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## ***Ferroelectric Properties of Class II Ceramic Dielectrics***

### **INTRODUCTION**

The selection of a capacitor manufactured with Class II dielectric materials like X5R, X7R, X5U, Z5U, etc., offer significant advantages due to their high dielectric constant (K) and their ability to offer substantial improvement in volumetric efficiency, when compared to typical Class I, lower dielectric constant materials like NPO / COG. That said, the engineer intending to utilize these high K type of capacitors, also needs to consider the relative instability of these materials and how they might behave when subjected to actual application conditions.

### **OVERVIEW**

The most common formulation used for ferroelectric materials is comprised of Barium Titanate ( $\text{BaTiO}_3$ ) and the inherent variation in the electrical properties of this material, which can be further influenced by changes in operating temperature, can present some unexpected consequences in the field. If for example, the actual operating temperature of the capacitor is likely to transition the Curie Point of the material, the resulting change in the crystal lattice structure can have a dramatic impact on the Dielectric Constant and the effective capacitance value of the device. In addition, one needs to consider the Aging characteristics or decay in capacitance as the operating temperature drops below the Curie Point.

Furthermore, even if the operating temperature were to remain below the Curie Point, these ferroelectric dielectrics can be influenced by the application of an electric field and exhibit other features like Dielectric Absorption. Operators need to be aware that even when shorted, capacitors manufactured with a ferroelectric material can maintain a charge due to Dielectric Absorption and present a risk of shock to anyone handling the capacitor.

This paper discusses how ferroelectric materials behave when subjected to normal operating conditions associated with changes in temperature and the application of an electric field.

### **TEMPERATURE INFLUENCE TO CRYSTAL LATTICE STRUCTURE**

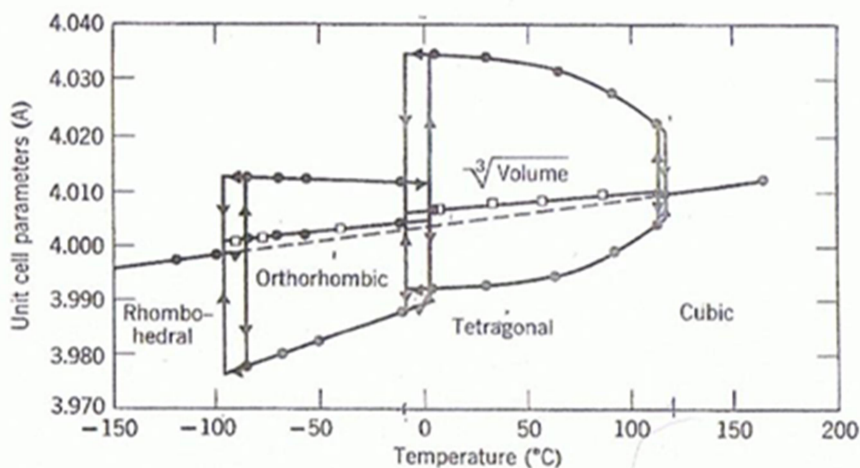
For practical purposes, Barium Titanate ( $\text{BaTiO}_3$ ) ceramics can exist in as many as four crystal phases, including Rhombohedral, Orthorhombic, Tetragonal and Cubic. These phases are temperature dependent, and certainly there is a possibility that within a specific application, a capacitor may assume one, or more of these phases, which would result in a corresponding crystallographic change (Reference Figure 1), but for the purpose of this discussion this application note will focus on the Tetragonal and Cubic structures, as they best match the more likely operating temperatures of between  $0^\circ\text{C}$  and  $+125^\circ\text{C}$



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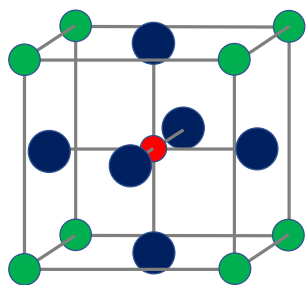
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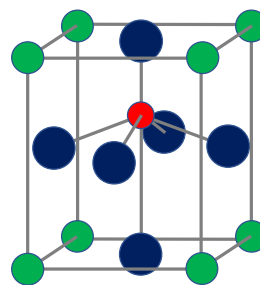
**Figure 1: Dimensions of Pseudocubic Unit Cell of BaTiO<sub>3</sub>**

Courtesy: Introduction to Ceramics. Kingery, Bowen, Uhlmann

The Curie Temperature or Curie Point is the temperature below which dielectric like Barium Titanate, gains its ferroelectric properties. Above the Curie Temperature, which depending on impurities or dopants, typically ranges from between +120 and +130°C, the crystal structure takes on a stable, cubic phase (See Figure 2a). When transitioning below the Curie Temperature, the titanium and oxygen atoms become displaced and this distortion results in a tetragonal configuration that is permanently polarized and susceptible to spontaneous polarization along a cell axis (See Figure 2b).



2a. Cubic Lattice Structure



2b. Tetragonal Lattice Structure

**Figure 2: Barium Titanate Lattice Structure**

If an external electric field were now to be applied, reorientation of these spontaneously polarized BaTiO<sub>3</sub> cells occurs in the direction of the applied field. It is the ability of this material to reorient spontaneously polarized cells that makes it desirable for ferroelectric, opto-electrical and piezoelectric applications



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## MECHANISM FOR POLARIZATION OF FERROELECTRIC CERAMICS

Unlike Class I paraelectric dielectrics, which are extremely stable and display a linear response to an applied field, Class II and Class III ferroelectric materials like those made with Barium Titanate ( $\text{BaTiO}_3$ ), demonstrate a non-linear response and exhibit a hysteresis effect of polarization (Figure 3). The resulting hysteresis loop is due to presence of permanent electric dipoles which as mentioned previously, form spontaneously below the Curie temperature of the material.

At the point in which a barium titanate capacitor first completes manufacturing, ferroelectric domains are random in orientation and the material crystal structure exhibits no sense of polarization (Figure 1, Point A). Below the Curie Temperature and with an electric field ( $E+$ ) applied, the inherently low energy barrier between atoms compels the titanium (Ti) atoms to be displaced in such a manner as to polarize the material in the direction of the applied field ( $P+$ ). This polarization affect continues, until such time as a maximum point of orientation with the electric field is achieved (Point B).

If the electric field is simply removed, the polarization affect is eliminated, but the Ti atoms remain oriented in the direction of the initial electric field (Point  $p^+$ ). The only way to remove this residual polarization would be to apply an electric field of the opposite polarity ( $E-$ ). This causes the Ti atoms to now align in the direction of the new electric field ( $P-$ ) and this reorientation continues until such time as the Ti atoms again reach a maximum point of polarization (Point C). As with the initial polarization affect, removal this electric field results in a remnant polarization of the Ti atoms in the opposite direction ( $p^-$ ).

Additional polarization cycles cause a similar realignment of the Ti atoms, which retraces the original hysteresis loop (i.e. Points  $B \rightarrow p^+ \rightarrow C \rightarrow p^-$ ). The only way to again achieve the original point of zero polarization (Point A), would be to 1) short circuit the capacitor and then 2) re-heat the capacitor above the Curie Point of the material. Of course, allowing the capacitor to again cool below the Curie Point, would again result in the spontaneous formation of permanent electric dipoles and application of an electric field would create the same hysteresis effect of polarization.

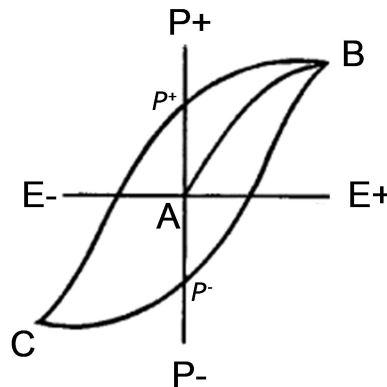


Figure 3: Hysteresis Loop

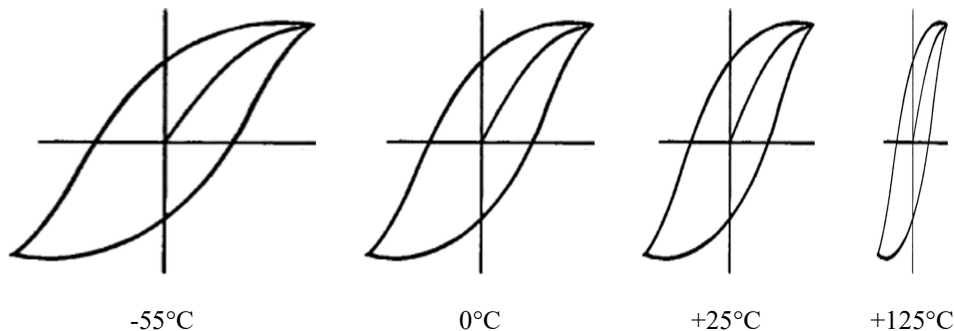


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It should be noted that the above hysteresis loop can also vary depending on the ambient temperature in which the capacitor is being operated. The lower the temperature, the greater the electric field needed to reorient the ferroelectric domains (See Figure 4).



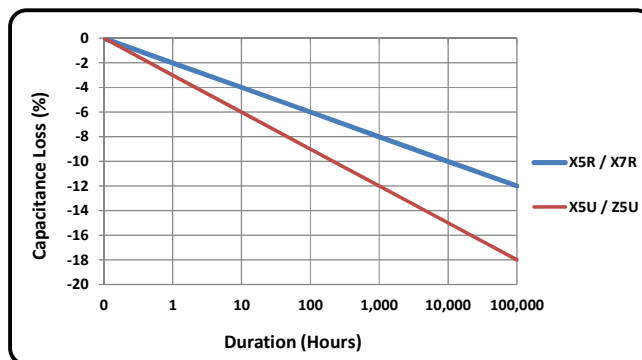
**Figure 4: Hysteresis Loop Vs Temperature**

## CAPACITOR AGING

Unlike Class I dielectrics which are stable, ceramic capacitors made with Class II ferroelectric materials like X5R, X7R, X5U and Z5U, etc., exhibit a loss in capacitance with time known as Aging. This condition occurs when the capacitor transitions from a point above its Curie temperature ( $\approx +120^{\circ}\text{C}$ ), to a point below, causing the crystal lattice structure of the material to relax and change from a cubic to a tetragonal symmetry.

Capacitance loss due to aging is time dependent and follows a logarithmic curve, which means that the degree to which the capacitance drops becomes much less pronounced the longer the part is maintained below its Curie temperature. Typical loss due to capacitor aging for an X7R capacitor would be in the range of 1 to 2% per decade hour for example and when plotted on semi-log paper, the decay approximates a straight line. Examples of typical Aging curves are shown in Fig 5.

To further illustrate this point, consider that a 1000 pF, X7R capacitor with a 2% aging rate, would be expected to measure roughly 920 pF after 1000 hours, or 41.7 days aging and that the same capacitor would need 10,000 hours or 417 days of elapsed time to lose another 2% of its sub-Curie temperature capacitance value. The predictability of Aging and subsequent long term capacitance stability, allows the manufacturer to provide a process margin that ensures that the overall loss in capacitance is maintained above a minimum threshold value.



**Figure 5: Typical Aging Curves**



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Although Aging is an inherent characteristic of all ferroelectric materials, it can be reversed by again heating the capacitor above its Curie temperature, which restores the crystalline structure back to its original cubic state. This situation will occur for example during solder installation and the operator needs to be aware that they may encounter inconsistent and rapidly changing values for capacitance, especially if the part is tested a short time after exposure. Of course, the Aging mechanism will recommence once the part is allowed to cool, following the same predictable path for capacitance loss seen during its previous Aging sequence.

## **DIELECTRIC ABSORPTION**

When discharged, it would seem only natural to assume that a capacitor if measured, would exhibit zero capacitance or residual charge across its terminals. This would in fact be a correct assumption if the device were an ideal capacitor, but in reality capacitors, especially those manufactured with higher K dielectric bodies, are characterized by a condition where a residual charge may persist within the capacitor for a long period of time after discharge. This condition, which is known as dielectric absorption, is expressed as the percent ratio of residual voltage to the initial charging voltage.

Certainly care needs to be taken when handling any capacitor and as a precautionary measure, higher capacitance value devices are often provided with shorting bars or bleed resistors.

## **SUMMARY / KEY CONSIDERATIONS**

Ceramic capacitors offer highly reliable, predictable performance characteristics related to key attributes like capacitance, insulation resistance, dielectric strength and dissipation factor, making them extremely suitable for a wide range of applications. In addition, those capacitors manufactured with Class II dielectric materials offer significant advantages in volumetric efficiency when compared to Class I alternatives, making these capacitors ideal in those instances where board real estate is at a premium and miniaturization is key design component. That said, the engineer still needs to take into consideration the ferroelectric properties of Class II dielectrics and how they might behave in their intended application. The key to proper performance is making sure that there is a clear understanding of the operating conditions in which the system is intended to work and selecting a capacitor that will properly match those parameters. Failure to consider how your capacitor might behave when exposed to voltage bias and changes in temperature might result in unintended repercussions and possible system failure.

*For additional information on capacitor selection and information related to Dielectric Absorption, Capacitor Aging, and other capacitor performance characteristics, please refer to Application Note AN109-5, Capacitor Basics, which is available on our website, or contact CalRamic Technologies LLC with your questions. We are always here to help!*



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