Frequency and temperature dependence of the dielectric constant

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This experiment primarily deals with the study of the phenomena of Hall effect and magneto-resistance in semiconductors. First we explore the Drude model to lay down the foundation for the concepts and origin of Hall voltage and magneto-resistance and then using the well-known instrumentation like the four-probe, we establish various results. We determine the Hall coefficients of Bi, p-Ge and n-Ge and its relation to carrier density and carrier mobility, which are also determined for Bi. The unusual case of Bi is especially studied theoretically and experimentally. Then the magneto-resistance of Bi and n-Ge is determined and several plots are studied and results are drawn regarding them.

Is it right to probe so deeply into Nature's secrets? The question must here be raised whether it will benefit mankind, or whether the knowledge will be harmful.

Pierre Curie

I. INTRODUCTION

In electromagnetism, a dielectric (or dielectric material or dielectric medium) is an electrical insulator that can be polarised by an applied electric field. When a dielectric material is placed in an electric field, electric charges do not flow through the material as they do in an electrical conductor, because they have no loosely bound, or free, electrons that may drift through the material, but instead they shift, only slightly, from their average equilibrium positions, causing dielectric polarisation. Because of dielectric polarisation, positive charges are displaced in the direction of the field and negative charges shift in the direction opposite to the field (for example, if the field is moving parallel to the positive x axis, the negative charges will shift in the negative x direction). This creates an internal electric field that reduces the overall field within the dielectric itself. If a dielectric is composed of weakly bonded molecules, those molecules not only become polarised, but also reorient so that their symmetry axes align to the field. The study of dielectric properties concerns storage and dissipation of electric and magnetic energy in materials.

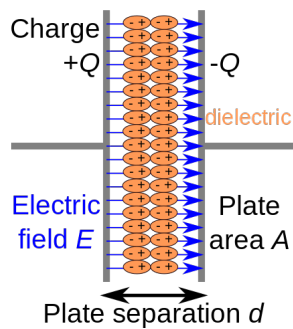The absolute permittivity, often simply called permittivity
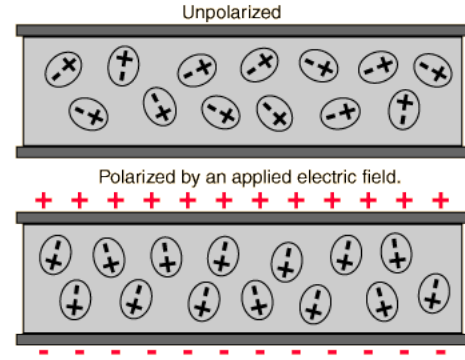

FIG. 1. A polarised dielectric material

FIG. 2. A dielectric medium showing orientation of charged particles creating polarization effects. Such a medium can have a lower ratio of electric flux to charge (more permittivity) than empty space

(ε) is a measure of the electric polarizability of a dielectric. A material with high permittivity polarizes more in response to an applied electric field than a material with low permittivity, thereby storing more energy in the material.

In the simplest case, the electric displacement field $\mathbf{D}$ resulting from an applied electric field $\mathbf{E}$ is

$$\mathbf{D} = \varepsilon \mathbf{E} \tag{1}$$

More generally, the permittivity is a thermodynamic function of state. It can depend on the frequency, magnitude, and direction of the applied field. In this experiment we will study the variation of this permittivity or dielectric constant with frequency and temperature.

II. AIM

The primary aim of this experiment is the study of frequency dependence of dielectric constant and ferroelectric to paraelectric phase transition of $BaTiO_3$ by study of dielectric constant as a function of temperature and frequency.
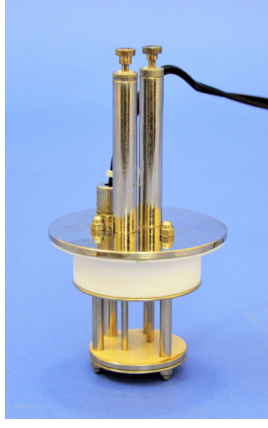
FIG. 3. Dielectric Constant Arrangement

FIG. 4. Panel Diagram of the Unit

III. APPARATUS

The apparatus used throughout the experiment is:

1. Probe arrangement: As shown in figure (3), it has two spring loaded probes. These probes move in pipes and are insulated by Teflon bush, which ensure a good electrical insulation. The probe arrangement is mounted in suitable stand, which also hold the sample plate and RTD sensor. The RTD is mounted in the sample plates such that it is just below the sample, separated by a very thin sheet of mica. This ensures the correct measurement of sample temperature. This stand also serves as a lid of the oven. The leads are provided for the connection to RTD and capacitance meter,

2. Barium titanate ($BaTiO_3$) plate with top and bottom conducting surface,

3. Standard Multilayer Ceramic Capacitor,

4. Disc Ceramic Capacitor,

5. Main experimental setup unit

6. Oscilloscope

The set-up consists of the main unit (figure (4)) for the measurement of capacitance at different frequencies from $1\,kHz$ to $50\,kHz$. This is done with the help of a Schering Bridge and a built-in oscillator. The basic bridge structure is shown in figure (5).

Here, C_1 is the unknown capacitance ($BaTiO_3$) whose value is to be determined with series electrical resistance R_1. C_2 is a standard silver mica capacitor of $1000\,pF$. C_4 is a variable capacitor divided in two levels – Coarse and Fine. Coarse variation is divided in 3 steps and correspondingly Fine variation in further 8 steps. R_3 is a metal film resistance of $3.0\,k\Omega$. R_4 is a variable resistance, *coarse* 0, 1k, 2k, 3k (selectable) in series with *fine* 1k/10T potentiometer, connected in parallel with C_4.
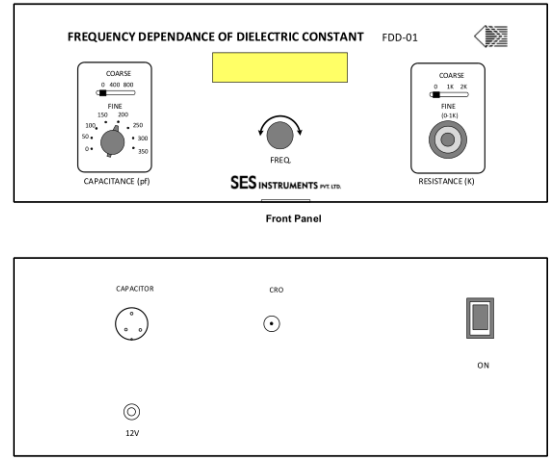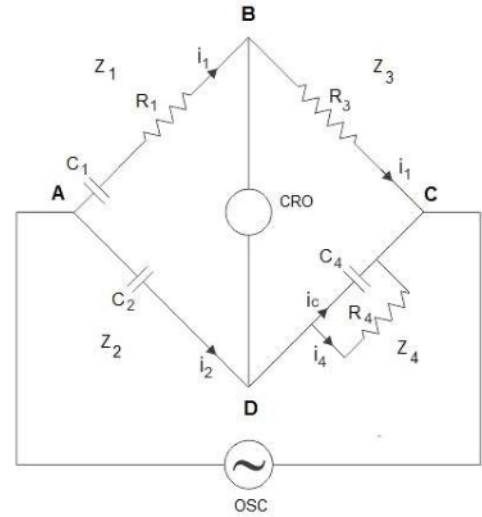

FIG. 5. Schering Bridge for Capacitance Measurement

IV. THEORY

In the classical approach to the dielectric, the material is made up of atoms. Each atom consists of a cloud of negative charge (electrons) bound to and surrounding a positive point charge at its center. In the presence of an electric field, the charge cloud is distorted, as shown in figure (6).

This can be reduced to a simple dipole using the superposition principle. A dipole is characterised by its dipole moment, a vector quantity shown in the figure as the blue arrow labeled M. It is the relationship between the electric field and the dipole moment that gives rise to the behaviour of the dielectric.
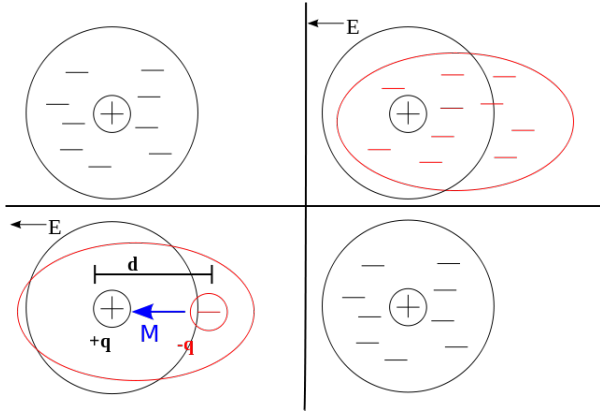
FIG. 6. Electric field interaction with an atom under the classical dielectric model

FIG. 7. Real and imaginary part of permittivity (dielectric constant) as function of frequency

A. Complex Permittivity

As opposed to the response of a vacuum, the response of normal materials to external fields generally depends on the frequency of the field. This frequency dependence reflects the fact that a material's polarization does not change instantaneously when an electric field is applied. The response must always be causal (arising after the applied field), which can be represented by a phase difference. For this reason, permittivity is often treated as a complex function of the (angular) frequency ω of the applied field:

$$\varepsilon \to \hat{\varepsilon}(\omega) \quad (2)$$

(since complex numbers allow specification of magnitude and phase). The definition of permittivity therefore becomes

$$D_0 e^{-i\omega t} = \hat{\varepsilon}(\omega) E_0 e^{-i\omega t} \quad (3)$$

where D_0 and E_0 are the amplitudes of the displacement and electric fields, respectively.

At the plasma frequency and below, dielectrics behave as ideal metals, with electron gas behavior. The static permittivity is a good approximation for alternating fields of low frequencies, and as the frequency increases a measurable phase difference δ emerges between $\mathbf{D}$ and $\mathbf{E}$. The frequency at which the phase shift becomes noticeable depends on temperature and the details of the medium. For moderate field strength (E_0), $\mathbf{D}$ and $\mathbf{E}$ remain proportional, and

$$\hat{\varepsilon} = \frac{D_0}{E_0} = |\varepsilon| e^{-i\delta} \quad (4)$$

Since the response of materials to alternating fields is characterized by a complex permittivity, it is natural to separate its real and imaginary parts, which is done by convention in the following way:

$$\hat{\varepsilon}(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) = \left|\frac{D_0}{E_0}\right| (\cos\delta - i\sin\delta) \quad (5)$$

where ε' is the real part of the permittivity, ε'' is the imaginary part of the permittivity and δ is the loss angle.
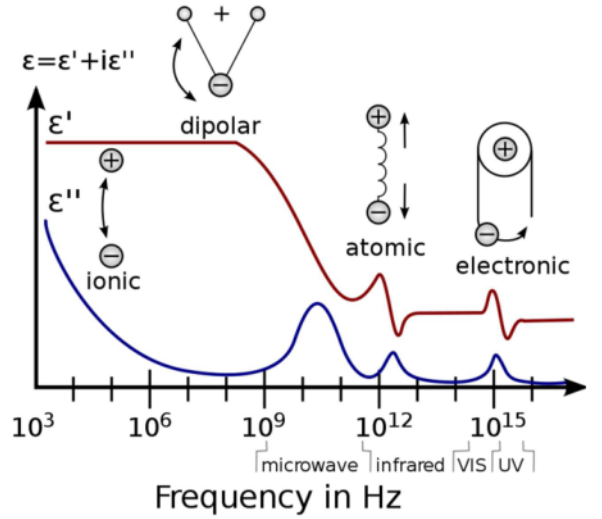
B. Dielectric Polarization

Real part of permittivity depends on the polarizability. The total polarizability may usually be separated into three parts or four parts (when interfaces are involved): electronic, ionic (or atomic), dipolar (or orientation) and space charge. Each dielectric mechanism effect has a characteristic relaxation frequency. As the frequency becomes larger, the slower mechanisms drop off. This in turn leaves only the faster mechanisms to contribute to the dielectric storage or real part. The dielectric loss (imaginary part) will correspondingly peak at each critical frequency.

Electronic polarization occurs in neutral atoms when an electric field displaces the nucleus with respect to the electrons that surround it. Atomic polarization occurs when neighboring positive and negative ions *stretch* under an applied electric field. Both electronic and atomic polarization create induced moments depending on the polarizability of the atoms or molecules. A permanent dipole moment is caused by unbalanced sharing of electrons by atoms of a molecule. In an absence of an external electric field, these moments are oriented in a random order such that no net polarization is present. Under an external electric field, the dipoles rotate to align with the electric field causing orientation polarization to occur. The ionic polarization is composed of ionic conductivity and interfacial or space charge polarization. At low frequencies ionic conduction is the most prevalent mechanism. Ionic conduction only introduces losses into a system. Space charge polarization occurs when more than one material component is present or when segregation occurs in a material containing incompatible chemical sequences and when translating charge carriers become trapped at the interfaces of these heterogeneous systems. The electric field distortion caused by the accumulation of these charges increases the overall capacitance of a material which appears as an increase in real part
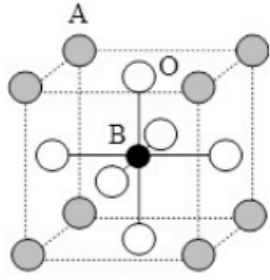
FIG. 8. Perovskite ABO_3 structure with the A and B cations on the corner and body centre positions, respectively. Three oxygen anions per unit cell occupy the faces and form octahedra surrounding the B-site.

FIG. 9. Perovskite structure (Ba: Grey; Ti: Black; O: White)

of dielectric constant.

The dielectric permittivity at optical frequencies arises almost entirely from the electronic polarizability.

C. Dielectric Heating

Both real and imaginary part are important for applications. For example, in the microwave heating, the dielectric constant (ε') represents a measure of the ability of a material to be polarized by an external electric field (as that of microwaves) storing energy within it. On the other hand, the dielectric loss factor (ε'') represents the ability of the material to dissipate the absorbed electromagnetic energy, converting it into heat. The higher the dissipation capacity for a sample the lesser will be the penetration of microwaves into the same sample. Thus, the ratio ($\varepsilon''/\varepsilon'$) suggests the capability of each material to convert electromagnetic energy (microwaves) into heat at specific temperatures and frequencies.

The loss factor is defined as

$$\tan \delta = \frac{\varepsilon'_r}{\varepsilon''_r} \qquad (6)$$

D. Barium titanate

Barium titanate has a very large room temperature dielectric constant. It has perovskite structure. Perovskite is a family name of a group of materials and the mineral name of calcium titanate ($CaTiO_3$) having a structure of the type ABO_3. Many piezoelectric (including ferroelectric) ceramics such as Barium titanate ($BaTiO_3$), Lead titanate ($PbTiO_3$), Potassium niobate ($KNbO_3$) etc. have a cubic perovskite type structure (in the paraelectric state) with chemical formula ABO_3 (figures (8), (9)).

As conventionally drawn, A-site cations occupy the corners of a cube, while B-site cations sit at the body centre. Three oxygen atoms per unit cell rest on the faces. The lattice constant of these perovskite is always close to the 4 Å due to rigidity of the oxygen octahedral network and the well-defined oxygen ionic radius of 1.35 Å.
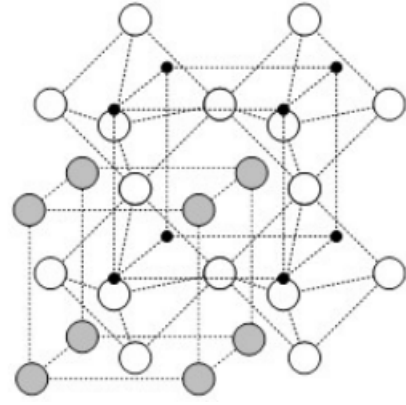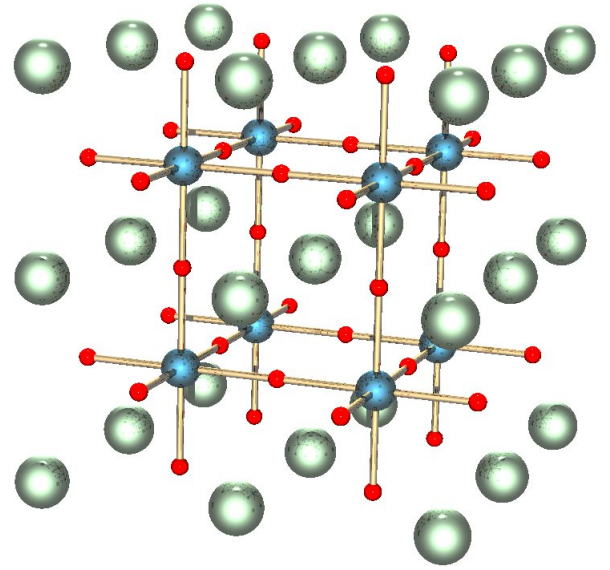

FIG. 10. Structure of cubic $BaTiO_3$. The red spheres are oxide centres, blue are Ti^{4+} cations, and the green spheres are Ba^{2+}

A practical advantage of the perovskites structure is that many different cations can be substituted on both the A and B sites without drastically changing the overall structure. Complete solid solutions are easily formed between many cations, often across the entire range of composition. Even though two cations are compatible in solution, their behaviour can be radically different when apart from each other. Thus, it is possible to manipulate a material's properties such as Curie Temperature or dielectric constant with only a small substitution of a given caution.

Barium Titanate ($BaTiO_3$) has a ferroelectric tetragonal phase below its curie point of about 120 °C and paraelectric cubic phase above Curie point. The temperature of the Curie point appreciably depends on the impurities present in the sample and the synthesis process.

In the paraelectric cubic phase the centre of positive charges (Ba^{2+}, Ti^{4+}) coincide with the centre of negative charges (O^{2-} ion) and on cooling below T_C, a tetragonal phase develops
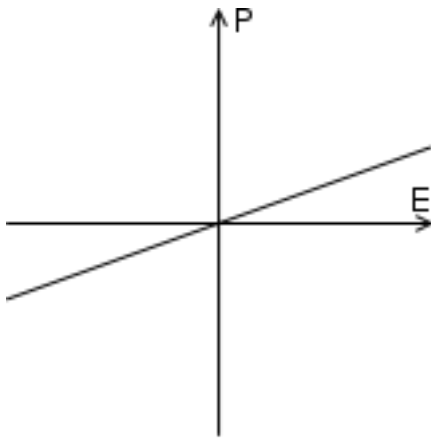
FIG. 11. Linear dielectric polarization

FIG. 12. Paraelectric polarization

where the centre of Ba^{2+} and Ti^{4+} ions are displaced relative to the O^{2-} ions, leading to the formation of electric dipoles.

As the barium titanate ceramics have a very large room temperature dielectric constant, they are mainly used in multilayer capacitor applications. The grain size control of these polycrystalline sample used in the experiment is very important for these applications.

E. Ferroelectricity, Paraelectricity and Curie Temperature

Ferroelectricity is a characteristic of certain materials that have a spontaneous electric polarization that can be reversed by the application of an external electric field. All ferroelectrics are pyroelectric[1], with the additional property that their natural electrical polarization is reversible. The term is used in analogy to ferromagnetism, in which a material exhibits a permanent magnetic moment. Ferromagnetism was already known when ferroelectricity was discovered in 1920 in Rochelle salt by Valasek.

When most materials are electrically polarized, the polarization induced, P, is almost exactly proportional to the applied external electric field E; so the polarization is a linear function. This is called linear dielectric polarization (figure (11)). Some materials, known as paraelectric materials, show a more enhanced nonlinear polarization (figure (12)). The electric permittivity, corresponding to the slope of the polarization curve, is not constant as in linear dielectrics but is a function of the external electric field.

In addition to being nonlinear, ferroelectric materials demonstrate a spontaneous nonzero polarization (figure (13)) even when the applied field E is zero. The distinguishing feature of ferroelectrics is that the spontaneous polarization can be reversed by a suitably strong applied electric field in the opposite direction; the polarization is therefore dependent not only on the current electric field but also on its history, yielding a hysteresis loop. They are called ferroelectrics by analogy to ferromagnetic materials, which have spontaneous magnetization and exhibit similar hysteresis loops.

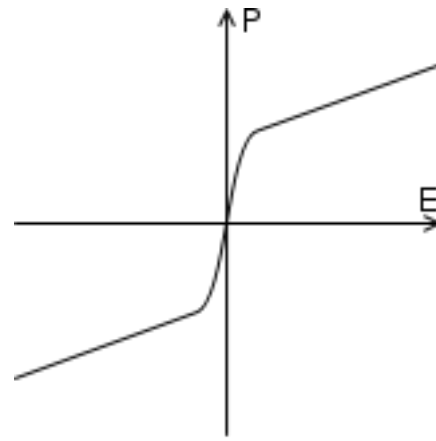Typically, materials demonstrate ferroelectricity only below

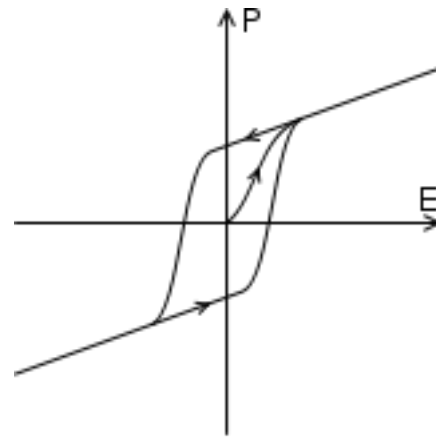
FIG. 13. Ferroelectric polarization

a certain phase transition temperature, called the Curie temperature (T_C) and are paraelectric above this temperature: the spontaneous polarization vanishes, and the ferroelectric crystal transforms into the paraelectric state. Many ferroelectrics lose their pyroelectric properties above T_C completely, because their paraelectric phase has a centrosymmetric crystal structure.

The Curie temperature is named after Pierre Curie, who showed that magnetism was lost at a critical temperature.

F. The Schering Bridge

This circuit component is a important part of the experiment. Figure (14) shows the configuration of the Schering Bridge where C_1 is the unknown capacitance with series electrical resistance R_1, C_2 is a standard capacitor, C_4 is a variable capacitor, R_3 is a pure resistor (i.e. non inductive in nature), and, R_4 is a variable non inductive resistor connected in parallel with variable capacitor C_4. Now the supply is given to the bridge between the points A and C, and the detector (Oscilloscope) is connected between B and D. In the balance condition the Oscilloscope shows zero signal, i.e., there is no potential
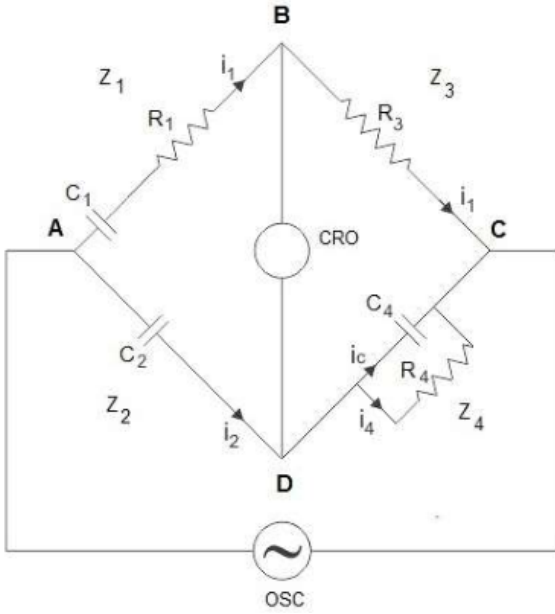
FIG. 14. The Schering Bridge

TABLE I. Variation of unknown capacitance as a function of frequency for multi-layer ceramic capacitor (MLCC)

Frequency f (kHz)	C_4 (pF)	R_4 (Ω)	C_1 (pF)
1	500	1780	593.33
3	600	1764	588.00
5	600	1758	586.00
7	600	1762	587.33
10	600	1738	579.33
15	600	1742	580.67
20	600	1710	570.00
25	600	1714	571.33
30	600	1664	554.67
35	600	1658	552.67
40	600	1626	542.00
50	600	1580	526.67

difference between points B and D. This implies the balance equation as,

$$Z_1/Z_3 = Z_2/Z_4 \qquad (7)$$

From here, upon solving the equations in terms of impedance and resistances and comparing the real and imaginary parts we get

$$R_1 = \frac{R_3 C_4}{C_2} \qquad (8)$$

and

$$C_1 = \frac{R_4 C_2}{R_3} \qquad (9)$$

The unknown capacitor and its equivalent series resistance may therefore be computed from the above equation.

The equivalent series resistance or ESR of a capacitor act like any other resistor giving rise to voltage drops and energy dissipated as heat. Although the ESR figure of a capacitor is mentioned more often, dissipation factor and loss tangent are also widely used and closely associated with the capacitor ESR. When a sinusoidal alternating voltage is applied to an ideal capacitor, the current leads by $\pi/2$ in phase. In the case of a practical capacitor, however, advance in phase is $(\pi/2 - \delta)$, which is smaller than $\pi/2$. δ is referred to as the *loss angle*.

V. OBSERVATIONS

Following preliminary observations for BaTiO$_3$ were made: diameter, $d = 10.65$ mm and thickness, $t = 2.24$ mm. This

implies area of the sample is $A = 89.02$ mm^{-2}. As permittivity of space is given by $\varepsilon_0 = 8.85 \times 10^{-3}$ pF mm^{-1}, we can write $C_0 = \varepsilon_0 A/t = 0.35$ pF. Now, $\varepsilon = C_1/C_0$. R_4 is the dial reading of resistance and from discussion on the Schering bridge, we have $C_1 = C_2(R_4/R_3)$ with $C_2 = 1000$ pF and $R_3 = 3$ kΩ.

For the multi-layer ceramic capacitor and the disc ceramic capacitor, in the absence of dimensional information of commercially available capacitors, the value of C_0 cannot be computed. Hence, we tabulate value of capacitance, which is proportional to the dielectric constant, as a function of frequency in table (I) and (II). The respective plots between variation of capacitance with frequency are shown in figures (15) and (16).

The data for variation of capacitance parameters (C_1 and R_1) and dielectric constant as a function of frequency for BaTiO$_3$ is tabulated in (III). Figure (17) shows the variation of dielectric constant of BaTiO$_3$ with frequency over a frequency range of 0 to 50 kHz. This follows the same general variation as shown in figure (7) over this frequency range.

Figure (18) shows the variation of the dissipation factor of barium titanate sample with frequency.

The temperature dependence of dielectric constant at various frequencies is tabulated in table (IV) and the corresponding plot is given in figure (19).

The diffuseness parameter, δ, is defined as the slope of the plot between $\ln\left(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}}\right)$ versus $\ln(T - T_C)$, where ε is the dielectric constant at a temperature T, ε_{max} is the maximum value of the dielectric constant at the curie temperature, T_C, which corresponds to the peaks in the plot of variation of dielectric constant with temperature (figure (19)). The above is valid in the paraelectric phase, i.e., only beyond the Curie temperature. Therefore, the values of dielectric constant and other parameters after phase transition at the Curie temperature T_C are tabulated in table (V) and the corresponding plots between $\ln\left(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}}\right)$ and $\ln(T - T_C)$ for different frequencies are plotted in figure (20). The slopes in figure (20) represent the diffuseness parameter δ.
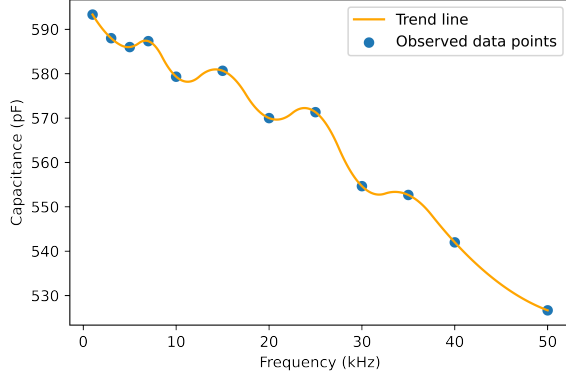
FIG. 15. Variation of unknown capacitance as a function of frequency for multi-layer ceramic capacitor (MLCC)
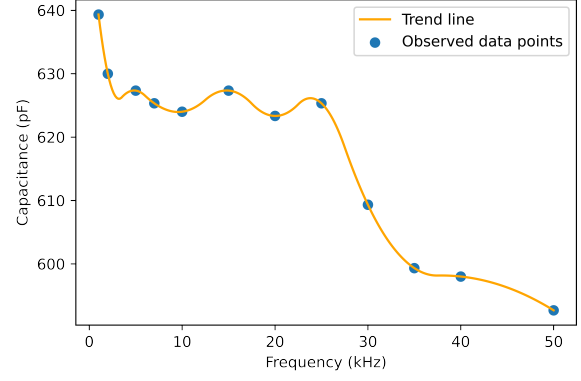

FIG. 16. Variation of unknown capacitance as a function of frequency for disc ceramic capacitor

TABLE II. Variation of unknown capacitance as a function of frequency for disc ceramic capacitor

Frequency f (kHz)	C_4 (pF)	R_4 (Ω)	C_1 (pF)
1	500	1918	639.33
2	500	1890	630.00
5	500	1882	627.33
7	500	1876	625.33
10	500	1872	624.00
15	500	1882	627.33
20	500	1870	623.33
25	500	1876	625.33
30	500	1828	609.33
35	500	1798	599.33
40	500	1794	598.00
50	500	1778	592.67

FIG. 17. Variation of dielectric constant as a function of frequency for BaTiO$_3$

VI. ERROR ANALYSIS

Major part of this experiment is concerned with studying the general trend lines, like the effect on the value of dielectric constant when frequency and temperature are changed, that is qualitative analysis. So there is little to no scope in performing rigorous error analysis as we can ascertain the behaviour just by looking the plots and nothing more is required.

Further, figure (19) provides us with value of Curie temperature as around 140 °C. Note that the data entries were erroneously taken in steps of 10 °C during the range of 120 °C to 140 °C instead of steps of 5 °C as is recommended. This led to the peak appearing much later than expected (around 140 °C, instead of the literature value of 130 °C. It is understood that if the resolution of steps was much higher (less number of steps, more data entries) than the experimental value could have been a lot closer. As the changing of temperature was done using the PID controller oven, it is hard to quantitatively analyse the obtained data set for the error in Curie temperature for such large step values (10 °C).

The log-log plots given in figure (20) do present a oppor-

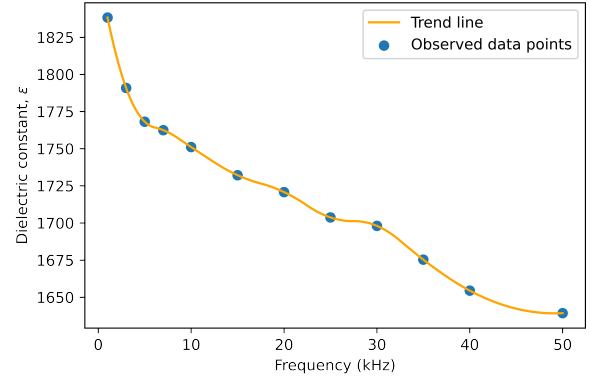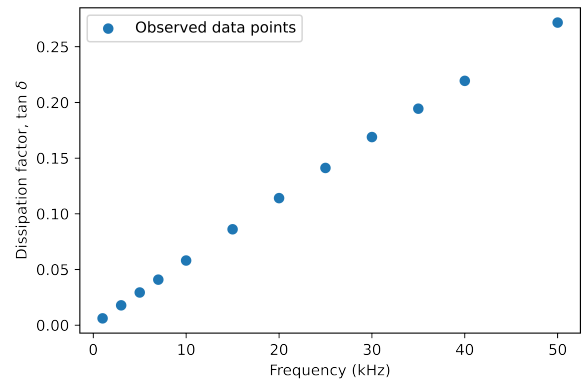FIG. 18. Variation of the dissipation factor of barium titanate sample with frequency

TABLE III. Variation of capacitance parameters (C_1 and R_1) and dielectric constant as a function of frequency

Frequency f (kHz)	C_4 (pF)	R_4 (Ω)	C_1 (pF)	R_1 (Ω)	Dielectric constant ($\varepsilon = C_0/C_1$)	Dissipation factor ($2\pi f CR$)
1	500	1940	646.7	1500	1838.30	0.006
3	500	1890	630.0	1500	1790.92	0.018
5	500	1866	622.0	1500	1768.18	0.029
7	500	1860	620.0	1500	1762.49	0.041
10	500	1848	616.0	1500	1751.12	0.058
15	500	1828	609.3	1500	1732.17	0.086
20	500	1816	605.3	1500	1720.80	0.114
25	500	1798	599.3	1500	1703.74	0.141
30	500	1792	597.3	1500	1698.06	0.169
35	500	1768	589.3	1500	1675.32	0.194
40	500	1746	582.0	1500	1654.47	0.219
50	500	1730	576.7	1500	1639.31	0.272

TABLE IV. Variation of dielectric constant of BaTiO$_3$ with temperature at various frequencies

Temperature (°C)	Operating frequency											
	5 kHz			15 kHz			25 kHz			35 kHz		
	R_4 (Ω)	C_1 (pF)	ε (pF mm^{-1})	R_4 (Ω)	C_1 (pF)	ε (pF mm^{-1})	R_4 (Ω)	C_1 (pF)	ε (pF mm^{-1})	R_4 (Ω)	C_1 (pF)	ε (pF mm^{-1})
50	1856	618.7	1758.7	1798	599.3	1703.7	1800	600.0	1705.6	1792	597.3	1698.1
60	1858	619.3	1760.6	1818	606.0	1722.7	1788	596.0	1694.3	1750	583.3	1658.3
70	1880	626.7	1781.4	1884	628.0	1785.2	1816	605.3	1720.8	1778	592.7	1684.8
80	1912	637.3	1811.8	1880	626.7	1781.4	1828	609.3	1732.2	1826	608.7	1730.3
90	1958	652.7	1855.4	1940	646.7	1838.3	1920	640.0	1819.3	1842	614.0	1745.4
100	2010	670.0	1904.6	1966	655.3	1862.9	1940	646.7	1838.3	1940	646.7	1838.3
110	2130	710.0	2018.3	2076	692.0	1967.2	2028	676.0	1921.7	1984	661.3	1880.0
120	2314	771.3	2192.7	2230	743.3	2113.1	2208	736.0	2092.3	2190	730.0	2075.2
130	2588	862.7	2452.3	2518	839.3	2386.0	2504	834.7	2372.7	2440	813.3	2312.1
140	2726	908.7	2583.1	2658	886.0	2518.7	2590	863.3	2454.2	2530	843.3	2397.4
150	2514	838.0	2382.2	2430	810.0	2302.6	2422	807.3	2295.0	2378	792.7	2253.3
160	2264	754.7	2145.3	2196	732.0	2080.9	2192	730.7	2077.1	2174	724.7	2060.0
170	2028	676.0	1921.7	1992	664.0	1887.6	1992	664.0	1887.6	1940	646.7	1838.3
180	1866	622.0	1768.2	1840	613.3	1743.5	1822	607.3	1726.5	1812	604.0	1717.0

tunity of reasonable quantitative analysis, on the other hand. We are required to find the diffuseness parameter δ which is, as already calculated, given by the slope of the plots in (20). Error in this slope can be calculated as well. The code for calculating both the slope and its error in given in the Jupyter Notebook at my GitHub. Upon running the code (which employs the use of popular Python library NumPy), we obtain the diffuseness parameters (with their corresponding uncertainties) as following

$$\begin{aligned}
\delta_5 &= 1.23 \pm 0.03 \\
\delta_{15} &= 1.13 \pm 0.02 \\
\delta_{25} &= 1.30 \pm 0.03 \\
\delta_{35} &= 1.34 \pm 0.06
\end{aligned} \tag{10}$$

where δ_i is the diffuseness parameter for ith frequency (in kHz).
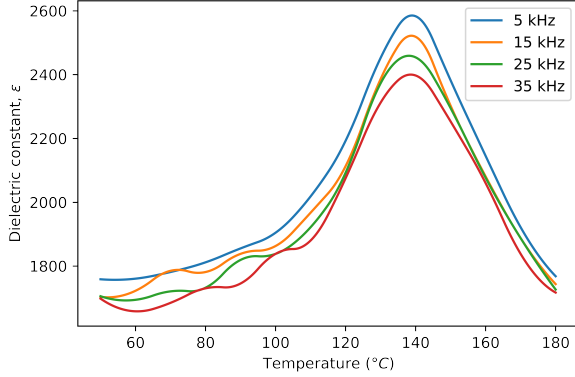
VII. RESULTS

1. For the multi-layer ceramic capacitor (MLCC), the general trend that was observed was that capacitance (thus dielectric constant) decreases with increase in frequency.

2. For the disc ceramic capacitor, the general trend that was observed was that capacitance (thus dielectric constant) decreases with increase in frequency.

3. For BaTiO$_3$, the general trend that was observed was that dielectric constant decreases with increase in frequency.

4. The plot of dissipation factor $\tan \delta$ against frequency was obtained as a straight line. This is not a general trend.

5. The plots while studying temperature dependence of dielectric constant at various frequencies were obtained as

TABLE V. Log-log plots to study the diffuseness parameter δ at various frequencies

Temperature (K)	5 kHz $\varepsilon_{max} = 2583.1\,\mathrm{pF\,mm^{-1}}$		15 kHz $\varepsilon_{max} = 2518.7\,\mathrm{pF\,mm^{-1}}$		25 kHz $\varepsilon_{max} = 2454.2\,\mathrm{pF\,mm^{-1}}$		35 kHz $\varepsilon_{max} = 2397.4\,\mathrm{pF\,mm^{-1}}$		$\ln(T - T_C)$
	ε	$\ln(1/\varepsilon - 1/\varepsilon_{max})$	ε	$\ln(1/\varepsilon - 1/\varepsilon_{max})$	ε	$\ln(1/\varepsilon - 1/\varepsilon_{max})$	ε	$\ln(1/\varepsilon - 1/\varepsilon_{max})$	
423.15	2382.2	-10.33	2302.6	-10.20	2295.0	-10.47	2253.3	-10.53	2.30
433.15	2145.3	-9.45	2080.9	-9.39	2077.1	-9.51	2060.0	-9.59	3.00
443.15	1921.7	-8.92	1887.6	-8.93	1887.6	-9.01	1838.3	-8.97	3.40
453.15	1768.2	-8.63	1743.5	-8.64	1726.5	-8.67	1717.0	-8.71	3.69

FIG. 19. Variation of dielectric constant of BaTiO$_3$ with temperature at various frequencies
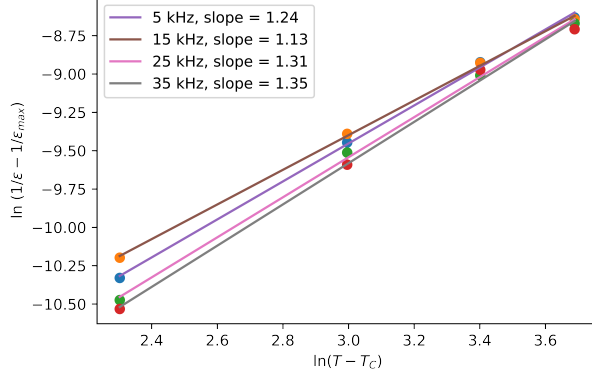
FIG. 20. Plot for diffuseness parameter at various frequencies, the slope represents the diffuseness parameter δ

the dielectric constant of BaTiO$_3$ increased till a critical temperature (the Curie temperature, T_C), after which it quickly tapered off.

6. The experimental Curie temperature was obtained around to be at 140 °C which is little more than the literature value due to possible reason in taking reading with larger steps than is recommended.

7. The straight line plots to find diffuseness parameter, δ, were obtained as expected with all δ values lying between 1 and 2 (as is expected) according to equation

(10).

VIII. DISCUSSIONS

1. Dielectric dispersion is the dependence of the permittivity of a dielectric material on the frequency of an applied electric field. Because there is a lag between changes in polarisation and changes in the electric field, the permittivity of the dielectric is a complicated function of frequency of the electric field. Dielectric dispersion is very important for the applications of dielectric materials and for the analysis of polarisation systems.

2. When the frequency becomes higher dipolar polarisation can no longer follow the oscillations of the electric field in the microwave region, ionic polarisation and molecular distortion polarisation can no longer track the electric field past the infrared or far-infrared region and electronic polarisation loses its response in the ultraviolet region.

3. Dielectric loss quantifies a dielectric material's inherent dissipation of electromagnetic energy.

4. The Curie temperature is originally discussed as the temperature above which certain materials lose their permanent magnetic properties, which can (in most cases) be replaced by induced magnetism.

5. The diffuseness parameters relations are valid in the paraelectric phase, i.e., beyond the Curie temperature.

6. This aspect which is a structural phase change [Tetragonal to Cubic in the case of BT] with temperature therefore does not depend on the frequency.

7. The value of the dielectric constant however decreases as the frequency increases in conformity with the results.

8. The general trend of dielectric constant decreasing with frequency in the case of BaTiO$_3$ is contributed by space charge polarization caused by mobile charge carriers whose motion is impeded by interface due to a grain or phase boundary.

9. The general trend of the dissipation factor plot can be explained by the increase with frequency reflects the increase in friction between dipoles due to their inability

to follow up the first variation of the applied alternating electric field.

IX. CONCLUSIONS

1. In most cases, the results so obtained were satisfactory.

2. As a precautionary measure, the reading for temperature part must be taken in small steps around the expected value of Curie temperature for better results.

3. The Schering bridge apparatus often gives the resistance values which are edge on the switch between 1K, 2K or 3k dials. This can lead to some errors as exact value is hard to determine.

4. The spring loaded probe should be allowed to rest on the sample very gently, otherwise it may damage the conducting surface of the sample or even break the sample.

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[1] Property of certain crystals which are naturally electrically polarized and as a result contain large electric fields; can be described as the ability of certain materials to generate a temporary voltage when they are heated or cooled.