

Investigating the effect of temperature on the dielectric
constant of ceramic (BaTiO_3)

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Abstract

According to literature, the dielectric constant (k) of barium titanate, a ferroelectric ceramic material that is very commonly used in Class 2 capacitors as the dielectric matter, shows irregular behavior for varying temperatures. Thus, the aim of this particular investigation was to observe and study how the temperature affected the dielectric constant (k) of barium titanate. As it is only possible to speak of dielectric in the presence of a capacitor, an experimentation was carried out to observe the temperature's effect on capacitance. After obtaining the data of varying capacitance through increased temperature, dielectric constant values were calculated according to the equation $k = \frac{Cd}{A\epsilon_0}$, where k is the alleged dielectric constant of barium titanate. After such calculation, the relation between the temperature and the dielectric constant was investigated. It proved to be a quadratic one. However, to obtain a linear relation and thus a formula, the radicals of the dielectric constant values were taken. A robust formula, $\sqrt{k} = -0.303T + 40.528$, was derived using the aforementioned linear graph with a Pearson's r correlation coefficient value of 0.94. In return, this study in overall successfully investigated the behavior of the dielectric constant of barium titanate and found a fairly accurate (94.616%) formula for such behavior. This study was significant in that it illustrated an accurate methodology to understand the behaviors of various dielectric matters, which would then lead to the discovery of even more diverse uses of capacitors. For instance, considering this investigation obtained statistically significant ($p < 0.05$) data and an accurate formula, one can say that it is possible to create a temperature sensor from barium titanate Class 2 capacitors.

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1. INTRODUCTION

1.1 Capacitance

Capacitance is simply the ability of a body to store electrical charge [12]. Any object that can be electrically charged will have capacitance. A common energy storage device is the parallel-plate capacitor, a device that stores electric charge. Although these devices, capacitors, may have different shapes and sizes, capacitors are ultimately two conductors which carry equal yet opposite charges [Figure 1].

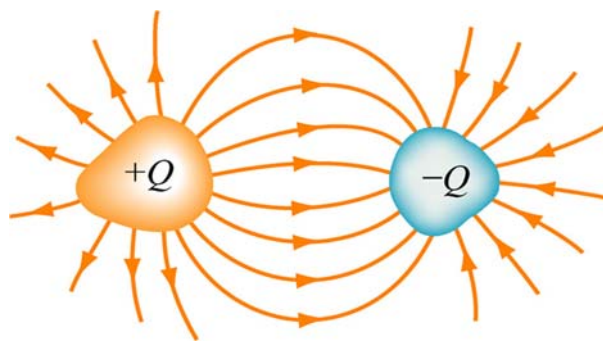


Figure 1: Basic Configuration of a Capacitor; reprinted from web.mit.edu/viz/EM/visualizations/notes/modules/guide05.pdf

A simple capacitor consists of two conducting plates of area A , which are parallel to each other, and separated by a distance d , as shown in Figure 2.

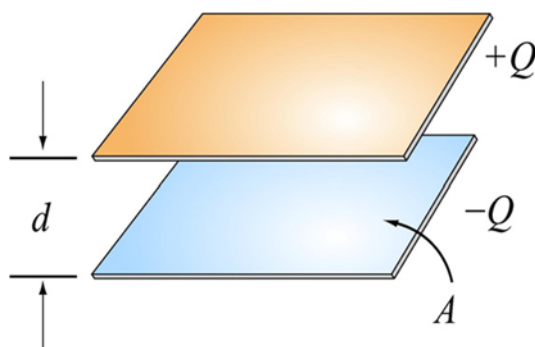


Figure 2 Illustration of a Parallel-Plate Capacitor. Reprinted from web.mit.edu/viz/EM/visualizations/notes/modules/guide05.pdf

The amount of charge Q stored in a capacitor is directly and linearly proportional to ΔV . Thus, it can be expressed as $Q = C \Delta V$, where C is a positive constant called capacitance, whose SI unit is farad (F). Thus, we may write $1\text{F} = 1 \text{ C/V}$. In the market, most common capacitance values range from picofarad ($1\text{E-}12\text{F}$) to millifarad ($1\text{E-}3$).

A capacitor is generally represented as [Figure 3] in an electrical circuit.



Figure 3 Illustration of the capacitor inside an electrical circuit

Capacitance (C) depends on geometric factors and the dielectric material the capacitor encloses [12]. Here, geometric factors mean two simple concepts: the area of the parallel plates and the distance between two parallel plates. The capacitance (C) increases linearly with the area A since for a potential difference ΔV , a bigger plate can hold more charge; C is inversely proportional to d , the distance of separation. The reason for this is, the smaller the value of d , the smaller the potential difference $|\Delta V|$ for a certain Q . C is also linearly proportional to the permittivity of space (or the material) between the parallel plates (for this concept, refer to section 1.2). From such definition, we may write that the capacitance at a parallel-plate capacitor is $C = \frac{k\epsilon_0 A}{d}$, where A is the area of parallel plates, d is the distance between two parallel plates, ϵ_0 is the dielectric constant of vacuum (also known as the permittivity of free space), and k is a multiplier of ϵ_0 (i.e. k is a relative permittivity constant).

1.2 Permittivity and Dielectric

Permittivity is a measure of how much resistance is encountered when an electric field is formed in a medium [10]. Permittivity is involved in the expression of capacitance ($C = \frac{k\epsilon_0 A}{d}$) because it affects the amount of charge that has to be placed on a capacitor to obtain a certain net electric field [5]. If there is a polarizable medium (which is called as dielectric), more charge is needed to achieve a net electric field. As a result, the effect of such a polarizable medium is stated in terms of a relative permittivity, with respect to that of vacuum. For instance, we may write that $C = \frac{\epsilon_0 A}{d}$ for vacuum. However, if there is a polarizable medium/material between the parallel plates of the capacitor, one needs to include the relative permittivity (k). So we generally use the expression $C = \frac{k\epsilon_0 A}{d}$.

The term dielectric is related to the aforementioned term, polarizable medium. A dielectric material is an electrical insulator that can be polarized by an applied electric field [9]. In the presence of a dielectric material in an electric field, electric charges do not flow through the material as they do in a conductor, but slightly vicissitude from their average equilibrium positions. This eventually results in dielectric polarization. As a result, positive charges are displaced toward the field and negative charges shift in the opposite direction as shown by Figures 4 and 5. This creates an internal electric field that reduces the overall field within the dielectric itself. If a dielectric consists of weakly-bonded molecules, those molecules not only become polarized, but also realign symmetrically to the field.

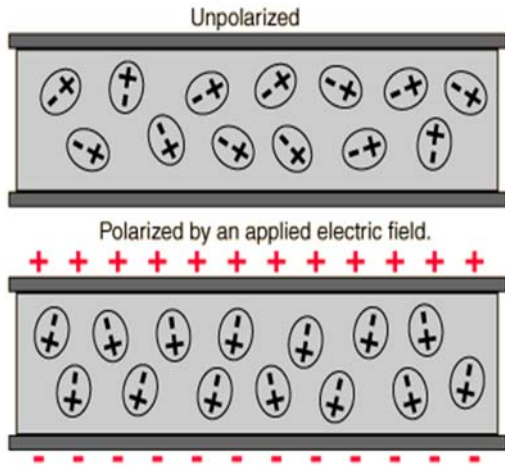


Figure 4: Illustration of the comparison of unpolarized and polarized media. Reprinted from <http://web.mit.edu/viz/EM/visualizations/notes/modules/guide05.pdf>

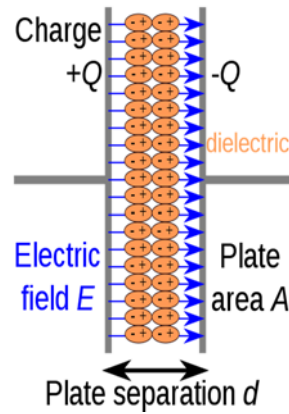


Figure 5: Illustration of the polarization of molecules. <http://web.mit.edu/viz/EM/visualizations/notes/modules/guide05.pdf>

The study of dielectric materials deeply concerns electrical and circuitry applications. Dielectric materials are of significant importance in the capacitance phenomena, which generally use solid dielectric material with high permittivity as the medium between the parallel plates. Figure 5 illustrates the dielectric medium between the oppositely charged plates.

In the market, capacitors have tremendously diverse uses, ranging from PlayStation processors to humidity sensors. Capacitors are so widespread today that it is very rare to face an electronic product without a capacitor for some purpose. Capacitors are used in many essential aspects of our lives: energy storage, power pulse and conditioning, suppression (e.g. noise filters), motor starters, signal processing, and sensing. These multi-faceted uses typically require different configurations of capacitors. Capacitors designed for sensing generally exploit from changing dielectric constant. For example, capacitors with an exposed dielectric (usually silicon) are utilized to measure the humidity of air.

Every charged substance has a dielectric constant (k) between the ranges $1\epsilon_0$ (vacuum) and $\infty \epsilon_0$ (perfect/ideal conductance). The dielectric constant (k) of a substance, however, is subject to change. The factors that affect the dielectric constants of substances vary by substance. For instance, while pressure can change the dielectric constant of air, it would not change the dielectric constant of wood at all. How humidity will change the dielectric constant of air will be different than how it will change that of silicon. It is possible to face many researches carried out to investigate the factors that

affect the dielectric constants of particular substances, e.g. silicon. This particular physics extended essay involves a similar approach. The aim of this study is to investigate the effect of temperature on the dielectric constant of ceramic (barium titanate), which is the dielectric material of a 1nF capacitor. According to literature, the dielectric constant of barium titanate is thought to change irregularly with respect to temperature [7]. The literature also suggests that the dielectric constant of barium titanate changes significantly with respect to temperature [2].

It is therefore essential to discuss the concept and definition of temperature and its particular significance in this work.

1.3 Temperature

Temperature is the measure of how hot or cold a body is [3]. A more convenient definition would be: a measure of the mean translational kinetic energy associated with the disordered microscopic motion of atoms and molecules. The flow of heat is from the higher temperature region toward the lower [3, 6]. Temperature is an intensive property, which means it is independent of the amount of material present, in contrast to energy, an extensive property, which is proportional to the amount of material in the system. For example a spark may well be as hot as the Sun [12]. It can also be indicated as the effect of the thermal energy arising from the motion of microscopic particles such as atoms, molecules and photons.

The lowest theoretical temperature is called the absolute zero, however it cannot be achieved in any actual physical device. It is denoted by 0 K on the Kelvin scale, $-273\text{ }^{\circ}\text{C}$ on the Celsius scale. In matter at absolute zero, the motions of microscopic constituents are minimal; moreover their kinetic energies are also minimal.

1.4 Temperature and Capacitance

Temperature is important in all fields of natural science, including physics, geology, chemistry, atmospheric sciences and biology. Temperature is also of significant importance in this particular study as it will change the dielectric constant of barium titanate, which is a type of ferroelectric ceramic and is the utilized dielectric of a 1-nanoFarad capacitor at 25 °C. As mentioned, barium titanate is a type of dielectric matter whose dielectric constant varies between 100 and 1250 [2], a significant range.

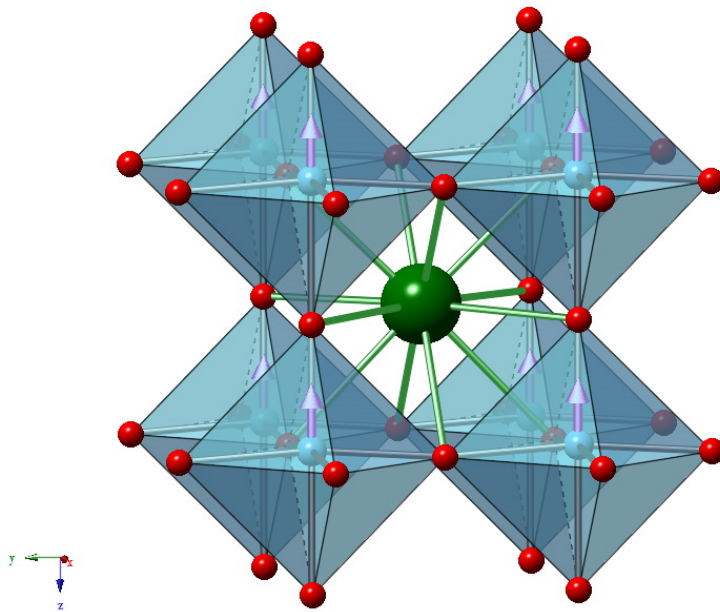


Figure 5: Molecular structure of barium titanate. Below 120 °C, the structure is tetragonal, the relative positions of the ions causes a concentration of positive and negative charges toward opposite ends of the crystal. Reprinted from <http://www.crystalmaker.com/crystalmaker/gallery/resources/gallery2/>

2. DESIGN AND METHOD

2.1 Aim of study

The dielectric constant of substances will vary by different external factors for different substances. This study will study the behavior of the dielectric constant of barium titanate (a type of ferroelectric ceramic), whose behavior with respect to altering temperature is described as irregular [7]. As it is possible to observe such behavior through capacitance, it was first desired to observe the capacitance's behavior. Then it would be possible to observe the behavior of dielectric with respect to temperature, from the equation $C = \frac{k\epsilon_0 A}{d}$. Observing and analyzing behavior, and thus developing a methodology will be pivotal to uncover new functions or purposes of capacitors. For example, if this study succeeds at observing a particular significant behavior of barium titanate's dielectric constant, an electronic temperature sensor can be built. It is, in fact, the case when various electronic sensors are made. For instance, humidity sensors exploit the change of the dielectric constants of their respective dielectric material and thus measure humidity from the change in capacitance [8].

In short, this study tries to answer the very following question:

2.1.1 Research Question

How does the dielectric constant of barium titanate, a ferroelectric ceramic substance, change as it is gradually subject to higher temperatures, whilst other environmental conditions (external pressure and humidity) are kept the same?

2.1.2 Hypothesis

The capacitance of a ceramic capacitor will decrease with increased temperature, because of its molecular structure. As its Curie Temperature is relatively low (120 °C), its ferroelectric behaviors will change at low temperatures as well. The structure of BaTiO₃ will become closer to cubic, leaving no net polarization of charge. Hence its dielectric constant will decrease.

2.1.3 Material and Equipment

- 10 of 1nF identical (at 25 °C) barium titanate capacitors.
- One multi-meter that can measure and output capacitance
- One Vernier electronic temperature probe to measure the temperature of the capacitor
- One Vernier data logger to read the temperature value obtained from the electronic temperature probe
- One ethanol burner to heat the capacitor

2.2 Variables

2.2.1 Independent variable:

- Temperature that the 1 nF (at 25 °C) ceramic capacitor is exposed to

2.2.2 Dependent variable:

- The capacitance of the capacitor.

2.2.3 Controlled variables:

For the accuracy of the results, some certain factors are, in an effort, kept constant. The material the dielectric substance is made, which is ceramic, is kept constant. The same multi-meter is used throughout the experiment. Identical 5 capacitors are used, therefore their material of the wires, copper, is also kept the same. The environmental conditions, which are humidity and, are kept identical. The humidity and pressure affect capacitance [8, 11]. While measuring the temperature of the capacitor, the place where the temperature probe is contacted is also kept the same; the temperature measurements were always carried out from the capacitor's tip.

2.3 Method

For the observation of change of ceramic's dielectric constant with respect to increased temperature, a particular method was followed. Initially, the change of capacitance had to be observed, and then from the equation $C = \frac{k\epsilon_0 A}{d}$, the dielectric constant k could be derived ($k = \frac{Cd}{A\epsilon_0}$), since the distance between the plates, the area of the plates and the permittivity of free space are known. Therefore, an experimentation to observe the correlation between the temperature and the capacitance was carried out.

First, the capacitor was placed inside the multi-meter to read an initial capacitance at room temperature (25 °C), and the temperature probe was contacted to the capacitor's tip. Then, ethanol burner was filled ethanol, and its wick brought 5 cm close to capacitor's tip. Afterwards the burner was ignited using a lighter. The capacitor was heated to 35 °C, 45 °C, 55 °C, 65 °C, 75 °C, 85 °C, and 95 °C respectively. The temperature of the capacitor was always tracked with the electronic temperature probe. For each of these temperature values, the measurements of capacitance were read from the multi-meter and noted down. The whole process is carried out with constant environmental conditions (humidity and pressure) as it is carried out on the same location. For the accuracy of results obtained, this method was carried out by 9 additional identical ceramic BaTiO₃ capacitors. The experimental setup during the heating process of capacitor is shown by the schematic below [Figure 5]. The realization of the setup can be seen from Figure 6.

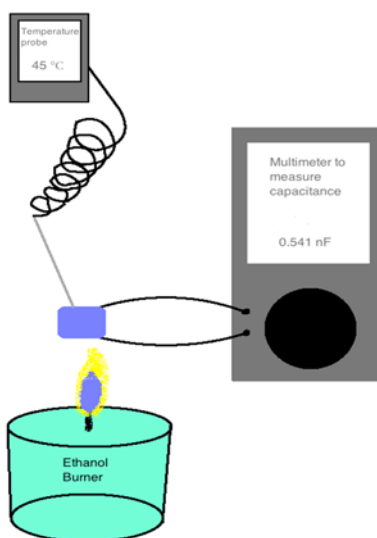


Figure 6: Illustration of the experiment



Figure 7 Realization of the experimental setup with the ethanol burner (left), the multi-meter (middle) and the temperature probe and data logger (right).

After the data collection of differing capacitance values, the dielectric constant k was computed for each temperature value (25 °C, 35 °C, 45 °C, 55 °C, 65 °C, 75 °C, 85 °C, 95 °C) from the equation $k = \frac{Cd}{A\epsilon_0}$, where C is the measured capacitance from the experiment, d is the distance between parallel plates of the capacitor (1 μ m), A is the area of the plates of the capacitor (0.1 μ m²) and ϵ_0 is the permittivity of free space (8.85 * 10⁻¹² F/m). Finally after this computation process, the relation of barium titanate's (BaTiO₃) dielectric constant between temperature was delineated and analyzed with a graph.

3. DATA COLLECTION AND PROCESSING

After the aforementioned method was carried out, the following raw data were obtained.

| TEMPERATURE (± 0.1 °C) | 25.0 °C | 35.0 °C | 45.0 °C | 55.0 °C | 65.0 °C | 75.0 °C | 85.0 °C | 95.0 °C |
|---|---------|---------|---------|---------|---------|---------|---------|---------|
| CAPACITANCE VALUES FOR 10 TRIALS (± 0.001 nF) | 0.956 | 0.798 | 0.635 | 0.501 | 0.381 | 0.273 | 0.253 | 0.118 |
| | 0.960 | 0.776 | 0.643 | 0.528 | 0.392 | 0.285 | 0.191 | 0.114 |
| | 0.980 | 0.788 | 0.620 | 0.554 | 0.392 | 0.293 | 0.162 | 0.156 |
| | 0.952 | 0.791 | 0.656 | 0.508 | 0.386 | 0.321 | 0.192 | 0.121 |
| | 0.913 | 0.733 | 0.669 | 0.511 | 0.361 | 0.286 | 0.191 | 0.151 |
| | 1.008 | 0.839 | 0.698 | 0.504 | 0.394 | 0.275 | 0.159 | 0.124 |
| | 0.964 | 0.788 | 0.640 | 0.505 | 0.429 | 0.264 | 0.194 | 0.129 |
| | 0.991 | 0.795 | 0.613 | 0.457 | 0.339 | 0.297 | 0.228 | 0.053 |
| | 0.992 | 0.783 | 0.622 | 0.486 | 0.382 | 0.243 | 0.179 | 0.138 |
| | 0.889 | 0.824 | 0.621 | 0.506 | 0.389 | 0.272 | 0.186 | 0.119 |

Table-1: Illustration of the raw data obtained from the aforementioned method in section 2.3. Uncertainty comes from the sensitivity of the multi-meter.

To ensure the statistical significance of the data obtained between consecutive temperatures, one-tailed t-tests were made among the trials ($p < 0.05$). In an attempt to know the uncertainties, standard deviations for each group (e.g. the capacitance values for 35 °C) have also been calculated. To observe the trend between increasing temperature and capacitance, mean of capacitance values were calculated for each reference-point temperature (25 °C, 35 °C, 45 °C, 55 °C, 65 °C, 75 °C, 85 °C, 95 °C). For the experimental errors, standard deviation was used to show uncertainties. These are all illustrated at the Table-2, below.

| TEMPERATURE (± 0.1 °C) | 25 °C | 35°C | 45°C | 55°C | 65°C | 75°C | 85°C | 95°C |
|--|-------|-------|-------|-------|-------|-------|-------|-------|
| ARITHMETICAL MEAN CAPACITANCE VALUES (nF) | 0.961 | 0.792 | 0.641 | 0.506 | 0.385 | 0.281 | 0.194 | 0.122 |
| STANDARD DEVIATION | 0.036 | 0.028 | 0.026 | 0.025 | 0.023 | 0.020 | 0.028 | 0.028 |

Table-2: The processed mean data of the capacitance values with respect to temperature. Standard deviations are calculated to show uncertainties.

As the relevant data were harvested, it is now pretty much possible to observe the relation between the capacitance of the ceramic (barium titanate) capacitor and the temperature via a graph.

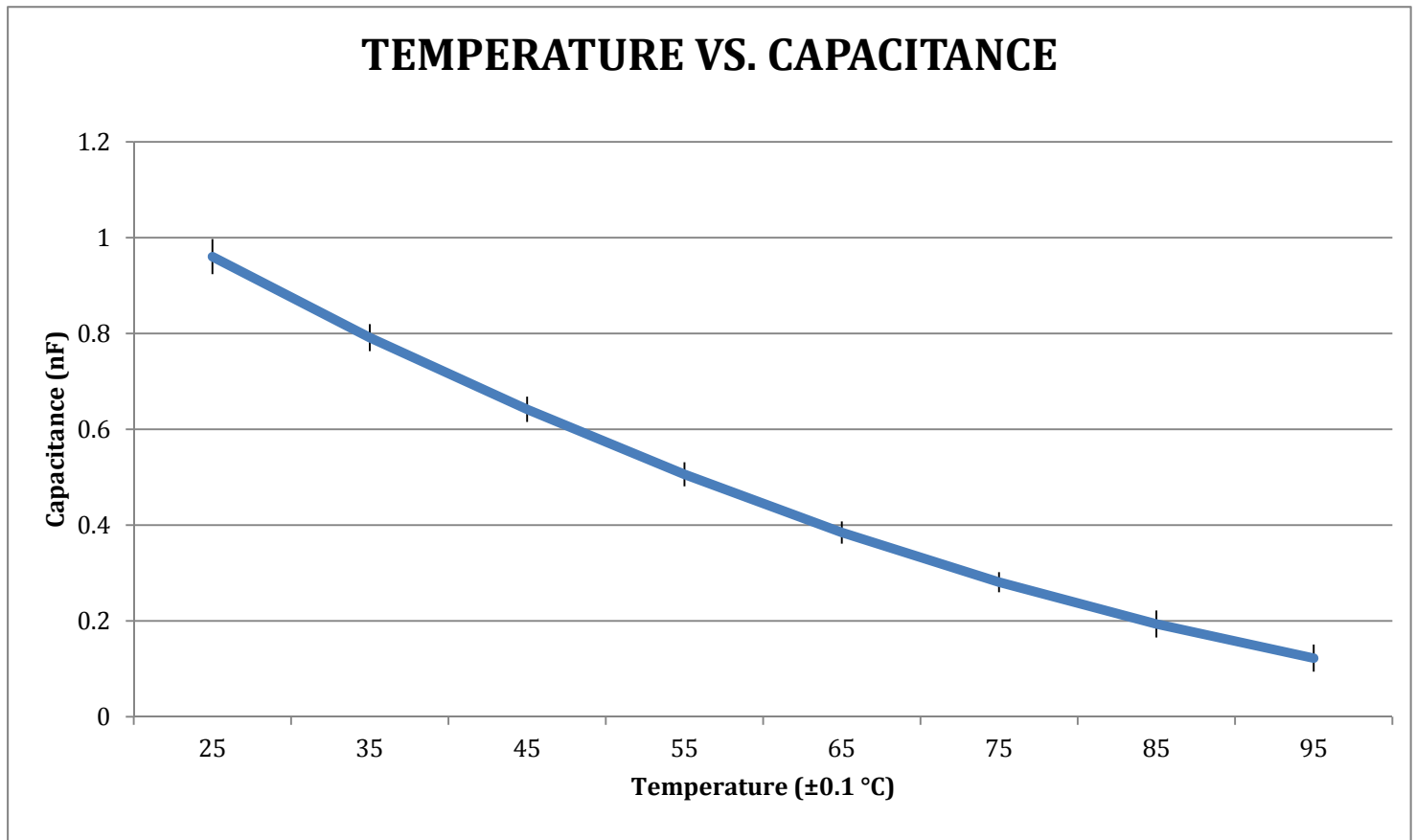


Figure 8 Illustration of the correlation between the temperature and capacitance. Uncertainties show standard deviation.

However, the ultimate goal of this particular investigation was to observe the relation between the dielectric constant (k) of ceramic (barium titanate) and the temperature, not solely the capacitance and the temperature. As we know from the equation $C = \frac{k\epsilon_0 A}{d}$ that dielectric constant (k) is proportional to C , the trend between the dielectric constant of the ceramic and the temperature will be very similar.

From the equation $C = \frac{k\epsilon_0 A}{d}$, we can algebraically write $k = \frac{Cd}{A\epsilon_0}$. As a result, we can compute the relevant dielectric constant values of ceramic (barium titanate) for different temperatures.

For one instance, the respective dielectric constant of the ceramic for 35 °C was calculated as follows:

$k = \frac{Cd}{A\epsilon_0}$, where C (capacitance) is, on arithmetic average, $0.792 * 10^{-9}$ F, d (distance between parallel plates) is $1\mu\text{m}$, A (the area of the plates of the capacitor) is $0.1\mu\text{m}^2$ and ϵ_0 is the permittivity of free space ($8.85 * 10^{-12}$ F/m).

$$\text{Thus, } k \text{ at } 35 \text{ }^\circ\text{C} = \frac{0.792 * 10^{-9} * 10^{-6}}{10^{-7} * 8.85 * 10^{-12}} = 894.91$$

For every respective mean capacitance at temperatures 25 °C, 35 °C, 45 °C, 55 °C, 65 °C, 75 °C, 85 °C, 95 °C, the calculation above was carried out. There is also a propagation of standard deviation. As the expression $\frac{10^{-9} * 10^{-6}}{10^{-7} * 8.85 * 10^{-12}}$ constantly multiplies the capacitance values for the calculation of dielectric constants, it will also multiply the initial standard deviation values. Table-3 shows the results of calculations of both dielectric constants and standard deviations.

| TEMPERATURE (± 0.1 °C) | 25 °C | 35°C | 45°C | 55°C | 65°C | 75°C | 85°C | 95°C |
|---|---------|--------|--------|--------|--------|--------|--------|--------|
| DIELECTRIC CONSTANT OF BARIUM TITANATE | 1085.88 | 894.91 | 724.29 | 571.75 | 435.03 | 317.51 | 219.21 | 137.85 |
| STANDARD DEVIATION | 40.678 | 31.751 | 29.378 | 28.248 | 25.989 | 23.729 | 31.638 | 31.638 |

Table-3: Calculated dielectric constant of barium titanate with respect to varying temperatures.

As the relevant data was obtained, it is possible to observe the trend between the dielectric constant of the ceramic capacitor (barium titanate) and temperature via a graph.

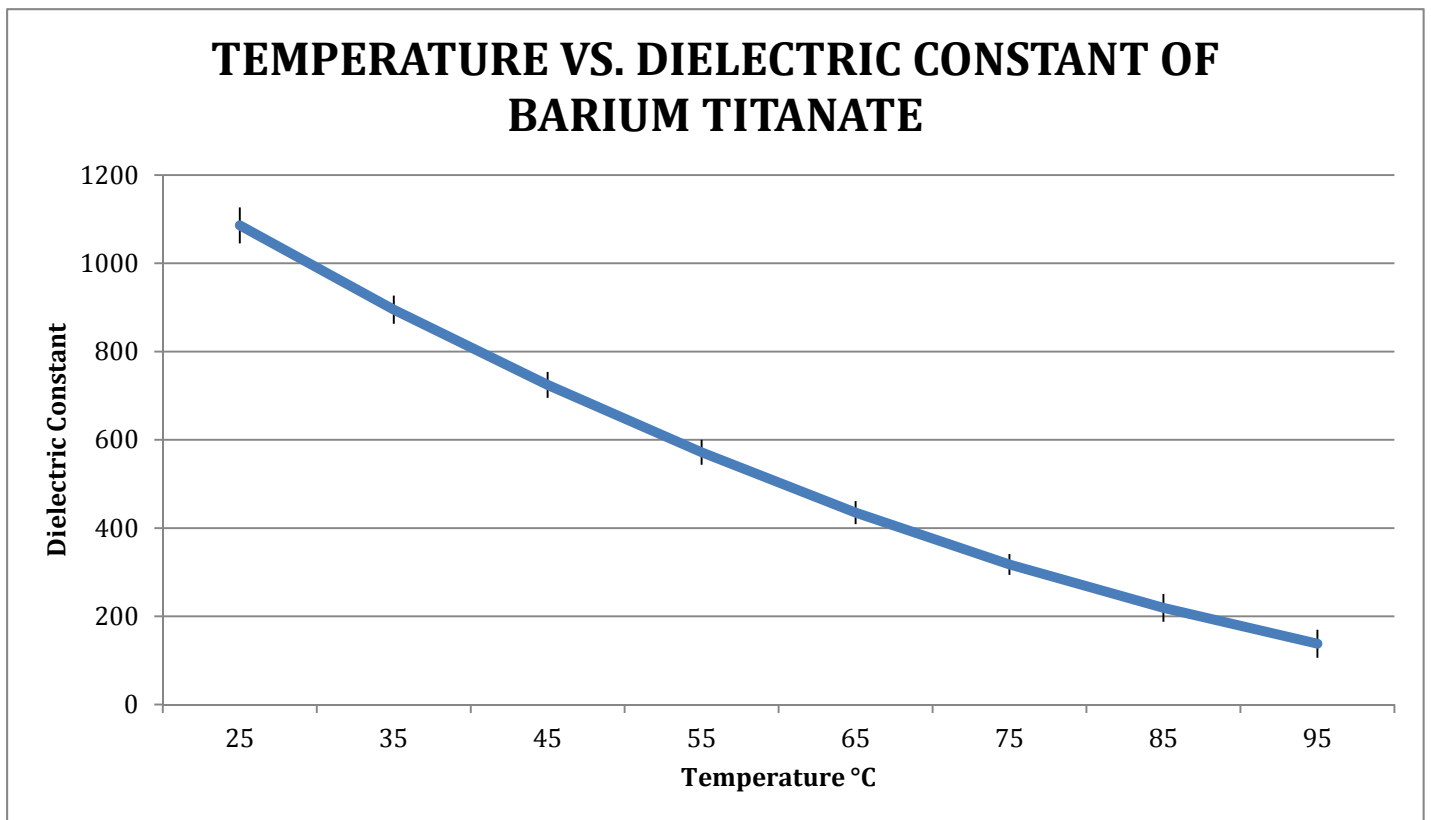


Figure 9 The ultimate relation between temperature and the dielectric constant of barium titanate. Uncertainties show standard deviation.

As seen, the relation between the temperature and the dielectric constant of barium titanate is somewhat exponential. This very much resembles an inversely proportional radical function. Thus, it would be possible to observe an inversely proportional and linear relation if the radicals of the dielectric values are computed. Also, the standard deviation values are included for the uncertainties.

| TEMPERATURE (°C) | 25 °C | 35°C | 45°C | 55°C | 65°C | 75°C | 85°C | 95°C |
|---|--------|--------|--------|--------|--------|--------|--------|--------|
| RADICAL OF THE DIELECTRIC CONSTANT OF BARIUM TITANATE | 32.953 | 29.915 | 26.913 | 23.911 | 20.857 | 17.819 | 14.806 | 11.741 |
| STANDARD DEVIATION | 0.549 | 0.593 | 0.632 | 0.665 | 1.054 | 1.526 | 0.549 | 0.593 |

Table-4: Calculated radical dielectric constants of barium titanate with respect to varying temperatures.

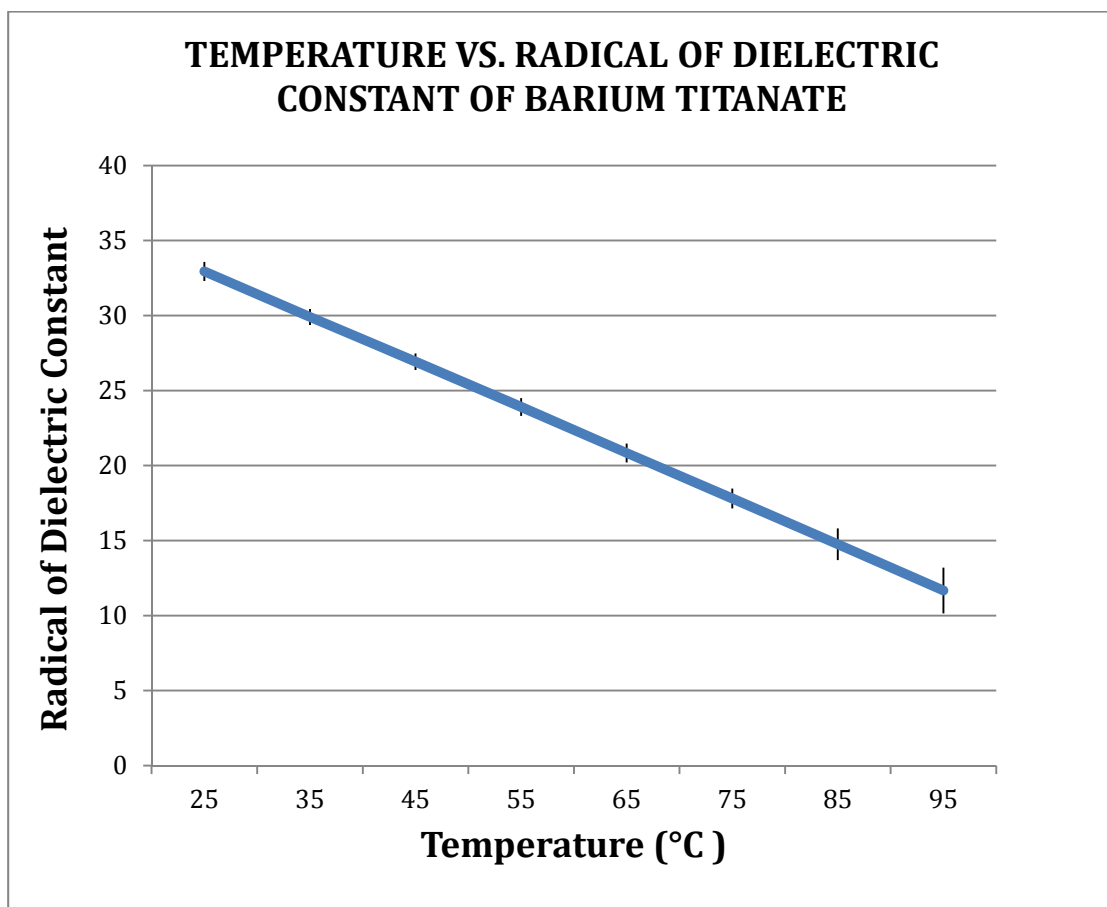


Figure 10: Graph illustrating the linear relation between the temperature and the radical of the dielectric constant of barium titanate. Uncertainties show standard deviation.

As seen from Figure 10, the relation between the temperature and the radical of the dielectric constant of barium titanate is linear. To quantify this, Pearson's r correlation coefficient was calculated, and found as 0.94. This mathematically proves the significance of linear relation.

Based on this linear relation, it is very much possible to find a formula for the relation. The graph above can be algebraically represented as $y = mx + n$, where m is the slope and n is the y-intercept of the graph. Similarly, we may write that $\sqrt{k} = mT + n$, where k is the dielectric constant of the ceramic, m is the slope, T is the temperature in Celsius and n is the y-intercept. The slope is calculated as follows: $\frac{\sqrt{k_{initial}} - \sqrt{k_{final}}}{T_{initial} - T_{final}} = \frac{32.953 - 11.741}{25 - 95} = -0.303$. Now, the equation turned out as $\sqrt{k} = -0.303T + n$. It is now needed to find n , the y-intercept. Substituting values (25, 32.953), n is found as 40.528.

Thus, it is now feasible to algebraically represent the relation between the temperature and the dielectric constant of Barium Titanate:

$$\sqrt{k} = -0.303T + 40.528$$

where k is the dielectric constant and T is the temperature in Celsius. The equation can also be revised as a quadratic one:

$$k = (-0.303T + 40.528)^2$$

Note that the two equations above are algebraically identical.

Although it will be discussed later on section 4, the x-intercept of the graph [Figure 10] is calculated as 133.756.

Error Calculation

The graph below [Figure-11], which is identical to the Figure-10, includes two worst fit lines to illustrate the possible rate of error made. It is possible to calculate the percentage reliability of the formula $\sqrt{k} = -0.303T + 40.528$ with the formula $\frac{m_{max} - m_{min}}{2} * 100$ where m_{max} is the worst fit graph with the maximum slope, m_{min} is the worst fit with the minimum slope and m_{best} is the slope of the best fit graph.

$$m_{max} = \frac{(32.953 + 0.549) - (11.741 - 0.593)}{25 - 95} = -0.319$$

$$m_{min} = \frac{(32.953 - 0.549) - (11.741 + 0.593)}{25 - 95} = -0.287$$

$$\frac{\frac{-0.319 + 0.287}{2}}{-0.303} * 100 = 5.384$$

$$\mathbf{Error = 5.384 \%}$$

Thus, the possible error of the formula $\sqrt{k} = -0.303T + 40.528$ is 5.384%, which means it is 94.616% reliable.

TEMPERATURE VS. RADICAL OF DIELECTRIC CONSTANT OF BARIUM TITANATE

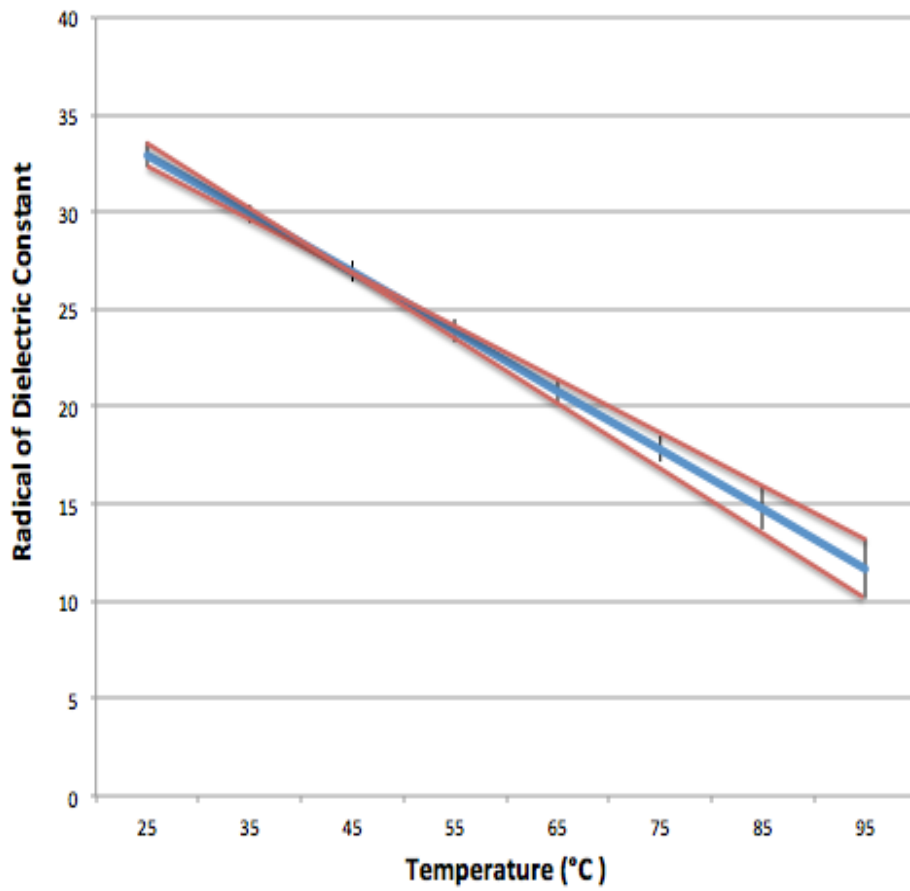


Figure 11 Illustration of the linear relation of temperature and the dielectric constant of barium titanate with two worst fit lines. Uncertainties show standard deviation.

4. CONCLUSION AND EVALUATION

This particular study's main goal was to observe and analyze the relation between temperature and the dielectric constant (k) of barium titanate, a ferroelectric ceramic material often used as the dielectric material of Class 2 capacitors. The literature suggested that the behavior of the barium titanate's dielectric constant (k) was irregular [7]. For this, this study aimed to investigate such alleged behavior. As the dielectric material is present inside a capacitor, and thus it was only possible to observe it through a capacitor, we first conducted an experiment to observe the relation between temperature and capacitance. The capacitance values for varying temperature values (25 °C – 95 °C) have thus been measured. And with the help of the equation, $C = \frac{k\epsilon_0 A}{d}$, the values of the dielectric constants (k) were calculated. These k values ranged between 1085.88 (at 25°C) and 137.85 (at 95 °C). These dielectric constant values of barium titanate fell well inside the ranges suggested by the literature [2], which are 100 and 1250. When these values of dielectric constants were delineated on a graph, this pure relation between temperature and the dielectric constant of barium titanate showed a somewhat exponential relation. To find a robust, formulaic relation between temperature and the dielectric constant, a linear relation had to be found. A graph (Figure-10) was sketched using the radicals of the dielectric values versus temperature values. This eventual investigation, graph (Figure-10) obtained in the previous section showed an almost-perfect linear relation, with a Pearson's r correlation coefficient 0.94. This graph, in return, helped find a robust algebraic relation between temperature and the dielectric constant (k). From the simple representation of a linear function, $y = mx + n$, and the values obtained, we derived a formula for the variation of dielectric constant with respect to temperature: $\sqrt{k} = -0.303T + 40.528$. This formula can also be revised as $k = (-0.303T + 40.528)^2$.

A particular interesting point from the latest graph (Figure-10) was the x-intercept, which is calculated as 133.756. This value is very close to the (by 88.54 %) to the Curie Point of Barium Titanate, which is 120 °C . At the x-intercept of this graph, it is obvious to expect a capacitance of 0 nF. At its Curie Point and above, Barium Titanate's once-

tetragonal molecular structure (Figure-5) becomes cubic and there will not be a net polarization of charge [Figure-11], which would yield a very small dielectric constant k . With such an interesting coincidence, the Figure-10 clearly proves the accuracy of the results and thus the eventual formulaic representation of the relation between barium titanate's dielectric constant and temperature. What's more, at the end of Section 3, an error calculation was conducted. According to this error calculation, the obtained linear relationship and thus the formula proved to be significantly accurate (94.616%).

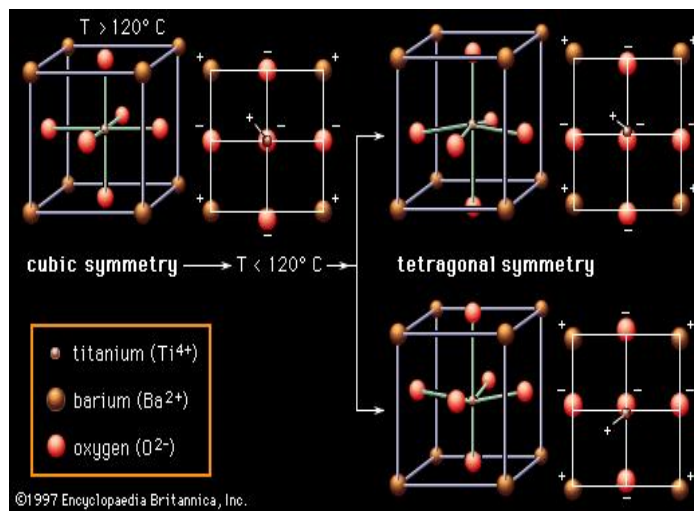


Figure 12: Illustration of the change of molecular structure of barium titanate according to its Curie Temperature.

Although the differing values of the dielectric constant of the matter fell well in the range suggested by the literature, and although the overall accuracy of the discovered relation proved to be fairly accurate (94.616%), there have been inevitable errors due to the limitation of the experiment. First of all, the capacitance is given by the equation $C = \frac{k\epsilon_0 A}{d}$, thus it is dependent to the area of the parallel plates and the distance between the parallel plates. The utilized capacitor's area was $0.1 \mu\text{m}^2$, and the distance between the parallel plates was $1 \mu\text{m}$. However, the expansion of these plates while they were being heated was not taken into account. While heating was only aimed to increase the temperature of the dielectric matter, barium titanate, it was definite that the small parallel plates were also heated. Thus, their area and the distance between them may very well have changed. This causes inaccuracy while calculating the dielectric constants from the equation $k = \frac{Cd}{A\epsilon_0}$, as d and A were always assumed as constants.

In conclusion, despite some aforementioned minor limitations, this particular study achieved its aim of observing and accurately investigating the relation between the temperature and the dielectric constant of barium titanate, a common ferroelectric ceramic material used inside the capacitors. The behavior of this type of dielectric material for varying temperatures was described as irregular, however this study shed light on the irregular behavior by finding a formula, which is 94.616% accurate, for the relation between the dielectric constant k of the barium titanate and temperature. Capacitors have tremendously diverse uses in today's world, and understanding the behaviors of other dielectric material with respect to temperature can be pivotal. For example, as statistically significant values between temperatures were obtained ($p < 0.05$), it is possible to use Class 2 barium titanate as temperature sensors. This methodology will also be useful for investigating the dielectric materials with unknown/ irregular behavior.

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