# STUDY OF PHASE TRANSITIONS IN $BaTiO_3$.

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## Abstract

The dielectric constant of $BaTiO_3$ was measured as a function of frequency & as a function of temperature. The frequency dependence exhibits of decreasing nature of dielectric constant, which is consistant with polarization relaxation mechanisms. The temperature variation has a peak ~~at~~ at $T = 135^\circ C$ (Curie temperature) indicating a phase transition. Diffuseness parameter obtained in the paraelectric region was ~~abt~~ in the expected range for $BaTiO_3$. The experiment confirms the characteristic dielectric constant behaviour & phase transition of ferroelectric $BaTiO_3$.

# Objective :-

i) Study of frequency dependence of dielectric constant.
ii) Ferroelectric to paraelectric phase transition of $BaTiO_3$ by study of dielectric constant as a function of Temperature and frequency.

# Theory :-

Dielectric materials are insulating substances that become polarized when subjected to an external electric field. This polarization of the medium leads to energy storage which depends on the dielectric constant / relative permittivity ($\varepsilon_r$)

In the presence of an alternating electric field, the permittivity is a complex quantity with the real part signifying energy stored & imaginary part signifying energy loss. (see fig. I)

$$\varepsilon = \varepsilon' + i\varepsilon''$$

Real part of permittivity ($\varepsilon'$) depends on the polarizability. The total polarizability may be separated into 4 parts:
i) electronic, ii) ionic (or atomic), iii) dipolar (or orientation) & space charge. Each mechanism has a characteristic relaxation frequency. At low frequency, all mechanisms can contribute, leading to a high dielectric constant. As the frequency increases, the slower mechanisms (especially dipolar & space charge polarization) fail to follow rapidly oscillating field. This causes dielectric constant to decrease with frequency.

The dielectric constant ($\varepsilon'$) represents a measure of the ability of a material to be polarized by an external electric field storing energy within it. The dielectric loss factor ($\varepsilon''$) represents the ability of the material to dissipate the absorbed electromagnetic energy, converting into heat. Thus, $\frac{\varepsilon''}{\varepsilon'}$ ratio is the capability of a material to convert EM energy into heat at given temperature & frequency.

The loss factor (dissipation factor) is defined as,

$$\boxed{\tan\delta = \frac{\varepsilon_r'}{\varepsilon_r''}}$$

* Barium Titanate ($BaTiO_3$)

$BaTiO_3$ is a ferromagnetic material with a form ($ABO_3$). ~~At $T > T_c \approx 120°C$~~ It has a perovskite structure.

An advantage of perovskite structure is that many different cations can be substituted on both A and B sites without drastically changing the overall structure.

$BaTiO_3$ has a ferroelectric tetragonal phase @ $T < T_c$ & paraelectric cubic phase @ $T > T_c$. ($T_c = 120°$ for $BaTiO_3$)

* <u>Dielectric constant</u>:

Dielectric constant ($\varepsilon$) is given by

$$\varepsilon = \frac{C}{C_0} \qquad C_0 = \frac{\varepsilon_0 A}{t}$$

where $C$ = capacitance using the material as dielectric
$C_0$ = capacitance using ~~air~~ vacuum as dielectric
$\varepsilon_0$ = permittivity of free space ($8.85 \times 10^{-12}\ \frac{F}{m}$)

A = Area of the plate / sample cross - section area

t = Thickness of the sample.

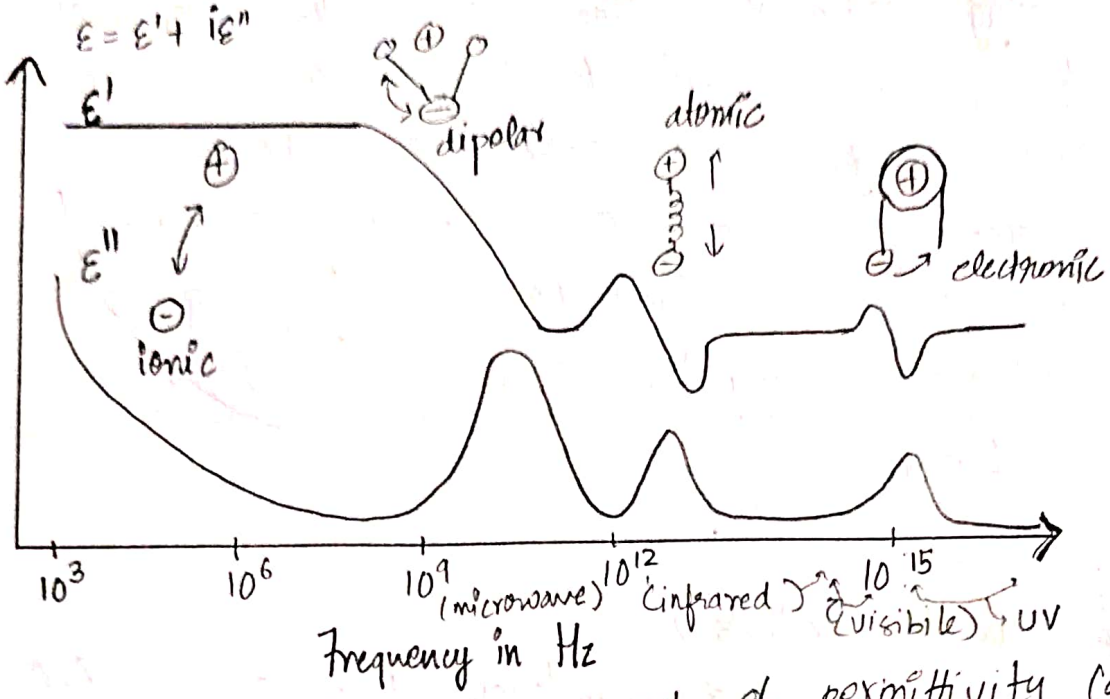
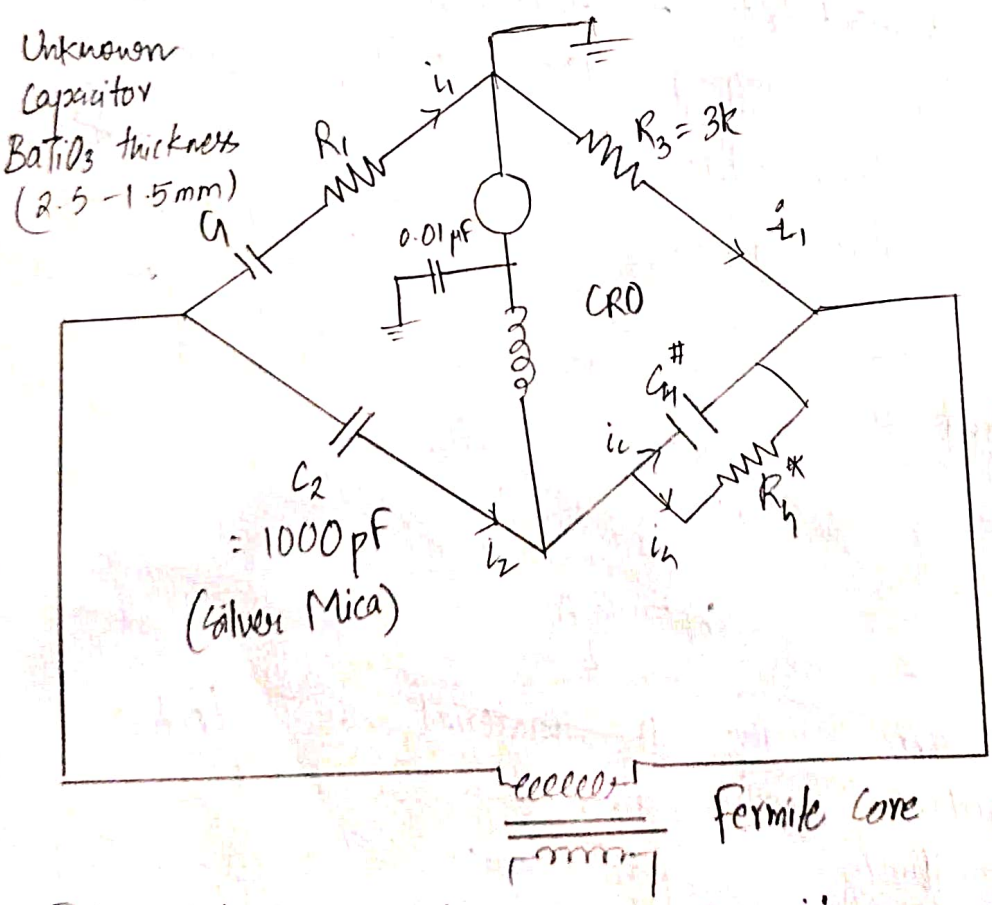



Fig I:- Real & imaginary part of permittivity (dielectric constant) as a function of frequency.




# $C_4$ = 100 pF to 1500 pF in a steps.

* Coarse 0, 1, 2 k
Fine 1 k/10T.

Fig. 2: Schering Bridge for Capacitance Measurement.

From the bridge balance condition in Schering Bridge (fig 2)

$$R_1 = \frac{R_3 C_1}{C_2} \quad \& \quad C_1 = \frac{C_2 R_4}{R_3}$$

$C_1$ = unknown capacitor  $R_1$ = equivalent series resistance

Dissipation factor,

$$\tan\delta = \omega C_1 R_1 = \omega C_1 R_4 = 2\pi f (CR)$$

# Apparatus Required :-

i) Probe Arrangement with RTD (Resistance Temperature Detector) sensor

ii) Samples :- $BaTiO_3$ plate with top & bottom conducting surface, Standard Multilayer Ceramic Capacitor & Disc Ceramic Capacitor.

iii) Frequency dependence of dielectric constant (range 0 - 50 kHz)

iv) Oscilloscope (to balance the bridge)

v) PID controlled oven

# Observations :- $C_1 = C_2\left(\frac{R_4}{R_3}\right)$ $R_3 = 1\,k\Omega$ (from the setup). $C_2 = 1000\,pF$

$BaTiO_3$ --> Diameter = 10.56 mm thickness = 1.60 mm

| Frequency (kHz) (f) | $C_4$ (pF) | $R_4$ (kΩ) | $C_1$ (pF) | $R_1$ (Ω) | Dielectric constant $\varepsilon = \frac{C}{C_0}$ | Dissociation factor ($2\pi f C_1 R_1$) |
|---|---|---|---|---|---|---|
| 3 | 800 | 0.900 | 900 | 800 | 1856.9 | 0.013572 |
| 5 | 850 | 0.890 | 890 | 850 | 1836.3 | 0.023766 |
| 7 | 800 | 0.888 | 888 | 800 | 1832.2 | 0.031245 |
| 10 | 450 | 0.880 | 880 | 450 | 1815.7 | 0.024881 |
| 15 | 300 | 0.876 | 876 | 300 | 1807.4 | 0.024768 |
| 20 | 250 | 0.872 | 872 | 250 | ~~1807~~ 1799.2 | 0.027395 |
| 25 | 200 | 0.870 | 870 | 200 | 1795.1 | 0.027332 |
| 30 | 150 | 0.866 | 866 | 150 | 1786.8 | 0.024486 |
| 35 | 150 | 0.864 | 864 | 150 | 1782.7 | 0.028501 |
| 40 | 150 | 0.862 | 862 | 150 | 1778.5 | 0.032497 |
| 45 | 100 | 0.860 | 860 | 100 | 1774.4 | 0.024316 |
| 50 | 100 | 0.858 | 858 | 100 | 1770.3 | 0.026955 |

4/2/2026

# Disc Capacitor

$C_1 = 550$ pF  $R_3 = 1$ kΩ

| Frequency f (kHz) | $R_4$ (kΩ) | $C_4$ (pF) | $C_1$ (pF) |
|---|---|---|---|
| 3 | 0.590 | 590 | |
| 5 | 0.590 | 590 | |
| 7 | 0.590 | 590 | |
| 10 | 0.590 | 590 | |
| 15 | 0.590 | 590 | |
| 20 | 0.588 | 588 | |
| 25 | ~~0.588~~ 0.588 | 588 | |
| 30 | 0.586 | 586 | |
| 35 | 0.586 | 586 | |
| 40 | 0.588 | 588 | |
| 45 | 0.590 | 590 | |
| 50 | 0.588 | 588 | |

Akash
4/02/26

$$C_0 = \frac{\varepsilon_0 A}{t} = \frac{\varepsilon_0 \pi D^2}{t}$$

# MLCC

(Multi-Layered Ceramic Capacitor)

$C_4 = \cancel{550}\ 400\ pF$

$R_3 = 1.5\ k\Omega$ for this setup.

| Frequency f (kHz) | $R_4$ (kΩ) | $C_4$ (pF) |
|---|---|---|
| ~~3~~ | ~~0.590~~ | |
| ~~5~~ | ~~0.590~~ | |
| 7 | 0.902 | 601.34 |
| 10 | 0.896 | 597.34 |
| 15 | 0.892 | 594.67 |
| 20 | 0.888 | 592.0 |
| 25 | 0.892 | 594.67 |
| 30 | 0.886 | 590.67 |
| 35 | 0.886 | 590.67 |
| 40 | 0.884 | 589.34 |
| 45 | 0.880 | 586.67 |
| 50 | 0.876 | 584.0 |

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0.902
0.896

# Temperature variation :-

| Temperature (°C) | Operating frequency = 15 kHz | | | | Operating frequency - 25 kHz | | | |
|---|---|---|---|---|---|---|---|---|
| | $R_4$ (kΩ) | $C_4$ (pF) | C (pF) | ε | $R_4$ (kΩ) | $C_4$ (pF) | C (pF) | ε |
| 50 | 0.876 | 350 | 876 | 1807.5 | 0.866 | 200 | 866 | 1786.5 |
| 60 | 0.892 | 350 | 892 | 1840.5 | 0.884 | 250 | 884 | 1824.0 |
| 70 | 0.922 | 400 | 922 | 1902.4 | 0.916 | 250 | 916 | 1890. |
| 80 | 0.964 | 500 | 964 | 1989 | 0.952 | 250 | 952 | 1964.3 |
| 90 | 1.010 | 500 | 1010 | 2083.9 | 1.002 | 350 | 1002 | 2067.4 |
| 100 | 1.094 | 600 | 1094 | 2257.3 | 1.082 | 350 | 1082 | 2232.5 |
| 110 | 1.210 | 600 | 1210 | 2496.6 | 1.184 | 450 | 1184 | 2442.9 |
| 120 | 1.398 | 650 | 1398 | 2884.5 | 1.372 | 400 | 1372 | 2830.9 |
| 125 | 1.532 | 750 | 1532 | 3161 | 1.498 | 600 | 1498 | 3090.8 |
| 130 | 1.680 | 950 | 1680 | 3466.3 | 1.606 | 600 | 1606 | 3313.7 |
| 135 | 1.772 | 600 | 1772 | 3656.2 | 1.736 | 600 | 1736 | 3581.9 |
| 140 | 1.744 | 1150 | 1744 | 3598.4 | 1.684 | 850 | 1684 | 3474.6 |
| 150 | 1.528 | 1150 | | 3152.7 | 1.484 | 1100 | 1484 | 3060.9 |
| 170 | | | | | | | | |
| 168 | 1.202 | 400 | 1202 | 2480.1 | 1.174 | 400 | 1174 | 2422.3 |
| 168 | | | | | | | | |

1.528

| Temperature (°C) | Operating frequency = 35 kHz | | | | Operating frequency = 45 kHz | | | |
|---|---|---|---|---|---|---|---|---|
| | $R_4$ (kΩ) | $C_4$ (pF) | C (pF) | ε | $R_4$ (kΩ) | $C_4$ (pF) | C (pF) | ε |
| 50 | 0.862 | 150 | 862 | 1778.6 | 0.858 | 150 | 858 | 1770.3 |
| 60 | 0.878 | 200 | 878 | 1811.6 | 0.874 | 150 | 874 | 1803.3 |
| 70 | 0.910 | 200 | 910 | 1877.6 | 0.906 | 150 | 906 | 1869.4 |
| 80 | 0.948 | 200 | 948 | 1956.0 | 0.942 | 150 | 942 | 1943.6 |
| 90 | 0.996 | 350 | 996 | 2055 | 0.996 | 250 | 996 | 2055 |
| 100 | 1.066 | 350 | 1066 | 2199.5 | 1.060 | 250 | 1060 | 2187.1 |
| 110 | 1.170 | 300 | 1170 | 2414.1 | 1.166 | 300 | 1166 | 2405.8 |
| 120 | 1.348 | 350 | 1348 | 2781.3 | 1.334 | 300 | 1334 | 2752.4 |
| 125 | 1.460 | 450 | 1460 | 3012.4 | 1.440 | 450 | 1440 | 2971.2 |
| 130 | 1.592 | 450 | 1592 | 3284.8 | 1.556 | 350 | 1556 | 3210.5 |
| 135 | 1.720 | 500 | 1720 | 3548.9 | 1.690 | 350 | 1690 | 3487 |
| 140 | 1.682 | 750 | 1682 | 3470.5 | 1.624 | 750 | 1624 | 3350.8 |
| 150 | 1.466 | 900 | 1466 | 3024.8 | 1.428 | 700 | 1428 | 2946.4 |
| ~~170~~ | | | | | | | | |
| 168 | 1.170 | 400 | 1170 | 2414.1 | 1.152 | 400 | 1152 | 2376.9 |

# Calculations & Discussion

i) Frequency Dependence of Dielectric constant

(a) Barium Titanate ($BiTiO_3$)

Diameter = 10.56 mm  Thickness = 1.6 mm

* Capacitance, $C_0 = \frac{\varepsilon_0 A}{t} = \frac{\varepsilon_0 \pi d^2}{4t} = \frac{8.85\times10^{-12}\times 3.14\times(10.56)^2\times10^{-6}}{4\times(1.6)^{-3}}$

$= 0.484\times10^{-12}$ F

$C_0 = 0.484$ pf

This is the capacitance of the capacitor with 'vacuum' as medium.

* The attached plot of Dielectric constant v/s frequency has a ~~der~~ 'monotonically decreasing' nature.

Dielectric constant ($\varepsilon$) $= \frac{C_1}{C_0}$  where $C_1 = C_2\left(\frac{R_4}{R_3}\right)$

where $C_1$ is capacitance of capacitor with '$BaTiO_3$' as dielectric. (Balanced condition in Schering bridge)

* Dissipation factor,

$\tan\delta = 2\pi f C_1 R_2$.

* The plot of dissipation factor of $BaTiO_3$ v/s frequency, is not monotonic, but still increasing over a longer range of frequency. This increase reflects the increase in friction b/w dipoles due to their inability to follow up the, ~~variant~~ variations in alternating electric field.

(b) MLCC & Disc.

The variation of capacitance with frequency is plotted for the standard Multi-Layerd Ceramic Capacitor & Disc Ceramic

capacitor.

* We observe the general trend of decreasing capacitance with increasing frequency in case of MLCC.
* However, for Disc capacitor, the variation of capacitance is overall decreasing, but with minor fluctuations which can be attributed to the sources of error discussed at the end.

ii) <u>Study of temperature dependence of $\varepsilon$ for various frequencies.</u>

* The attached plot of dielectric constant v/s temperature for $BaTiO_3$ ~~exh~~ has a maxima at $T = 135°C$. This is due to a phase transition in $BaTiO_3$ at its Curie Temperature.
* This phase transition represents a change in perovskite structure from ferroelectric tetragonal phase ~~to~~ below its Curie temperature to paraelectric cubic phase after its Curie point.

iii) <u>Study of Diffuseness parameter</u>

The diffuseness parameter $\delta$ is defined as slope of $\ln\left(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}}\right)$ v/s $\ln(T - T_c)$ plot for $T > T_c$ (paraelectric phase)

* A least square linear fit was performed for each frequency & the diffuseness parameter & its uncertainty were obtained (errors explained in next section). (plots & tables attached)

* We ~~the~~ calculated.

for $f = 15$ kHz, $\delta = 1.31 \pm 0.20$

for $f = 25$ kHz, $\delta = 1.46 \pm 0.07$

for $f = 35$ kHz $\delta = 1.62 \pm 0.16$

for $f = 45$ kHz $\delta = 1.30 \pm 0.05$

For each frequency, we had only 3 observed data points for $T > T_c$ region, hence we obtain different values of $\delta$ which have large uncertainties & are not in agreement with each other. However, since $\delta$ is expected to lie b/w 1 & 2, the measured values are in agreement with the theoretical expectations.

# NOTE:-
For ~~all~~ all frequencies, the phase transition is observed @ $T = 135°C$ hence the structural phase change in $BaTiO_3$ is independent of frequency.

# NOTE:- The value of dielectric constant for $BaTiO_3$ were calculated to be in the range of ~1800 for room temperature for the frequency range of 3 - 15 kHz, which is a little higher than expected. This can be due to inaccurate measurement of ~~thickness~~ diameter 'd' of the sample. Since $C_0 = \frac{\varepsilon_0 \pi d^2}{4t}$ & ~~thickness~~ diameter is in the order of ~mm, & $\varepsilon = \frac{C}{C_0}$, small error in ~~thickness~~ diameter 'd' measurement can cause a large shift in the calculation of $\varepsilon$. (since $\varepsilon \propto \frac{1}{C_0}$ & $C_0 \propto d^2$ $\Rightarrow \varepsilon \propto \frac{1}{d^2}$)

# Error Analysis (Least squares Method)

* We perform a linear fit to the plot $\ln\left(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}}\right)$ v/s $\ln(T - T_c)$ for $T > T_c$. The slope & its uncertainty were obtained by least squares method.

The least squares method fits the data points into an eqn of the form $y = ax + b$.

The loss function to minimize is:

$$\mathcal{L}(a, b) = \sum_{i=1}^{N} (\hat{y}_i - (ax_i + b))^2$$

$\hat{y}_i$ = true values
$a, b$ = parameters
$N$ = no. of observat$^n$.

Choosing optimal parameters a & b to minimize the loss function.

$$\frac{\partial \mathcal{L}}{\partial a} = -2\sum_{i=1}^{N} x_i (y_i - (ax_i + b))^2 = 0$$

$\{x_i, y_i\}_{i=1}^{N}$ are the data points.

$$\frac{\partial \mathcal{L}}{\partial b} = -2\sum_{i=1}^{N} (y_i - (ax_i + b))^2 = 0$$

$$\Rightarrow \begin{cases} a\sum_{i=1}^{N} x_i^2 + b\sum_{i=1}^{N} x_i = \sum_{i=1}^{N} x_i y_i \\ a\sum_{i=1}^{N} x_i + bN = \sum_{i=1}^{N} y_i \end{cases}$$

Solving the linear system with two equations ~~to~~ the with two unknowns. gives a & b.

Error in $y$, $\sigma_y = \sqrt{\frac{1}{N-2}\sum_{i=1}^{N} (y_i - (ax_i + b))^2}$

Error in slope (a), $\sigma_a = \sigma_y \sqrt{\frac{N}{\Delta}}$ where, $\Delta = N\sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2$

Error in intercept (b). $\sigma_b = \sigma_y \sqrt{\frac{\sum_{i=1}^{N} x_i^2}{\Delta}}$

# Results & Conclusion :-

i) We observed the general trend of decreasing dielectric constant with increasing frequency for $BaTiO_3$, MLCC & Disc Ceramic capacitor.

ii) An increase in dissipation factor was observed with frequency in $BaTiO_3$, which matches the theoretical expectations.

iii) The temperature variation of dielectric constant for $BaTiO_3$ exhibits a phase transition @ $T = 135°C$ (the Curie temperature for $BaTiO_3$), going from a ferroelectric tetragonal phase to a ~~cubic~~ ~~to~~ paraelectric cubic phase, as the temperature is increased beyond the Curie point.

iv) The diffuseness parameter was calculated for various frequencies. It was obtained to be:

a) for $f = 15$ kHz, $\delta = 1.81 \pm 0.20$

b) for $f = 25$ kHz, $\delta = 1.46 \pm 0.07$

c) for $f = 35$ kHz, $\delta = 1.62 \pm 0.16$

d) for $f = 45$ kHz, $\delta = 1.30 \pm 0.05$

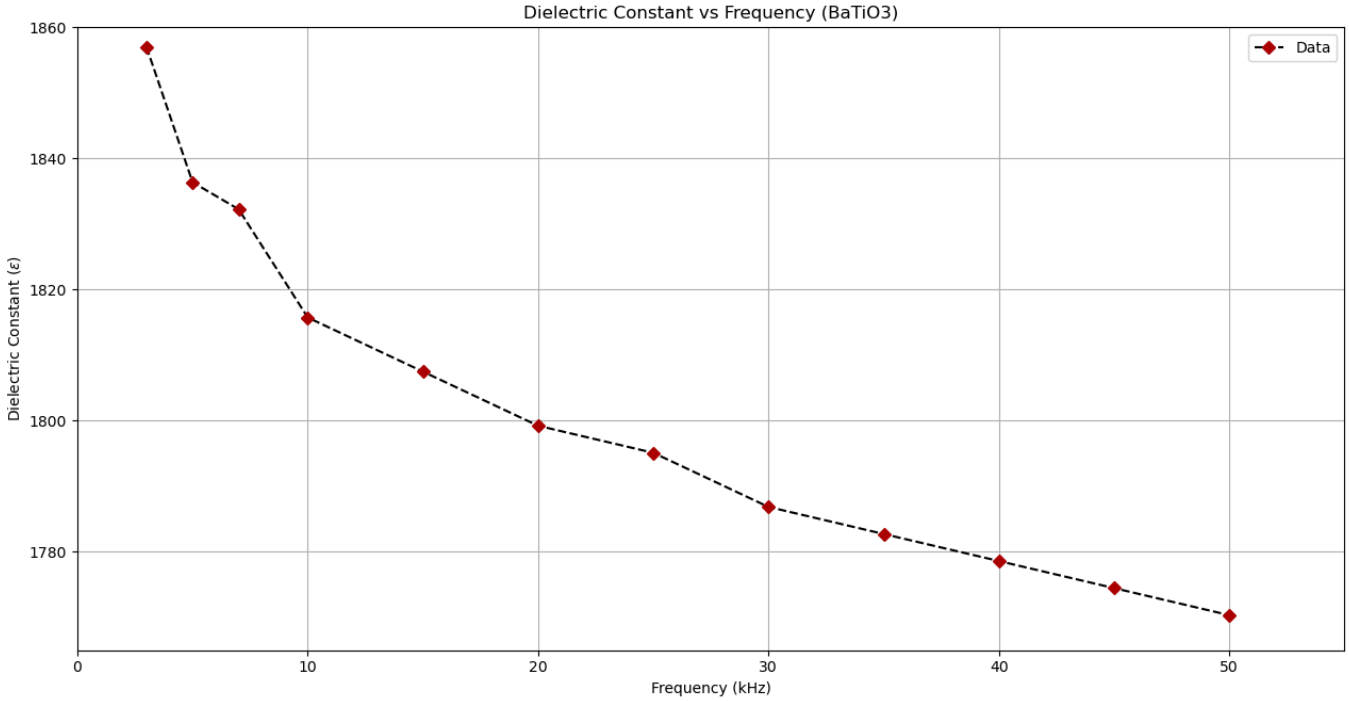
v) All the plots & calculations match the theoretical expectations in this experiment. A few minor fluctuations can be attributed to the sources of error discussed.

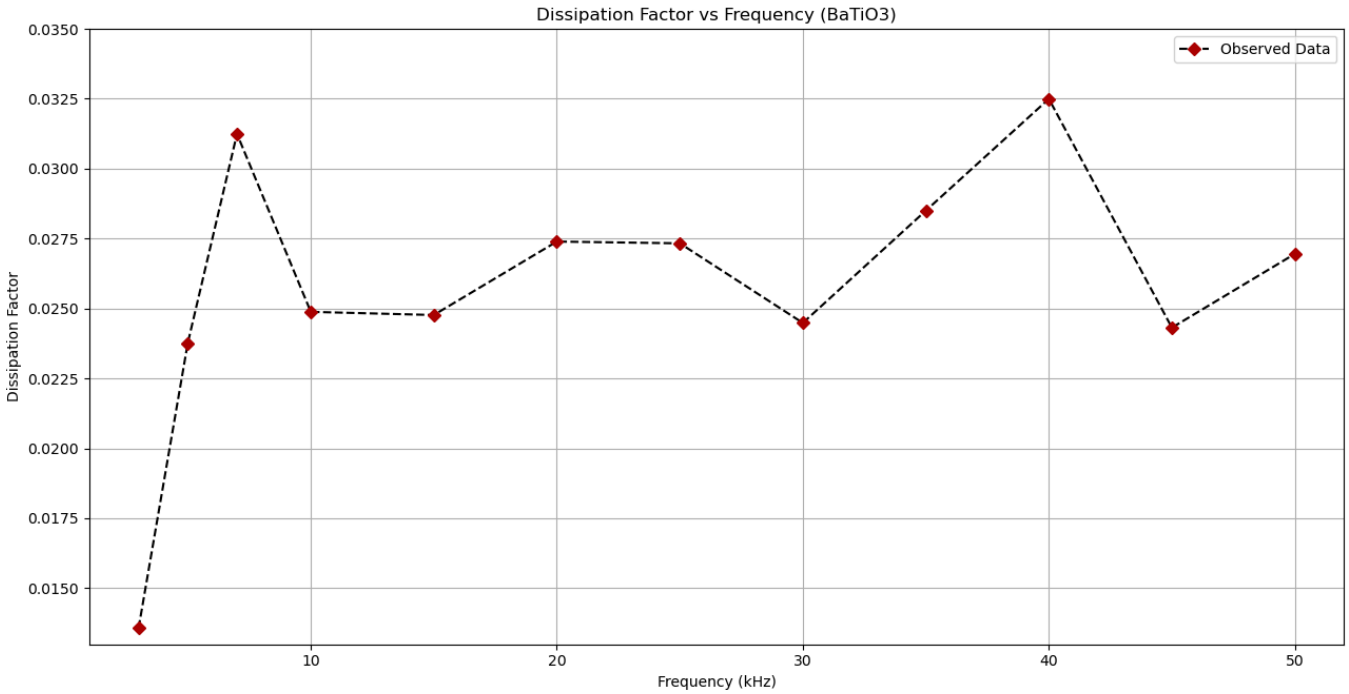
# Sources of Error

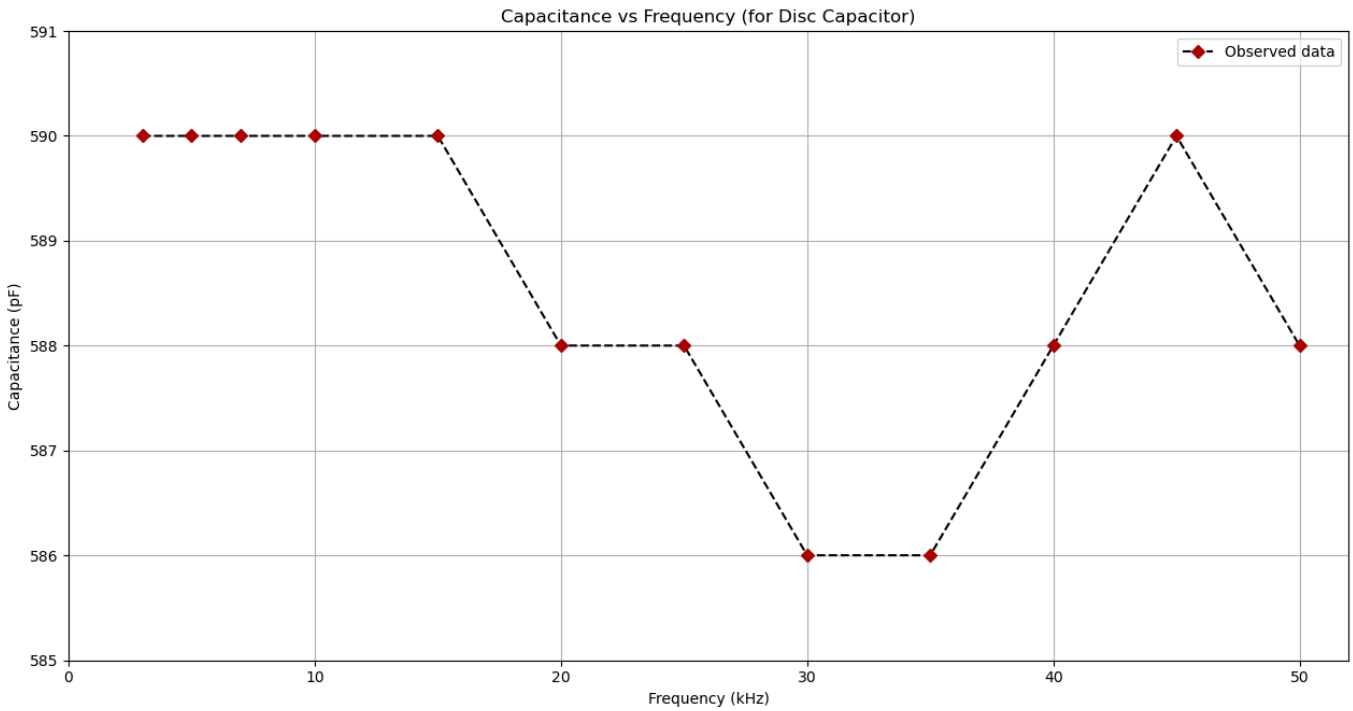
i) Improper contact b/w probe & sample especially at high temperatures can change the effective capacitance. & cause unwanted noise.

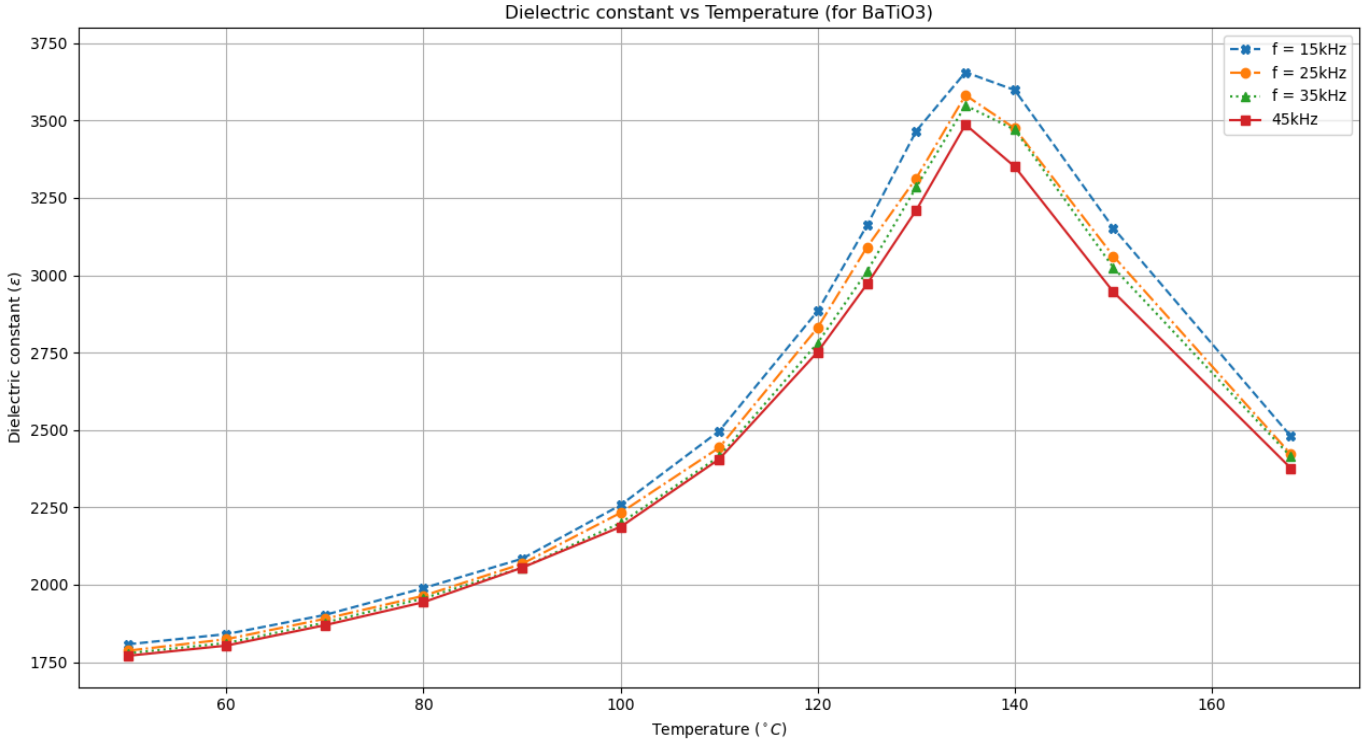
ii) Uncertainty in sample dimensions : As discussed earlier the dielectric constant is highly sensitive to these measurements of thickness & diameter. ~~It~~ ~~A~~ small error (in d or t) can produce large deviation in $\varepsilon$.

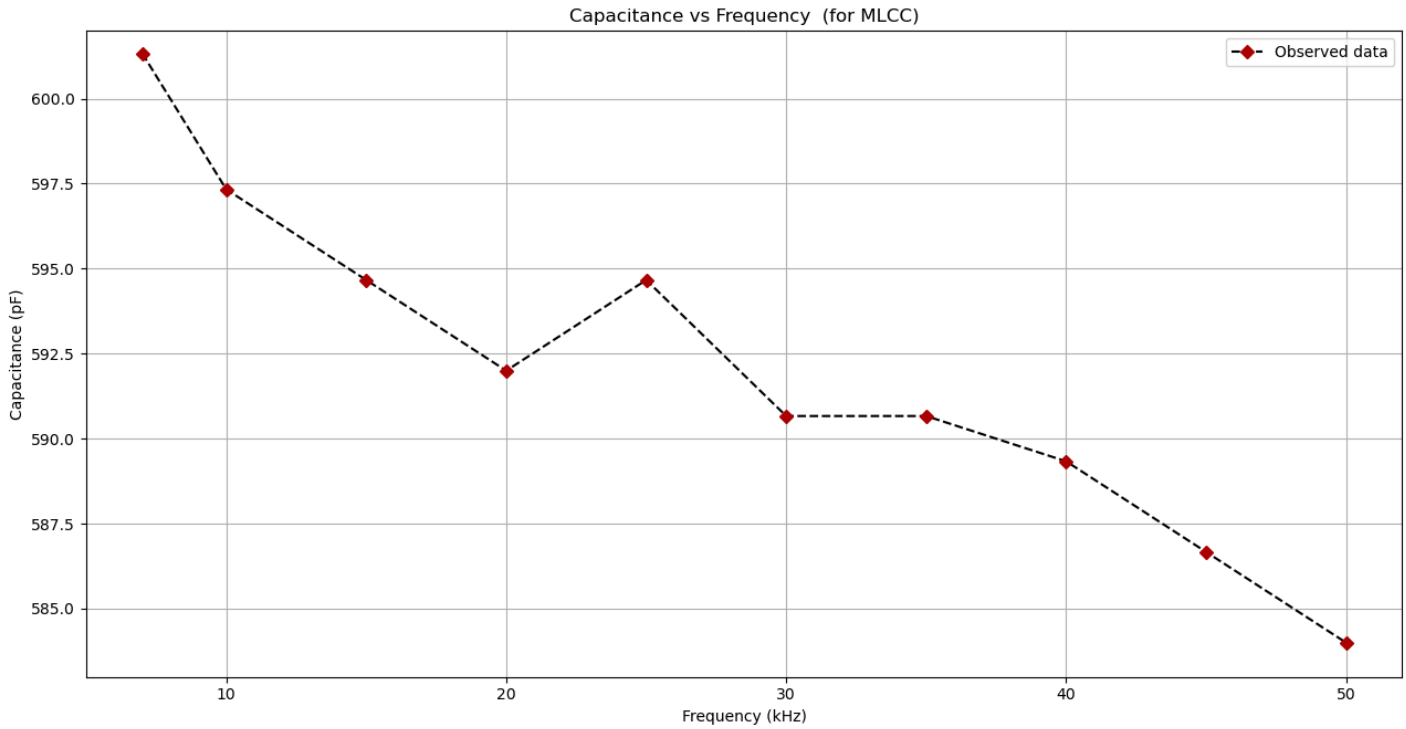
iii) The RTD may not exactly represent the sample temperature especially at high temperatures.


Dielectric Constant vs Frequency (BaTiO3)
Data
Dielectric Constant (ε)
Frequency (kHz)
1860
1840
1820
1800
1780
0
10
20
30
40
50


Dissipation Factor vs Frequency (BaTiO3)
Observed Data
Dissipation Factor
Frequency (kHz)
0.0350
0.0325
0.0300
0.0275
0.0250
0.0225
0.0200
0.0175
0.0150
10
20
30
40
50


Capacitance vs Frequency (for Disc Capacitor)
Observed data
Capacitance (pF)
Frequency (kHz)
591
590
589
588
587
586
585
0
10
20
30
40
50


Dielectric constant vs Temperature (for BaTiO3)
f = 15kHz
f = 25kHz
f = 35kHz
45kHz
Dielectric constant ($\epsilon$)
Temperature ($^{\circ}C$)
3750
3500
3250
3000
2750
2500
2250
2000
1750
60
80
100
120
140
160


Capacitance vs Frequency (for MLCC)
Observed data
Capacitance (pF)
600.0
597.5
595.0
592.5
590.0
587.5
585.0
10
20
30
40
50
Frequency (kHz)

| Input Data | | | | |
|---|---|---|---|---|
| i | x | y | $x^2$ | xy |
| 1 | 1.609 | -12.336 | 2.59 | -19.854 |
| 2 | 2.708 | -10.039 | 7.334 | -27.185 |
| 3 | 3.497 | -8.95 | 12.226 | -31.295 |
| Σ | 7.814 | -31.325 | 22.149 | -78.334 |

| Fit Results & Statistical Errors | | |
|---|---|---|
| Parameter | Value | Uncertainty |
| Slope ($a_1$) | 1.8129 | ±0.1978 |
| Intercept ($a_0$) | -15.1636 | ±0.5374 |
| σ_y (Std. Error) | 0.2651 | |
| Δ (delta) | 5.3896 | |

| Measured vs Fitted Values | | |
|---|---|---|
| x | y (measured) | y (fit) |
| 1.609 | -12.336 | -12.246 |
| 2.708 | -10.039 | -10.254 |
| 3.497 | -8.95 | -8.825 |

| Input Data | | | | |
|---|---|---|---|---|
| i | x | y | $x^2$ | xy |
| 1 | 1.609 | -11.661 | 2.59 | -18.768 |
| 2 | 2.708 | -9.957 | 7.334 | -26.963 |
| 3 | 3.497 | -8.92 | 12.226 | -31.19 |
| Σ | 7.814 | -30.538 | 22.149 | -76.921 |

| Fit Results & Statistical Errors | | |
|---|---|---|
| Parameter | Value | Uncertainty |
| Slope ($a_1$) | 1.4588 | ±0.0660 |
| Intercept ($a_0$) | -13.9791 | ±0.1794 |
| σ_y (Std. Error) | 0.0885 | |
| Δ (delta) | 5.3896 | |

| Measured vs Fitted Values | | |
|---|---|---|
| x | y (measured) | y (fit) |
| 1.609 | -11.661 | -11.631 |
| 2.708 | -9.957 | -10.029 |
| 3.497 | -8.92 | -8.878 |

| Input Data | | | | |
|---|---|---|---|---|
| i | x | y | $x^2$ | xy |
| 1 | 1.609 | -11.965 | 2.59 | -19.256 |
| 2 | 2.708 | -9.927 | 7.334 | -26.884 |
| 3 | 3.497 | -8.929 | 12.226 | -31.221 |
| Σ | 7.814 | -30.821 | 22.149 | -77.361 |

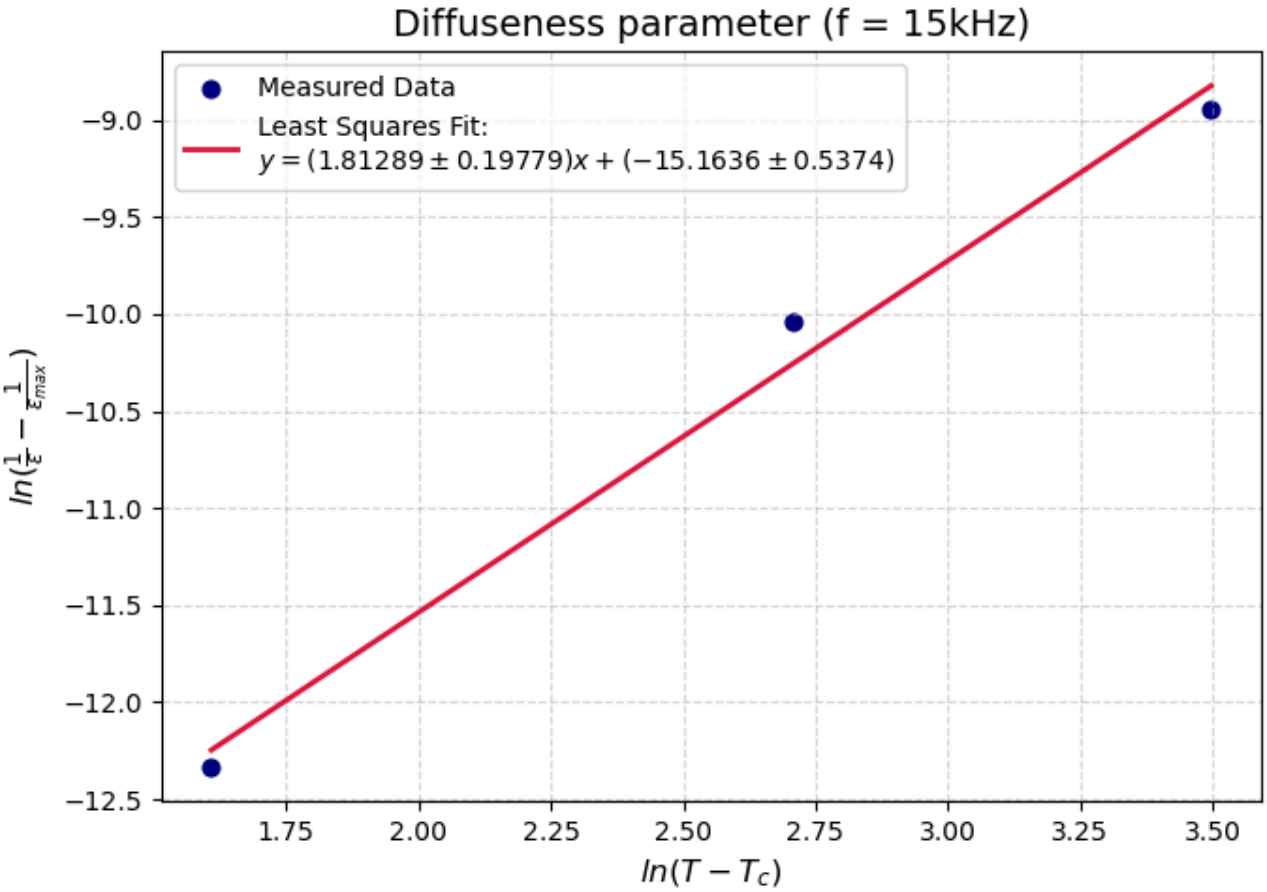
| Fit Results & Statistical Errors | | |
|---|---|---|
| Parameter | Value | Uncertainty |
| Slope ($a_1$) | 1.6240 | ±0.1638 |
| Intercept ($a_0$) | -14.5037 | ±0.4451 |
| σ_y (Std. Error) | 0.2195 | |
| Δ (delta) | 5.3896 | |

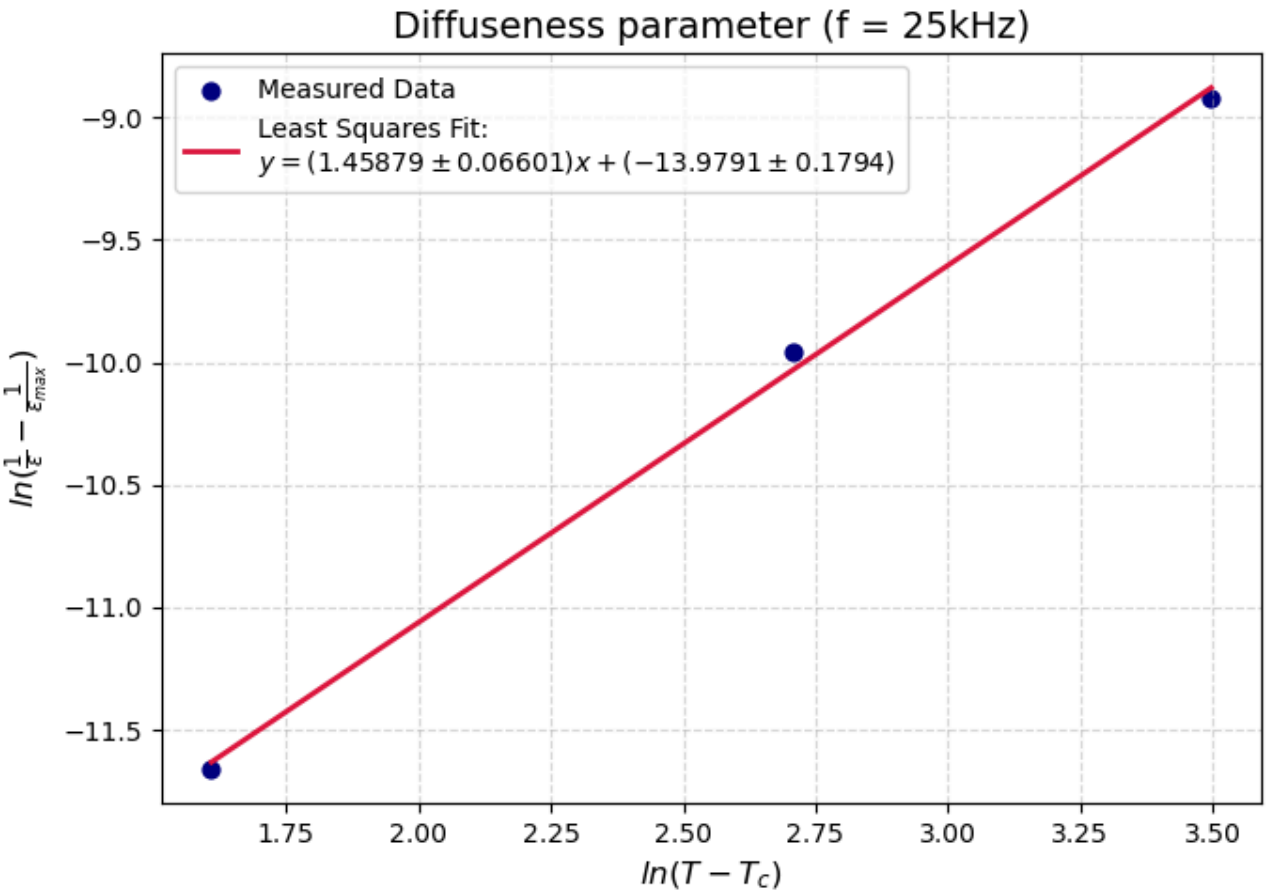
| Measured vs Fitted Values | | |
|---|---|---|
| x | y (measured) | y (fit) |
| 1.609 | -11.965 | -11.89 |
| 2.708 | -9.927 | -10.106 |
| 3.497 | -8.929 | -8.825 |

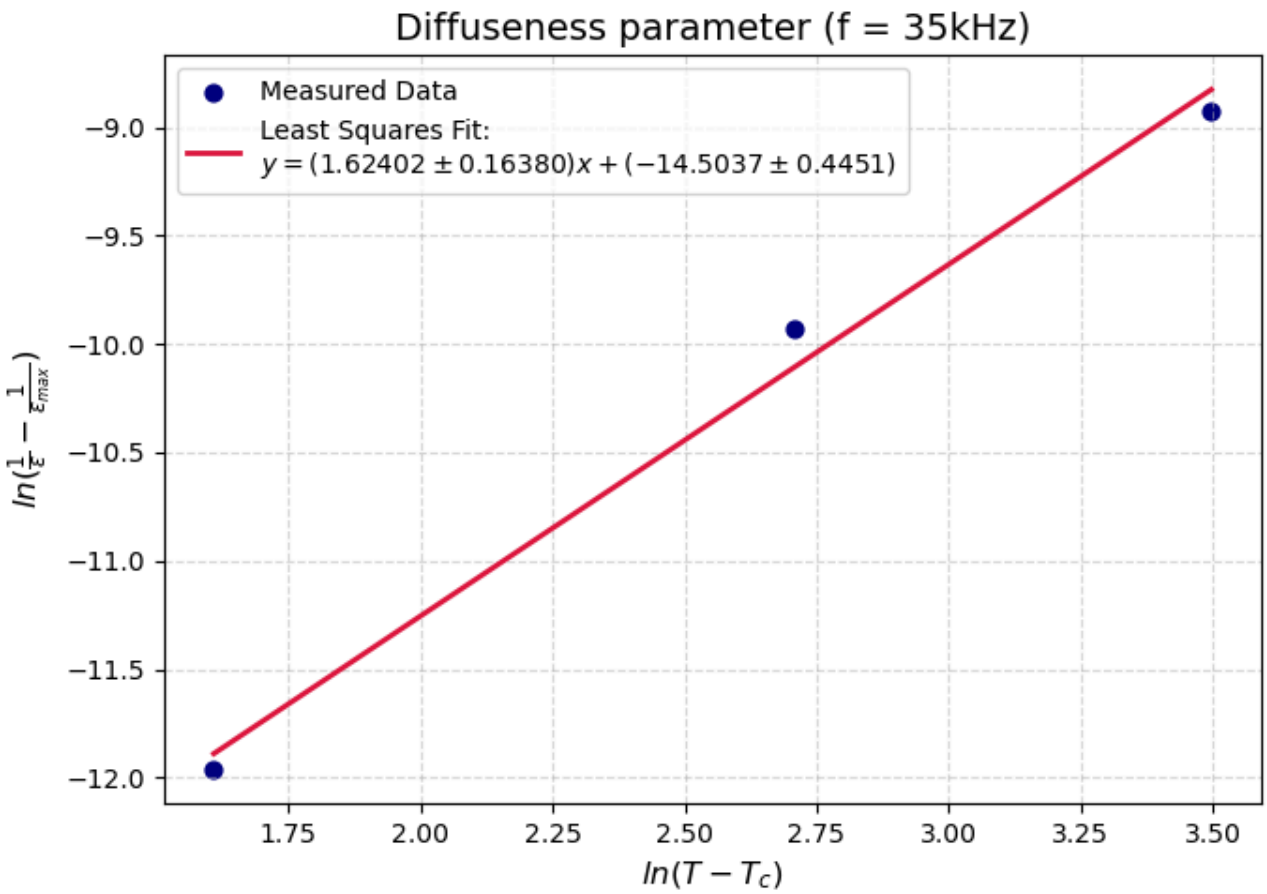
| Input Data | | | | |
|---|---|---|---|---|
| i | x | y | $x^2$ | xy |
| 1 | 1.609 | -11.36 | 2.59 | -18.283 |
| 2 | 2.708 | -9.852 | 7.334 | -26.681 |
| 3 | 3.497 | -8.918 | 12.226 | -31.183 |
| Σ | 7.814 | -30.13 | 22.149 | -76.146 |

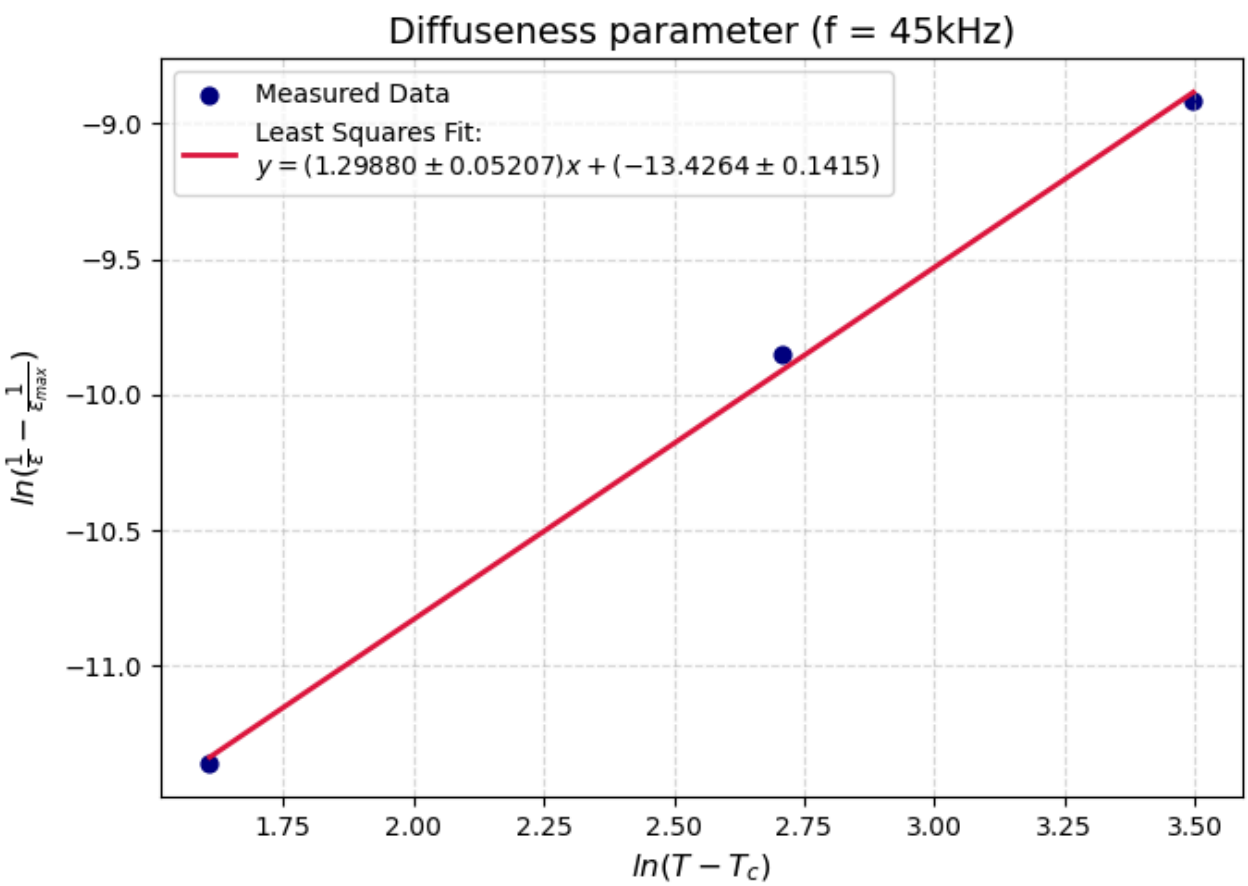
| Fit Results & Statistical Errors | | |
|---|---|---|
| Parameter | Value | Uncertainty |
| Slope ($a_1$) | 1.2988 | ±0.0521 |
| Intercept ($a_0$) | -13.4264 | ±0.1415 |
| σ_y (Std. Error) | 0.0698 | |
| Δ (delta) | 5.3896 | |

| Measured vs Fitted Values | | |
|---|---|---|
| x | y (measured) | y (fit) |
| 1.609 | -11.36 | -11.336 |
| 2.708 | -9.852 | -9.909 |
| 3.497 | -8.918 | -8.885 |


Diffuseness parameter (f = 15kHz)
Measured Data
Least Squares Fit:
$y = (1.81289 \pm 0.19779)x + (-15.1636 \pm 0.5374)$
$ln(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}})$
$ln(T - T_c)$
−9.0
−9.5
−10.0
−10.5
−11.0
−11.5
−12.0
−12.5
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50


Diffuseness parameter (f = 25kHz)
Measured Data
Least Squares Fit:
$y = (1.45879 \pm 0.06601)x + (-13.9791 \pm 0.1794)$
$ln(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}})$
$ln(T - T_c)$
−9.0
−9.5
−10.0
−10.5
−11.0
−11.5
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50


Diffuseness parameter (f = 35kHz)
Measured Data
Least Squares Fit:
$y = (1.62402 \pm 0.16380)x + (-14.5037 \pm 0.4451)$
$ln(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}})$
$ln(T - T_c)$
−9.0
−9.5
−10.0
−10.5
−11.0
−11.5
−12.0
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50


Diffuseness parameter (f = 45kHz)
Measured Data
Least Squares Fit:
$y = (1.29880 \pm 0.05207)x + (-13.4264 \pm 0.1415)$
$ln(\frac{1}{\varepsilon} - \frac{1}{\varepsilon_{max}})$
$ln(T - T_c)$
−9.0
−9.5
−10.0
−10.5
−11.0
1.75
2.00
2.25
2.50
2.75
3.00
3.25
3.50