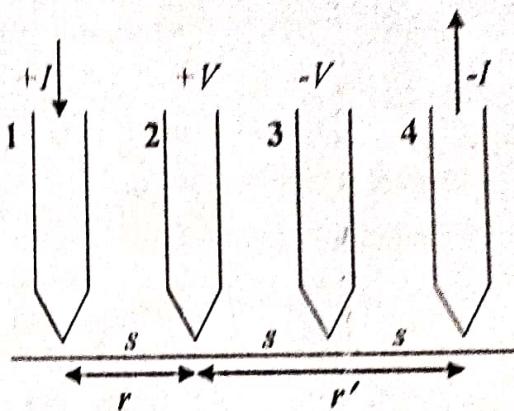


Fig. 2.2

In collinear equidistant four-probe method, four pointed, collinear equidistantly spaced probes are placed on the plane surface of the specimen (Fig. 2.2). A small pressure is applied using spring loaded electrical contacts. The diameter of the contact (which is assumed to be hemispherical) between the probe and the specimen surface is small compared to the spacing between the probes. The thickness of the sample  $d$  is small compared to the spacing between the probes  $s$  (i.e.,  $d \ll s$ ). Under this condition, the current streamlines inside the sample due to a probe carrying current  $I$  will have radial symmetry, so that  $\vec{E} = -\left(\frac{\partial V}{\partial r}\right)\hat{r}$  and from equation (1),

$$\frac{\partial V}{\partial r}\hat{r} = -\rho \vec{J} \quad (2)$$

If the outer two probes 1 and 4 (refer Fig. 2.2) are current carrying probes and the inner two probes 2 and 3 are used to measure the potential difference between the inner two points of contact, then total current density at the probe 2 which is at a distance  $r$  from probe 1 and  $r'$  from probe 4 can be written as,

$$\vec{J} = \frac{I}{2\pi d} \left( \frac{\hat{r}}{r} - \frac{\hat{r}'}{r'} \right) \quad (3)$$

From equations (2) and (3), the potential difference between probes (2) and (3) can be written as,

$$V = \frac{I\rho}{2\pi d} \int_s^{2s} \left( \frac{1}{r} + \frac{1}{3s - r} \right) dr = \frac{I}{\pi d} \rho \ln 2 \quad (4)$$

$$\therefore \rho = \frac{V\pi d}{I \ln 2}$$

The experimental set-up consists of an oven with the sample and probe assembly and an instrument box containing a constant current source, voltmeter and power supply for the oven. The collinear four-probe assembly consists of four spring loaded probes. These probes rest on a metal plate on which thin slices of samples (whose resistivity is to be determined) can be mounted by electrically insulating their bottom surface using a mica sheet. This assembly is mounted on the lid of the oven, so that the four probes and the sample can be kept inside the oven and sample can be heated up to a temperature of 200 °C. The temperature inside the oven can be measured by inserting a thermometer through a hole in the lid.

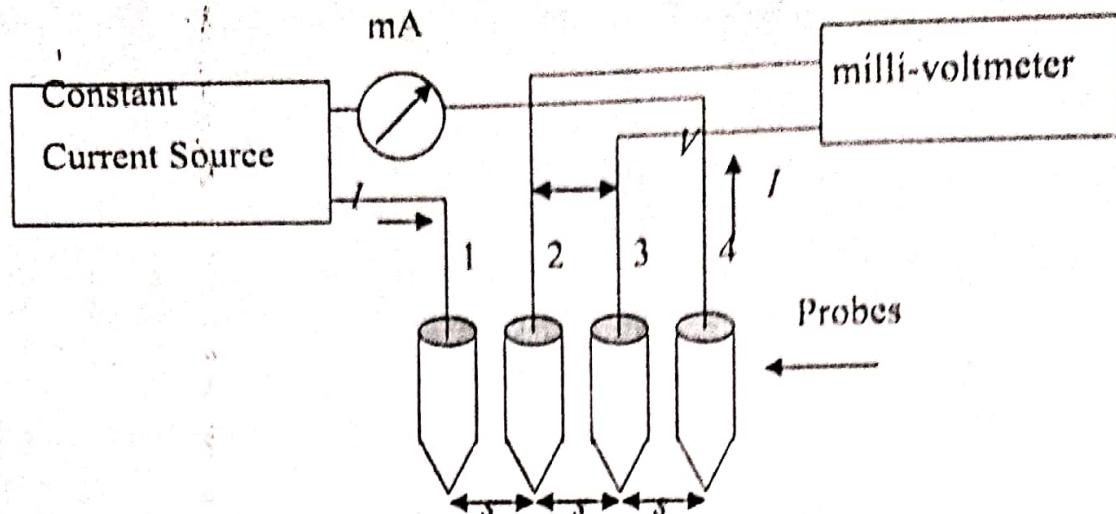


Fig. 2.3

The value of the current can be read from the LED display on the unit. The built-in digital voltmeter is used to measure the voltage drop between probes 2 and 3. Both the set current and the voltage drop can be monitored using the same display by appropriately setting the toggle switch. A scale changer switch provides  $\times 1$  and  $\times 10$  magnification of the voltage. Sample can be heated at low (L) or high (H) rate by appropriately setting the other toggle switch.

#### Procedure:

1. Make the connections as shown in Fig. 2.3. Set some suitable low value of current  $\sim 2$  to  $4$  mA from the constant current source. Note down this reading.
2. Switch over the LED display to milli voltmeter mode. Note the temperature and voltage.
3. Switch on the oven. Record the voltage as a function of temperature while heating (or cooling) the sample.
4. Calculate the experimental resistivity as a function of temperature using equation (4). Plot suitable curve to depict the temperature variation of resistivity.
5. Fit the experimental data to  $\rho = \rho_0 \exp(E_g/2kT)$ . Show the theoretical curve in the plot. Determine the band gap.
6. Estimate the maximum possible error in the measurement of resistivity and estimated value of  $E_g$ .

*Useful data: Distance between probes  $s = 2$  mm. Thickness of the sample  $d = 0.5$  mm*

#### Questions:

1. Do you feel that the temperature is sensed correctly in this experiment? Explain.
  2. Can you use this set-up for measuring the resistivity of a metal?
  3. Why is the absolute value of  $\rho(T)$  different for the heating and cooling cycles?
- Does  $\rho(T)$  follow the exponential law from room temperature to  $\sim 200$  °C? Why so?

## Experiment # 3: Geiger-Muller Counter: Beta decay

### Objectives:

1. To record the intensity vs. V characteristics of a Geiger-Muller (GM) counter.
2. To verify the inverse square law.
3. To measure the (beta) absorption coefficient of Aluminum.

### Theory:

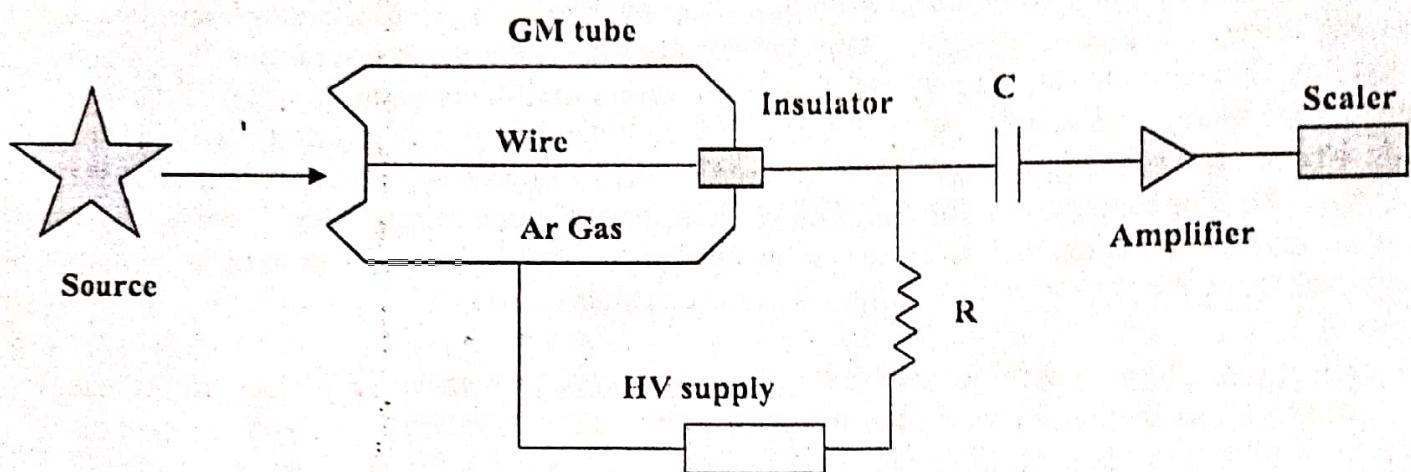
All nuclear radiations, whether they are charged particles or gamma rays, ionize atoms/molecules while passing through a gaseous medium. This ionizing property of a nuclear radiation is utilized for its detection. The Geiger-Muller counter commonly called as G-M counter or simply a Geiger tube is one of the oldest and widely used nuclear radiation detectors. It consists of a metallic tube with a thin wire mounted along its axis. The wire is insulated from the tube using a ceramic feed-through (Fig. 3.1). The central wire (anode) is kept at a positive potential of a few hundred volts or more with respect to the metallic tube, which is grounded. The tube is filled with argon gas mixed with 5-10% of ethyl alcohol or halogens (Chlorine or Bromine).

When an ionizing radiation enters the Geiger tube some of the energy of the radiation may get transferred to a gas molecule within the tube. This absorption of energy results in ionization, producing an electron-ion pair (primary ions). The liberated electrons move towards the central wire and positive ions towards the negatively charged cylinder. The electrons now cause further ionization by virtue of the acceleration due to the intense electric field. These secondary ions may produce other ions and these in turn still other ions before reaching the electrodes. This cascading effect produces an avalanche of ions. In an avalanche created by a single original electron many excited gas molecules are formed by electron collisions in addition to secondary ions. In a very short time of few nanoseconds these excited molecules return to ground state through emission of photons in the visible or ultraviolet region. These photons are the key element in the propagation of the chain reaction that makes up the Geiger discharge. If one of these photons interacts by photoelectric absorption in some other region of the tube a new electron is liberated creating an avalanche at a different location in the tube. The arrival of these avalanches at the anode causes a drop in the potential between the central wire and the cylinder. This process gives rise to a very large pulse with amplitude independent of the type and energy of the incident radiation. The pulse is communicated to the amplifier through an appropriate RC circuit, and then to a counter which is called as Scalar. Suitable arrangements are made to measure the counts for a preset time interval. The schematic diagram of the GM tube and the associated electronic components is given below:

### Procedure:

1. Make sure to begin with all the knobs are at **minimum** position.
2. After familiarizing yourself with the counter and its operation, record the background count (~60 sec) as a function of applied voltage at which counting starts
3. Place the given  $\beta$  source in one of the slots provided in GM tube assembly and record the counts as a function of voltage.

- From the plot find the operating point by marking the central voltage of the plateau.
- Set the counter for above voltage and count time ~06 minutes. Record the counts by changing the distance between the source and the GM tube.
- Keep the position of the source fixed and record the count as a function of thickness of the absorber (Al). Thickness of the absorber can be increased by increasing the number of aluminum sheets.
- Find the absorption coefficient of Al for  $\beta$  rays from the above data.



**Fig. 3.1 Schematic of the GM tube and the associated electronics**

#### Questions?

- Can the GM tube used in the “proportional” or “avalanche” region?
- How do you know that the given source is a  $\beta$  source?

#### References:

- G. Knoll, *Radiation Detection and Measurement*, John Wiley, 1999.
- K. S. Krane, *Introductory Nuclear Physics*, John Wiley, 1988.
- R. R. Roy and B. P. Nigam, *Nuclear Physics: Theory and Experiment*, New Age, 1967.

**Experiment # 4: Magnetic susceptibility of a paramagnetic liquid**

### Objective:

To determine the magnetic susceptibility of a given paramagnetic liquid using Quinck's method.

### Theory

The bulk magnetic effects of materials are normally described in terms of the magnetization  $M$  which may be defined as the magnetic dipole moment per unit volume. For a paramagnetic material the magnetization  $M$  is induced by the applied field  $B$  and  $M$  is parallel to  $B$ .

The volume susceptibility is defined by the relations,

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

Where the magnetic intensity  $H$  is related to  $B$  through  $B = \mu_0 \mu_r H$

Since the relative permeability  $\mu_r \approx 1$ , the magnetization is given by,

$$M = (\mu_r - 1) \frac{B}{\mu_0} = \frac{\chi B}{\mu_0} \quad (2)$$

On atomic level, the force  $F$ , on a magnetic dipole of moment  $m$  due to an applied magnetic field  $B$  is

$$F = \nabla(m \cdot B) \quad (3)$$

Thus using equations (2) and (3), the force per unit volume experienced at a point in the liquid in the U-tube illustrated in the figure is given by

$$F_x = \chi \frac{B_z}{\mu_0} \cdot \frac{dB_z}{dx} \quad (4)$$

Now the pressure on the liquid in  $x$  direction can be calculated by integrating in  $x$  direction. This pressure is balanced by the liquid by raising the level in one of the arms. Suppose the change in the liquid level is  $h$ , susceptibility is given by,

$$\chi = \frac{2(\rho - \rho_a)gh}{\mu_0 H^2} \quad (5)$$

The susceptibility of the liquid now can be obtained by plotting  $h$  as a function of the  $H^2$ .  $\rho$  and  $\rho_a$  are densities of the liquid and air respectively and  $g$  is the gravitational acceleration.

$\frac{\chi}{\rho} \propto \text{max susceptibility}$

$$B = \mu_0 (M + 1) \quad (\text{SI})$$

$$B = H + 4\pi M \quad (\text{CGS})$$

$$\text{tesla} = 10^4 \text{ gauss}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2$$

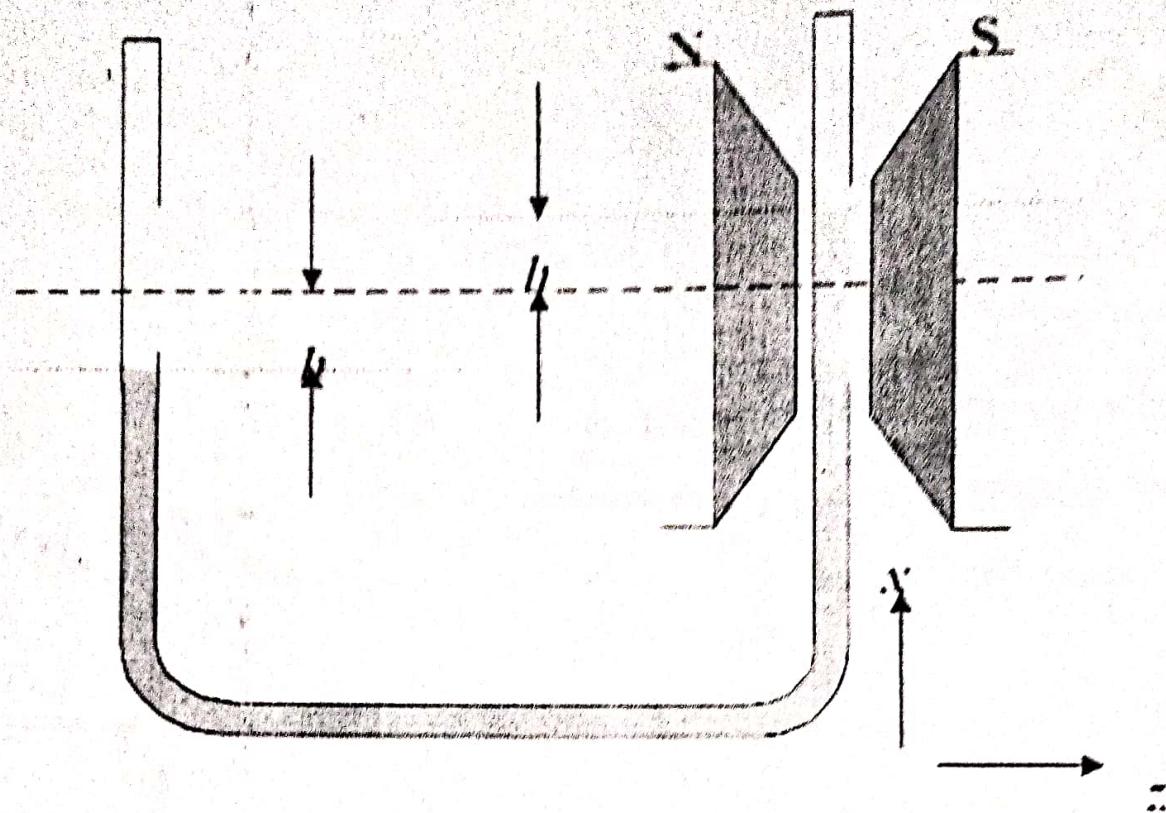


Fig. 4.1

**Procedure:**

1. Adjust the air-gap (~10mm) between the pole pieces of the electromagnet.
2. Measure the magnetic field in between the pole pieces of the electromagnet as a function of current through it with the help of the hall probe and gauss meter. Plot the calibration curve.
3. You will be given a master solution of  $\text{FeCl}_3$ .
4. Take ~ 10 ml of the given solution. Measure the density of the solution using specific gravity bottle. Fill the Quincke's tube with the solution and place the narrow limb of the tube between the pole pieces such that the solution level is at the center of pole pieces (or slightly lower).
5. Note the position of lower meniscus of the solution with a traveling microscope. Record the change in height of the liquid column as a function of magnetic field applied. Whenever the magnetic field is changed wait for few minutes before taking the observation.
6. Repeat steps 4 and 5 for 2 – 3 different concentrations of lower molarities by diluting the master solution with distill water.
7. Plot suitable graph and analyze the data to obtain the susceptibility of the liquid for various concentrations.

**Questions:**

1. Can you use the set-up for a diamagnetic liquid?

## Experiment # 5: Polarization of Light & Numerical aperture of Optical fibre

### Objective:

- (a) To study the change in the polarization state of light incident on a dielectric surface.
- (b) To determine the Brewster angle for a given glass plate.
- (c) To determine the numerical aperture (NA) of a given optical fiber.

### Part A & B : Theory

When an electromagnetic wave is incident upon the interface of two dielectric media, a part of the wave is reflected back and remaining part is transmitted through the medium. The magnitudes of reflected and transmitted waves for *s* and *p* polarization are governed by Fresnel's equations. Fresnel's equations for reflected electric field are

$$E_R^s = \left( \frac{n_1 \cos \theta_i - n_2 \cos \theta_r}{n_1 \cos \theta_i + n_2 \cos \theta_r} \right) E_i^s \quad (1)$$

$$E_R^p = \left( \frac{n_1 \cos \theta_r - n_2 \cos \theta_i}{n_1 \cos \theta_r + n_2 \cos \theta_i} \right) E_i^p \quad (2)$$

where  $E_i^s$ ,  $E_i^p$ ,  $E_R^s$  and  $E_R^p$  are the magnitudes of incident and reflected electric fields for *s* and *p* polarisation, respectively,  $\theta_i$  and  $\theta_r$  are the incident and transmitted angles and  $n_1$  and  $n_2$  are the refractive indices of two media. Thus the reflectivity for both the polarisation depends on the refractive index and angle of incidence. Reflectivity for *p* polarisation (eqn.2) becomes to zero at certain angle of incidence called Brewster's angle ( $\theta_B$ ) given by  $\tan \theta_B = n_2/n_1$ . This fact can be used to get a totally *s* polarised (reflected) beam of light from a randomly polarised (containing a mixture of *s* and *p* polarisation states) incident beam.

There is another way of converting a randomly polarised light into linearly polarized light. Suppose that you are given two polarising sheets (Polaroid). The light passing out of a polarizer is linearly polarized with the electric field  $E$  fixed in one direction in space as determined by the orientation of the polarizing sheet. If this light passes through a second polarizer (called an analyser), then the light output depends on the relative orientation of the two polarizers. If the pass plane of the second polarizer makes an angle  $\theta$  with respect to the electric field  $E$ , then the magnitude of the field in the output wave is proportional to  $\cos \theta$  and the output intensity is proportional to  $\cos^2 \theta$ . Malus' law gives the output intensity  $I$  of the light transmitted by the analyser, viz.,

$$I = I_0 \cos^2 \theta \quad (3)$$

where  $I_0$  is the intensity of the polarized light incident on the analyser.

#### Procedure:

The experiment set-up consists of a diode laser, a polarizer, an analyser, a glass slab acting as the dielectric medium and a photodiode. The analyser unit is fitted with a circular scale to record the angular readings. The photodiode is used to measure the intensity of light. All the components can be mounted on an optical bench for proper alignment.

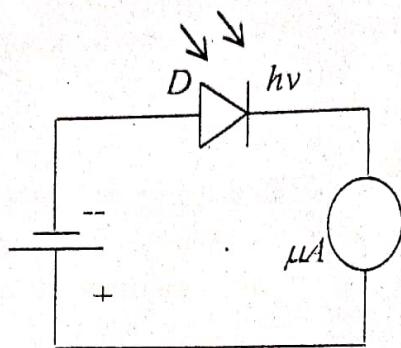


Fig. 5.1

#### Part A: Malus' Law

1. Assemble the photodiode circuit (reverse bias) in photoconductive mode as shown in Fig. 5.1. In this configuration the photocurrent will be directly proportional to the intensity of light falling on to it.
2. Align the light source, polarizer and analyzer so that the beam passes through both the polaroids and falls on to the detector. The plane of polaroids must be perpendicular to the beam.
3. Keeping the orientation of polarizer fixed and rotate the analyser in small angular steps and record the photocurrent current as a function of  $\theta$ . Use the data to verify Malus law and plot the same.

#### Part B: Measurement of Brewster's Angle

1. Place the glass slab placed on a horizontal rotating table and align it with the laser beam for normal incidence.
2. Record the intensity of reflected beam for the  $p$  polarisation components (the analyzer is to be set accordingly for this) for various angles of incidence. Plot the corresponding data to obtain the Brewster's angle.
3. Perform the necessary error analysis.

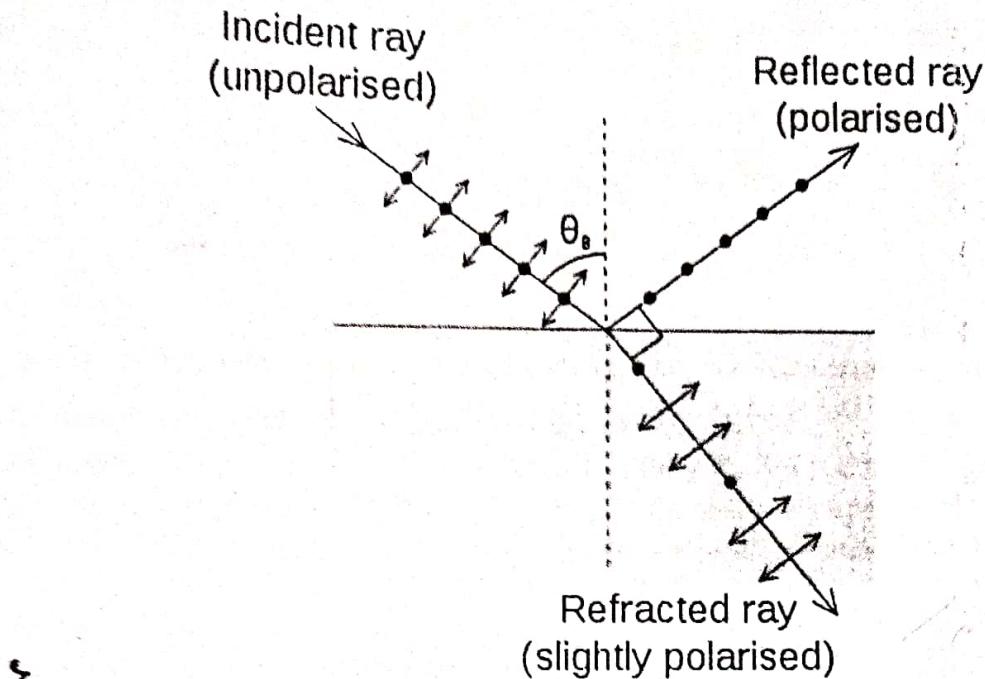


Fig. 5.2

#### Precautions:

1. Do not attempt to look at the LASER light (even scattered light). Ensure that your LASER beam avoids contact with others in the lab.
2. Subtract the contribution of stray light from each and every observation for both the parts.

#### Theory: PART C

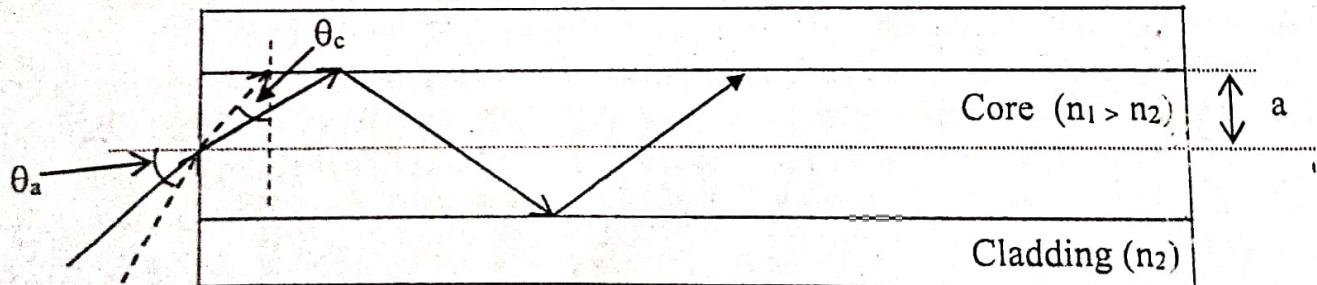


Fig. 5.3

Fig. 5.3 shows the schematic of an optical fiber. In its simplest form (e.g. step index fiber), it consists of a cylindrical central core region (of a glass/plastic material) of refractive index,  $n_1$ , cladded by a material of slightly lower refractive index,  $n_2$  ( $n_1 > n_2$ ). The refractive index distribution, in the transverse direction, is given by

$$n(r) = \begin{cases} n_1 & 0 < r < a \\ n_2 & r > a \end{cases} \quad \begin{matrix} \text{CORE} \\ \text{CLADDING} \end{matrix} \quad (1)$$

where,  $a$  is the radius of the core.

For a ray entering the fiber, if the angle of incidence at the core-cladding interface is greater than the critical angle  $\theta_c = [\sin^{-1}(n_2/n_1)]$ , then the ray will undergo total internal reflection. As the fiber possesses cylindrical symmetry, the ray gets guided through the core by repeated total internal reflection. While the ray entering at  $\theta_i < \theta_c$  will undergo partial reflection at the core cladding interface and with the repeated reflections will be lost.

### Numerical Aperture (NA):

Numerical Aperture, denoted by NA, of an optical fiber is an important parameter that determines the angle of the "light acceptance cone" at the input end of the fiber. Referring to the Figure 1, the dashed lines represent a ray which is incident at the core-cladding interface at the critical angle and  $\theta_a$  is the corresponding angle of incident at the entrance face of the fiber. The expression of  $\sin\theta_a$  is thus given by

$$\sin\theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \quad (2)$$

Thus, if a cone of light is incident on one end of the fiber, it will be guided through it provided the semi-angle of the cone is less than  $\theta_a$ . A ray of light incident on the core at an angle  $\theta \leq \theta_a$  undergoes total internal reflection at the core cladding interface and becomes the guided ray, while rays incident at angle  $\theta > \theta_a$  undergo only partial reflection at the core cladding interface and will eventually radiate completely into cladding. The quantity  $\sin\theta_a$  is known as the "Numerical Aperture (NA)" of the fiber and is a measure of the "light gathering power" of the fiber.

In a short length of straight fiber, ideally, a ray launched at an angle  $\theta$  at the input end should come out at the same angle from the output end provided the end faces are plane and cleaved perpendicular to the fiber axis. Therefore, the far field pattern at the output end will also appear as a cone of semi angle,  $\theta_a$  emanating from the fiber end. Thus  $\theta_a$  can be measured by recording far field on a plane perpendicular to the axis.

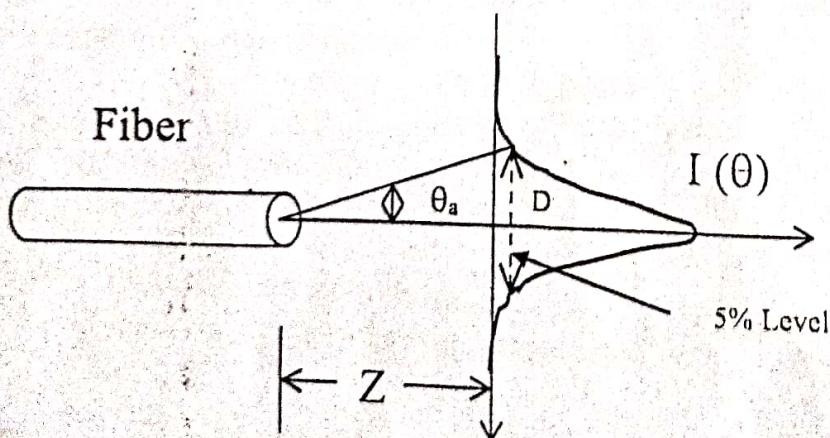


Fig. 5.4

The semi angle corresponding to 5% level of the far field intensity maximum is denoted as the acceptance angle. Since this angle is small ( $\sim 10^\circ$ ), one may carry out the measurements on the far field projected on a plane perpendicular to the fiber axis, and measure the diameter corresponding to 5% intensity level as shown in Fig. 5.4. The NA is then given by

$$NA = \sin^{-1} \left( \frac{D}{2z} \right)$$

#### Procedure:

1. Place the MO in front of the laser as shown in Fig. 5.5. Align the position of the MO so that back reflected spot nearly coincides with the output aperture of the laser and output beam is clear expanded beam coming out of the centre of the MO assembly.
2. Mount the fiber at the focus of the MO and do the finer adjustment with the help of positioning knobs so that beams come out from the other end with the maximum brightness.

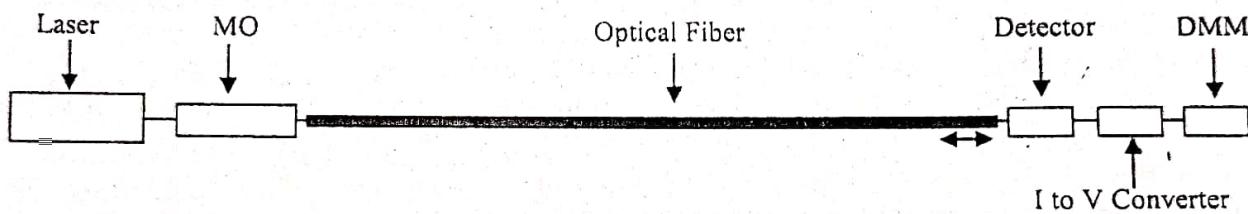


Fig. 5.5

3. Position the other photodiode with small sensor area to receive the output radiation.
4. Note down the Z position (say  $O_z$ ) of the output end of the fiber.
5. Scan the fiber far field pattern by moving the photodiode and record the intensity.
6. Plot the intensity and find the lateral distance,  $d_z$ , where intensity drops to 5% of the maximum (for a given  $O_z$ ).
7. Move the output end of the fiber by few mm in either of the directions shown by the double arrow and note down its position.
8. Repeat steps 4 and 5 for three different separations between the output end of the fiber and the detector.
9. Plot  $d_z$  vs  $O_z$ . Do a linear fitting. The slope of the straight line is  $\tan\theta_a$ .

#### Questions:

1. Can you perform Part B of the experiment using the light transmitted through the glass slab?
2. How will you verify whether the  $\theta_B$  obtained is correct?
3. Do you envisage any direct application of this experiment?
4. How does the diode LASER work? Compare it with a He-Ne LASER and try to understand its relative merits and demerits.

## Experiment # 6: Excitation energy of argon

### Objective:

To determine the first excitation energy of argon.

### Theory:

We know that the energy of an atom takes only discrete values. At the room temperature, most atoms are in ground state. An atom jumps to higher level by absorbing energy in many different ways, for example, interaction with electromagnetic radiation or collisions with other particles like electrons. In 1914, Frank and Hertz verified that the atoms absorb energy only in discrete values by bombarding atoms with low energy electrons. In this experiment, applying electric field accelerates electrons. If electrons have sufficient kinetic energy to excite atoms to the first excited state, then the collisions are inelastic. Otherwise, the collisions are elastic and the electrons do not lose kinetic energy (atoms are heavy). The schematic diagram of Frank-Hertz tube is shown in Fig. 6.1. The tube is filled with a gas of atoms under consideration. The electrons emitted by the cathode K are accelerated through potential  $V_{G2K}$ . The grid G1 helps in minimizing the space charge effects. The plate A is at a potential slightly negative with respect to G2. This helps in making the dips in the plate current more prominent.

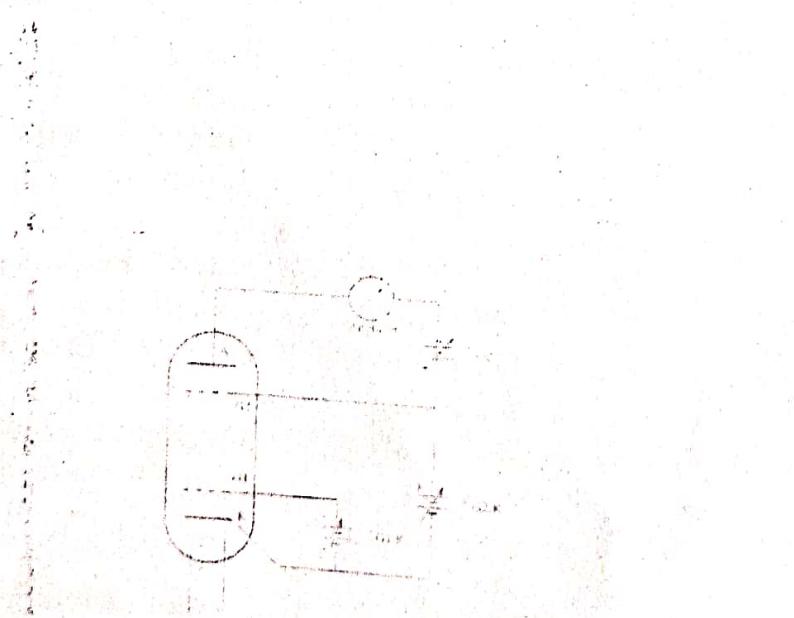
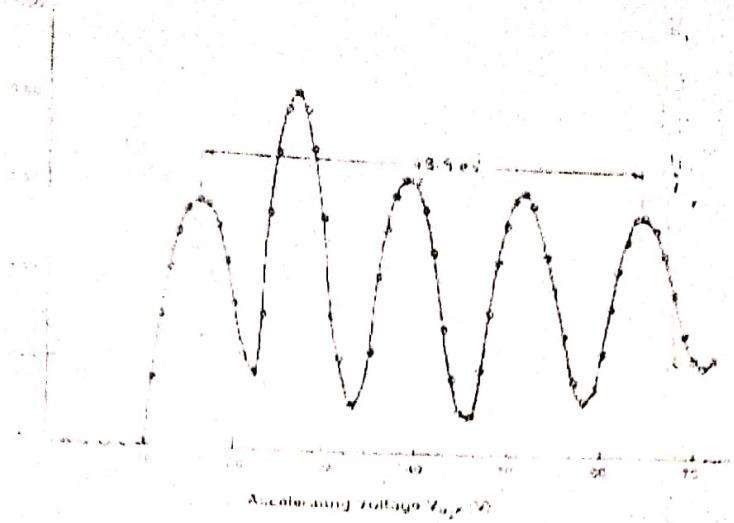


Fig. 6.1 Schematic Diagram of Frank-Hertz Experiment



**Fig. 6.2: Plot of anode current vs  $V_{G2,K}$**

As we increase  $V_{G2K}$ , the current through A increases. When the electron energies are just sufficient to excite atoms, they lose kinetic energy and cannot reach anode, resulting in the dip in the anode current. The elastic collisions occur near G2. If we increase  $V_{G2,K}$  further the current increases until the potential is such that an electron undergoes two collisions inelastic with the atoms. This results in the second dip in the anode current. The anode current vs  $V_{G2,K}$  graph is shown in the Fig. 6.2. The voltage difference between two successive peaks of anode current gives the excitation energy of the atom.

You have been provided with a Frank-Hertz tube filled with argon. You have to find the energy of an excited state. Table of first few levels is given below. Try to determine transitions that are possible in electron-Argon collision process.

Configuration	Term	J	Energy(eV)
$3p^6$	$^1S$	0	00.00
$3p^5(^2P_{3/2})4s$	$^2(3/2)$	2	11.54
		1	11.62
$3p^5(^2P_{1/2})4s$	$^2(1/2)$	0	11.72
		1	11.82
$3p^5(^2P_{3/2})4p$	$^2(1/2)$	1	12.90
		0	13.26

**Table: Energy levels of neutral Argon**

Typical operating parameters are given here.

Filament voltage	:	2.6V (minimum position)
$V_{G1,K}$	:	1.5 V
$V_{G2,A}$	:	7.5 V
$V_{G2,K}$	:	0-80 V
Current Multiplier	:	$10^{-7}$

1 3  
8 9  
—

#### Precautions:

1. Whenever you want to change any setting (including turning power ON/OFF switch), make sure  $V_{G2,K}$  is set to zero (minimum position).
2. If heating filament voltage is changed, allow 2/3 minutes before making any observation.
3. During the experiment, if voltage  $V_{G2,K}$  is over 60V, pay attention to the ammeter. If the current rises suddenly, decrease voltage at once.

#### Procedure:

1. Vary the accelerating potential ( $V_{G2,K}$ ) and record the anode current.
2. Plot I vs.  $V_{G2,K}$  and determine the energies of the excited states.

#### Questions?

1. Will the pressure inside the F-H tube matter?
2. Why are the second and third points in the precaution important?

## Experiment # 7: Magnetoresistance in semiconductors

### Objective:

To study the magnetic field dependence of the transverse magnetoresistance of a given semiconductor sample.

### Theory:

The magnetoresistance is defined as the ratio of change in resistance of a substance due to application of magnetic field to its resistance in zero field. Under the influence of a magnetic field, the electrons in a solid material do not follow the exact direction of superimposed electric field, instead take a curved path. This results in effective decrease of the mean free path and hence an increase in the resistivity of the sample. When magnetic field is applied normal to the current flow, the effect is termed as transverse magnetoresistance and when field is applied parallel to the current flow, it is termed as longitudinal magnetoresistance.

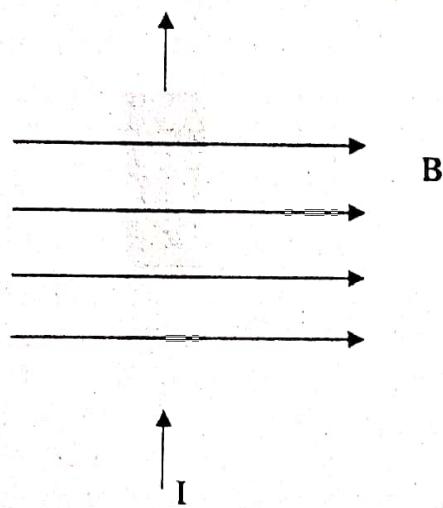


Fig. 7.1

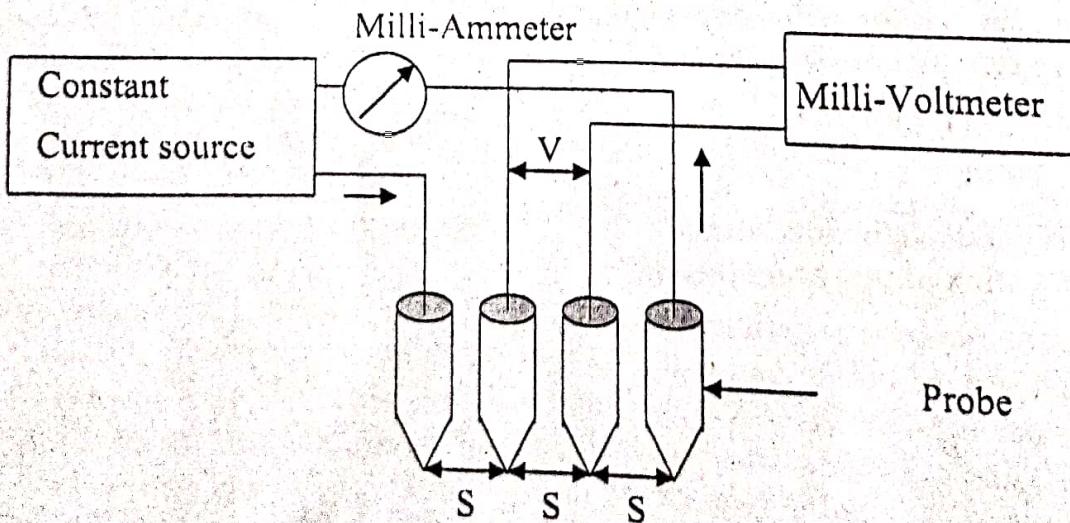


Fig. 7.2

For small field we can write transverse magnetoresistance as

$$\frac{\Delta\rho}{\rho_0} = \frac{\rho - \rho_0}{\rho_0} \propto H^2 \text{ or} \quad (1)$$

$$\frac{\Delta R}{R_0} \propto H^2$$

where  $\rho_0$  is resistivity of the material in zero field,  $\rho$  is resistivity in a magnetic field  $H$ . Similarly  $R_0$  and  $R$  represent corresponding resistances. However, in higher field the dependence is quite often linear. In case of longitudinal magnetoresistance, the Eq. (1) holds except that the constant of proportionality between  $\Delta R / R_0$  and  $H^2$  is much smaller than that of the transverse case. Fig. 7.1 shows the schematic of the setup and Fig. 7.2 shows the four probe configuration similar to four probe measurement set up used by you in previous semester.

#### Procedure:

1. Adjust the air-gap (10 mm) between the pole pieces of the electromagnet (EMU-50)
2. Measure the magnetic field in between the pole pieces of the electromagnet as a function of current through it with the help of the hall probe and gauss meter. Plot the calibration curve.
3. Place the sample in between the pole pieces of the magnet such that magnetic field is perpendicular to the direction of the current.
4. Outer two probes are to be used for passing current and inner two probes for the voltage measurement.
5. Measure the resistance  $R_0$  without any magnetic field by recording the voltage drop as a function of current.
6. Measure the resistance  $R$  for different magnetic fields.
7. Repeat the above step by reversing the direction of current.
8. Verify Eq. (1) by suitable plots.

#### Questions?

1. Can all materials have magnetoresistance?
2. What is the application of this phenomenon?

## Experiment # 8: Curie Temperature Measurement of Ferroelectric crystal

### Objective:

To measure the Curie temperature of a given Ferroelectric Material.

### Theory:

Ferroelectric materials exhibit electric dipole moment even in the absence of an external electric field. Ferroelectric materials are of theoretical and technical interest as they have unusually high and unusual temperature dependent values of the dielectric constant, the piezoelectric effects etc. Ferro electricity usually disappears above a certain temperature called the transition (or Curie) temperature. Knowledge of the Curie temperature and the variation of the dielectric constant below and above the Curie temperature is of interest to the physicists and the engineers.

Probably the best known ferroelectric material is Barium Titanate  $\text{BaTiO}_3$ . It is a representative of the so called oxygen octahedron group of ferroelectric materials. The reason for this name is that above the Curie temperature ( $\theta = 120^\circ\text{C}$ ),  $\text{BaTiO}_3$  corresponds to the cubic structure presented in Fig.8.1. In this structure, the  $\text{Ba}^{2+}$  ions occupy the corners of a cube. The centers of the cube faces are occupied by  $\text{O}^{2-}$  ions. The oxygen ions form an octahedron, at the center of which the small  $\text{Ti}^{4+}$  ion is located.

The  $\text{Ti}^{4+}$  ion is considerably smaller than the space, which is available inside the oxygen octahedron. It thus brings with it a high ionic polarizability for two reasons: (a) It has a charge of  $4e$  and, (b) It can be displaced

over a relatively large distance. This may be the explanation for the occurrence of spontaneous polarization in  $\text{BaTiO}_3$ . There is an intimate relationship between the ferroelectric properties and the atomic arrangement in ferroelectric materials. Above  $120^\circ\text{C}$ ,  $\text{BaTiO}_3$  has the cubic structure indicated in Fig.8.1. When the temperature is lowered through the critical temperature of  $120^\circ\text{C}$ , the material becomes spontaneously polarized and at the same time the structure changes. The direction of spontaneously polarization may lie along any of the cube edges, giving total 6 possible directions for the spontaneous polarization. Along the direction of spontaneous polarization of a given domain, the material expands, whereas perpendicular to the polarization

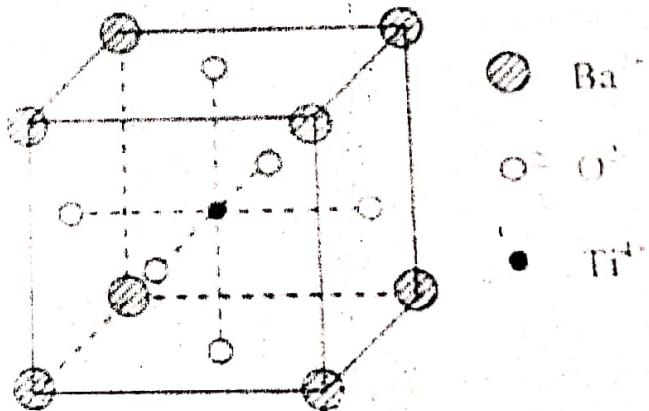


Figure 8.1: Structure of the lattice

direction it contracts. Thus, the material is no longer cubic but corresponds to a so-called tetragonal structure.

### Experimental Description

- Digital Voltmeter (DVM) to measure the voltage across the dielectric cell(DC) or standard capacitor(SC).
- Switch S1 to select di-electric cell or standard capacitor.
- Switch S2 to select one of the standard capacitors SC1, SC2 or SC3.

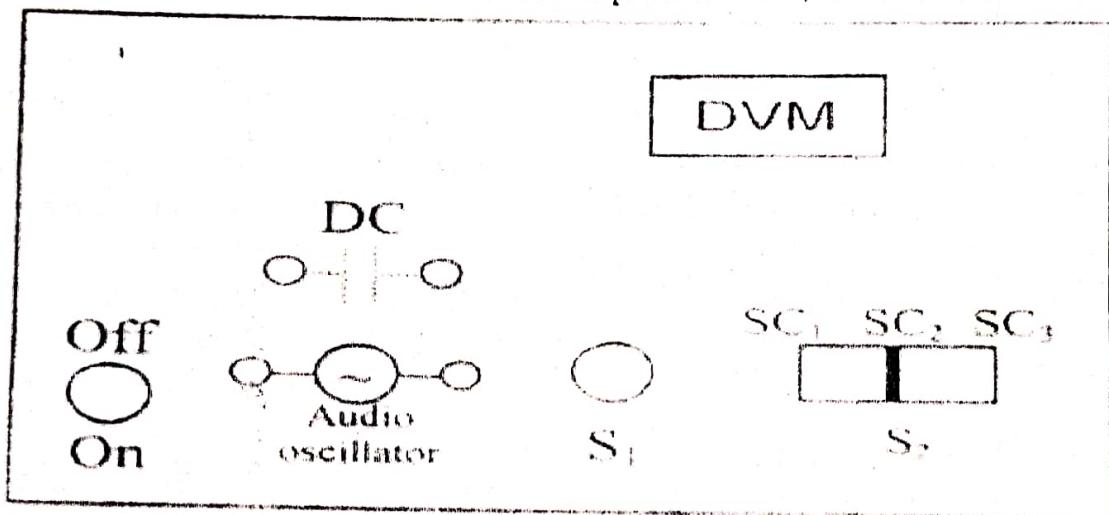


Figure 8.2: Experimental setup

### Dielectric Cell

Dielectric cell consists of two 1 cm dia, Gold plated brass discs fitted in between the cell holder (Teflon plates). Keep the ferroelectric sample in between the metal plates and tighten the three screws such that sample fits in between the metal plates without any air gap.

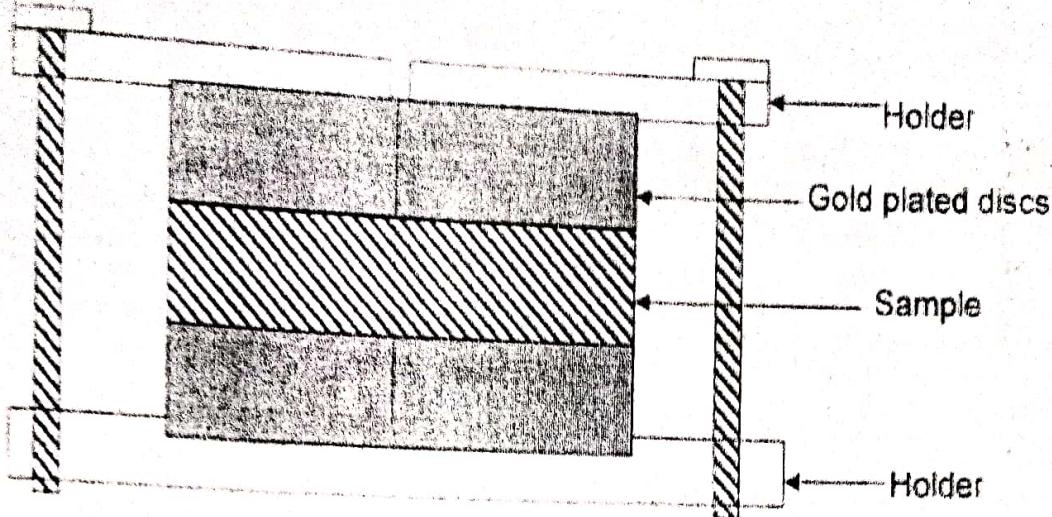


Figure 8.3: Dielectric cell schematic.

**IMPORTANT:** Dielectric cell (metal discs) and sample should be coaxial. Do not apply extra pressure on screws as that may damage the sample.

### Formulation

In this experiment a LC circuit is used to determine the capacitance of the dielectric cell and hence the dielectric constant. The circuit details are shown below:

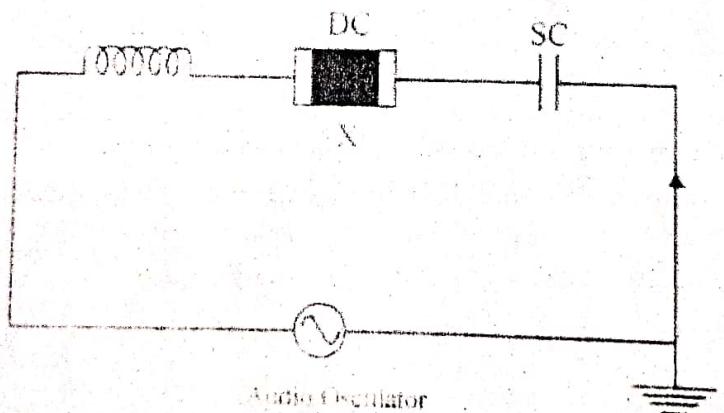


Figure 8.4: Schematic of the experiment ; DC: Dielectric cell,SC: Standard capacitor,L: Inductance,X: Ferroelectric sample

The dielectric cell DC is placed in a tubular furnace, which is fed by a variable ac

power supply. By changing the voltage the voltage applied to the furnace, the temperature of the furnace can be varied. The temperature of the furnace can be measured by inserting a thermocouple in a hole (provided on one of the Teflon discs), so that it touches one of the capacitor (metal) plates.

The audio oscillator is incorporated inside the instrument. If  $C_{SC}$  and  $C_{DC}$  represents the capacitances of the standard capacitor and dielectric cell respectively and if  $V_{C1}$  and  $V_C$  are the voltages across SC and DC then,

$$\frac{V_{SC}}{I} = \frac{1}{\omega C_{SC}} \text{ or } I = \omega C_{SC} V_{SC} \quad (1)$$

The same current I passes through the dielectric cell.

$$\frac{V_{DC}}{I} = \frac{1}{\omega C_{DC}} \text{ or } C_{DC} = \frac{I}{\omega V_{DC}} = \frac{\omega C_{SC} V_{SC}}{\omega V_{DC}} = \frac{C_{SC} V_{SC}}{V_{DC}} \quad (1)$$

By measuring  $V_{SC}$  &  $V_{DC}$  and using the value of  $C_{SC}$  we can determine the capacitance of the dielectric cell containing the sample.

If  $C_0$  represents the capacitance of the dielectric cell without the crystal and the plates separated by air gap whose thickness is the same as the thickness of the crystal then  $C_0$  is given by

$$C_0 = \frac{\epsilon_0 A}{d} = \frac{r^2}{36d} nf$$

where  $r$  represents the radius of the crystal and  $d$  represents its thickness. The dielectric constant of the crystal at any given temperature is given by

$$\epsilon_r = \frac{C}{C_0}$$

### Calibration

- Connect C.R.O. to the terminals provided on the front panel.
- Switch ON the unit and adjust CAL. such that sinusoidal waveform appears on C.R.O.

Adjust the CAL. such that amplitude of the sine wave is just before the clipping.

- Switch OFF the unit and disconnect C.R.O. from the main circuit.

### Procedure:

1. Connect C.R.O. to the terminals provided on the front panel. If no sinusoidal waveform appears on C.R.O. then follow calibration procedure first.
2. Assemble the dielectric capacitor as shown in figure 8.3 and connect it to the main unit.(For convenience we have the assembled dielectric cell.)
3. Connect hot air oven to the mains.
4. Place the dielectric cell DC in hot air oven and place the lid on the top. Insert the thermocouple to the hole provided on top Teflon disc of DC via hole provided on the

- insulating disc. Make sure that thermocouple touches the top metal disc.
5. Switch ON the unit.
6. Select SC1 among standard capacitors.
7. Measure the voltage (using digital voltmeter provided on front panel) across the dielectric cell DC, say  $V_{DC}$ , by throwing switch S1 towards SC, while heater is switched off (i.e. at room temperature).
8. Determine the dielectric constant of the crystal using the relation.

$$\varepsilon_r = \frac{C}{C_0} = \frac{C_{SC} V_{SC}}{V_{DG} C_0}$$

where  $C_0$  is calculated using relation Eq.(8.5).

9. Switch ON the oven and set the desired temperature (Follow instructions to set the temperature of the oven). Measure voltages  $V_{DC}$  and  $V_{SC}$  (as explained in step 8) at different temperatures at  $15^{\circ}C$  interval in the range  $60^{\circ}C - 100^{\circ}C$ .  
**NOTE:** Readings in  $V_{DC}$

**NOTE:** Readings should be taken in ascending order only.

10. Measure  $V_{DC}$  and  $V_{SC}$  at 5-10°C interval upto 170°C and at intervals of 2°C until you reach the maximum value of the dielectric constant (or C). Thereafter take few points.  
*NOTE: Choose a low voltage.*

**NOTE:** Choose standard capacitor SC1 For temperature upto  $130^{\circ}\text{C}$  and SC2 for temperature range  $130^{\circ}\text{C}$  to  $190^{\circ}\text{C}$  and SC3 for  $190^{\circ}\text{C}$  onwards.

**IMPORTANT: DO NOT INCREASE THE TEMPERATURE OF OVEN BEYOND 225°C AS IT MAY DAMAGE THE TEFLON DISCS/SCREWS.**

11. Make the observation table as shown below:

12. Calculate the dielectric constant (as explained in step 10).

13. Draw a graph of  $\epsilon_r$  vs  $T$ . At the transition the dielectric constant sharply rises and falls suddenly after the transition temperature and then decreases slowly beyond the transition temperature.

Fig. 8.5 shows the variations of dielectric constant of BaTiO<sub>3</sub> ceramic as a function of temperature (After W.B. Westphal, Laboratory for Insulation Research, M.I.T.). An

examination of Fig. 8.5 shows that it is difficult to make measurements at the Curie temperature due to sharp variation. Extension of the curves below and above the transition temperature allows one to estimate the Curie temperature.

14. Determine the transition temperature (Curie Temperature) from the graph.

*NOTE: As the measurements are repeated the nature of the curve remains same but it might not be possible to get the same values.*

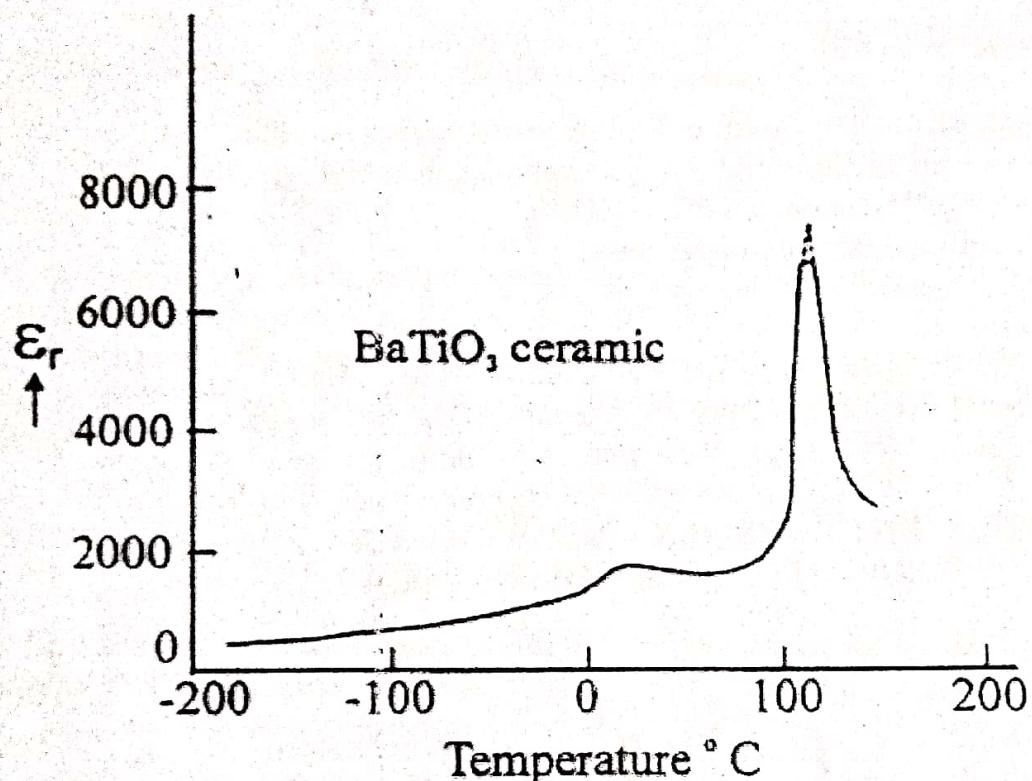


Figure 8.5: Variation of susceptibility with temperature

Component Values (S.No.1112 855)

L = 25mH

SC1 = 10.38nf

SC2 = 22.32nf

SC3 = 47.80nf

#### INSTRUCTIONS TO SET THE DESIRED TEMPERATURE OF OVEN( RT-210°C )

Note: Upper display (in red) shows current temperature reading and lower display (in green) shows set temperature.

1. Press up key (left most key on the controller cum indicator panel) or down key (middle key) to set the desired temperature.
2. Press enter (right most key) and hold for 1-2 sec.

*Note:*

*If after setting of desired temperature, enter key is not held for some time, it will go back to previous set value.*

*If thermocouple is not connected to the unit, upper display will show open.*

**IMPORTANT: DO NOT CHANGE THE SETTING PARAMETERS OF CONTROLLER CUM INDICATOR.**