Design solutions for DC bias in multilayer ceramic capacitors

By Mark D. Waugh

MULTILAYER CERAMIC CAPACITORS (MLCCs) have numerous benefits. Chief among them is their small size and unique ability to store energy; however, under certain conditions, the capacitance can decrease when DC voltage is applied. This is called DC-bias, and it can pose a challenge for design engineers if they are unfamiliar with MLCC's characteristics. As more engineers discover the advantages of MLCCs, particularly their importance in cutting-edge wireless applications, the need to understand DC-bias has grown. Thankfully, recent advances in materials technology have led to a mitigation of this effect in barium titanate based (BaTiO3) ceramics. In addition, simple and efficient online software tools, provided by suppliers and available right on the desktop, help engineers plan for DC-bias accordingly. These suppliers' online design tools can prevent engineers from making common mistakes by clearly demonstrating the relationship between high capacitance values and a strong DC-bias effect. MLCCs are key to the development of innovative technologies; therefore, understanding their properties and making use of suppliers' educational design tools are an important part of a design engineer's job.

Ceramic benefits

Ceramic components, regardless of the manufacturer, have been at the forefront of the miniaturization trend. Raw ceramics have been expertly manipulated to decrease capacitor size and make way for MLCCs to dominate the landscape. Their very low impedance, coupled with fairly high volumetric capacitance, often make them the logical choice over electrolytic capacitors (both solid state and liquid electrolytes).

Ceramics are also in demand because of their piezoelectric capabilities, which allow for the production of electricity (when ceramic crystals are submitted to mechanical stress) and ferroelectricity. Ferroelectric ceramics offer piezoelectric constants many times higher than other natural materials. Further, the process leads to spontaneous polarization and reverse spontaneous polarization.

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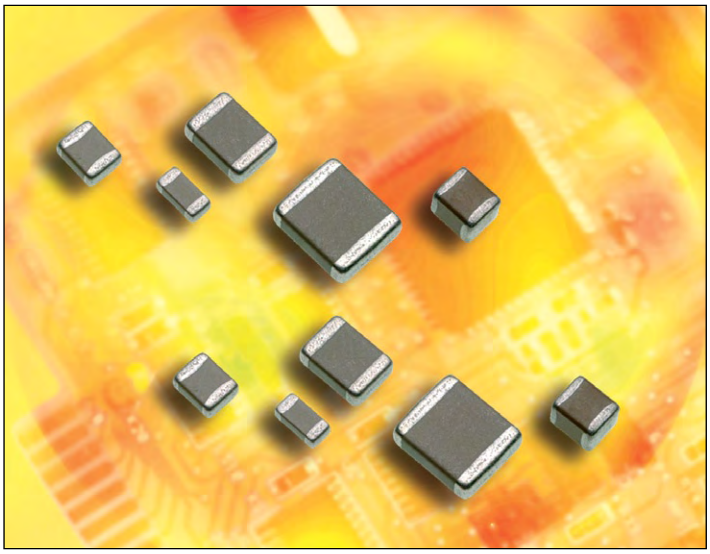

Example of high capacitance multilayer ceramic capacitors

Ferroelectricity and spontaneous polarization

Discovered in 1921, ferroelectricity began to play a much larger role in electronic applications during the 1950's after the increased use of BaTiO3. This ferroelectric material is part of the corner sharing oxygen octahedral structure, but ferroelectrics can also be grouped into three other categories: organic polymers, ceramic polymer composites and compounds containing hydrogen bonded radicals.

Even within the corner sharing oxygen octahedral structure, BaTiO3 is considered part of the perovskite family (see Figure 1). Specifically, BaTiO3 is ideal for MLCCs because of their large room temperature dielectric constant. For example, BaTiO3 ceramics with a perovskite structure are capable of dielectric constant values as high as 7,000, but other ceramics, like titanium dioxide (TiO2), have values between 20 and 70. Over a narrow temperature range, values as high as 15,000 are possible, whereas most common ceramic and polymer materials are less than 10.

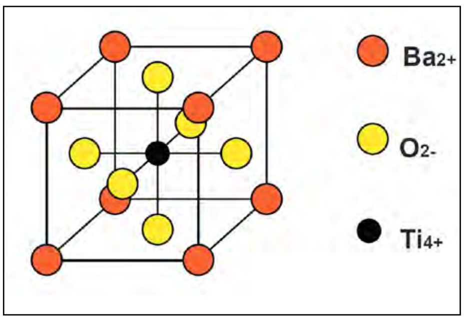

Fig. 1: Crystalline structure of $BaTiO_3$ ceramics

The perovskite structure is cubic at temperatures over the Curie point (approximately 130° Celsius, also referred to as the transition temperature for ferroelectric ceramics). When the temperature range is below the Curie point, one of the axes (C axis) stretches and another shrinks slightly to become tetragonal (see Figure 2). In this case, with the Ti4+ ion placed in the axial direction of the crystal unit away from the body center, polarization occurs. In other words, polarization is caused by asymmetry in the crystalline structure, which exists from the outset without an applied external electric field or pressure. This type of polarization is referred to as spontaneous polarization.

BaTiO3 type ceramics are an aggregation of micro crystallites (polycrystalline), having sub-_m diameter as shown in Figure 3. These micro crystallites are called grains, and their crystalline structures are neatly aligned. Those grains are divided into many randomly oriented domains at temperatures below the Curie point. Within each domain, there is a common direction of crystals, also known as spontaneous polarization.

When BaTiO3 type ceramics are heated above the Curie point, the crystalline structure goes through a transition from tetragonal to cubic phase. Along with this, spontaneous polarization in the domains disappears. When cooled below the Curie point, transition reverses from cubic to tetragonal. Simultaneously, grains receive stress from the distortion of its surroundings. At this point, several small domains in grains are generated, and spontaneous polarization of each domain can be easily reversed with a low electric field. Since relative dielectric constant corresponds with the reversal of spontaneous polarization per unit volume, it is measured as higher capacitance.

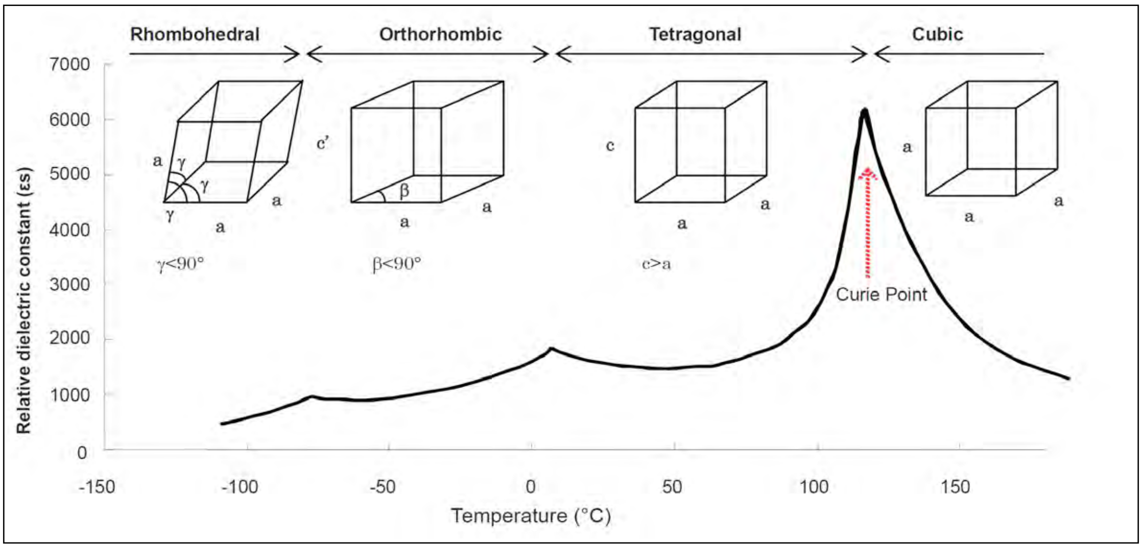

Fig. 2: Change in crystalline structure and relative dielectric constant on temperature change (pure $BaTiO_3$)

DC bias characteristic

The challenge lies not with spontaneous polarization, but in reversing it. When spontaneous polarization is reversed under no voltage stress (no DC bias), MLCCs achieve a high capacitance; however, if an external bias is applied to the spontaneous polarization process, the free reversal of spontaneous polarization is much more difficult. As a result, the capacitance gained is lower compared with the capacitance before the application of the bias. This is why capacitance decreases when DC bias is applied; hence the term, DC bias characteristic.

Even more than spontaneous polarization, this unique DC bias phenomenon in MLCC ferroelectric ceramics is little known and often comes as a surprise to design engineers who are used to using tantalum or electrolytic materials. Electrolytic capacitors are non-ferroelectric with a very low dielectric constant. Their capacitance is derived from a very high surface area and nanometer thick dielectric layers. Their capacitance is not a function of applied voltage.

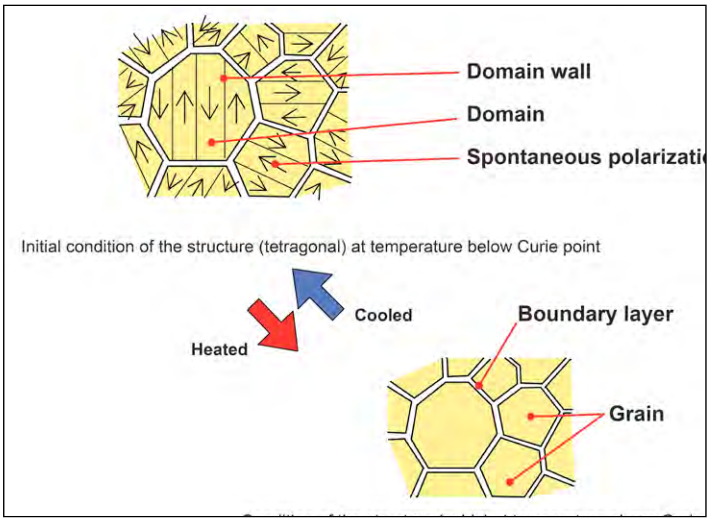

Fig. 3: Micro structure of $BaTiO_3$ type ceramics

Figure 4 indicates types of temperature characteristics for the DC bias characteristics of MLCCs at normal temperature. The main component of temperature compensation type (C0G, U2J characteristics, etc.) is paraelectricity ceramics, where capacitance does not vary due to DC bias. Conversely, the capacitance of high dielectric constant BaTiO3 based ceramics (X7R, X5R characteristics, etc.) decreases under DC bias.

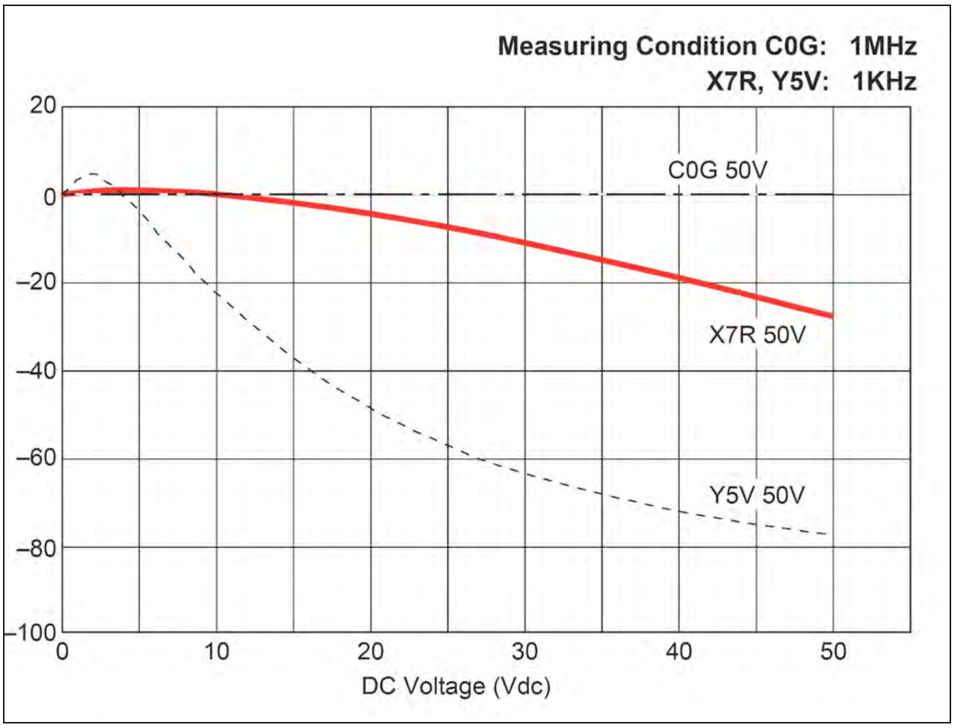

Fig. 4: Capacitance – DC Voltage Characteristics

Advances in ceramic technology

So here lies the challenge. How do you reduce the effects of DC bias voltage on capacitance? Fortunately, new developments by Murata Electronics in $BaTiO_3$ ceramic technology can control this effect by tailoring the $BaTiO_3$ based crystals to soften the effect of polarization reversal. This lowers the effect of DC bias, however, it is often accompanied with a lower initial capacitance. Murata has successfully developed a material that keeps the drop in zero bias capacitance to a minimum.

Better education and dissemination of information about DC bias characteristics have led to increased research activity. The properties of advanced ceramics continue to improve as the molecular levels of this natural material are researched further. Innovative solutions, like MLCCs, are at the cutting edge of technology and are leading the electronics evolution towards smaller and more capable components.

Online design tools

The most immediate way to control the effects of DC bias is to adjust for the issue in the planning stages of the design. This is now a simple task due to the availability of interactive online software tools that help the engineer on the component level of the circuit design. By just plugging in key details, the software will automatically plot the DC behavior based on measured data. Additional information (like heat resistance and ambient temperature) can also be added to provide a customized solution. Now, with just a few clicks of the mouse, the DC-bias effect is visible for the design engineer to aid in component selection. This solution is not only easy, but cost-effective because the engineer is able to make an educated choice based on actual performance.

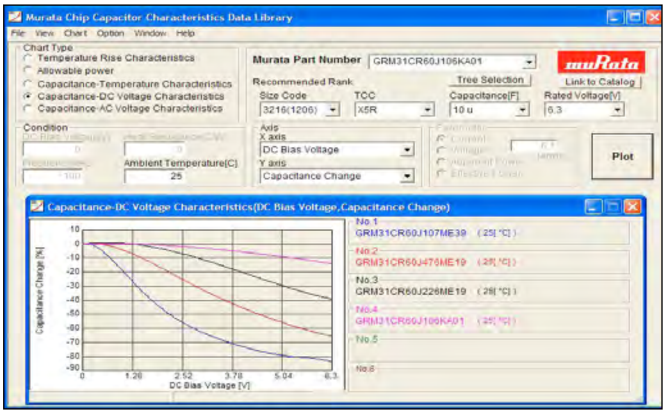

Fig. 5: Example of varying capacitance value and example of varying case size with voltage rating

For example, an engineer designing a power supply for a measurement control and automation equipment company, can use the online tools to easily adjust the design based on DC bias. For this engineer's designs, loop stability is directly related to output capacitance, and when the output capacitance is too low, it affects the design. To correct this problem, he compares several case sizes of multilayer ceramic capacitors with different voltage ratings. The engineer picks ones that provide the maximum capacitance given when accounting for DC bias. Specifically, after entering the appropriate details into the online design tools, the engineer knows that when taking DC bias into account, the design is better suited with two 0805 capacitors instead of one 1210. Also, if the design calls for a specific amount of energy storage or "hold-up", ceramic capacitors are a better alternative to tantalum capacitors because of tantalum's temperature ratings and the failure modes. Even with DC bias, ceramics are the ideal choice because the design tools make it simple to compare the capacitors that have the maximum energy storage for DC bias voltage - see figure 5.

It is also important to note that capacitance listed in data sheets does not take into account the DC bias characteristic. For example, if a design requires 10_F, the engineer may need a 22_F capacitor to achieve the capacitance value referenced in the data sheet. Knowing this up-front will save the design engineer valuable time. Also, a common design mistake is to choose a higher capacitance value without understanding how DC-bias affects capacitance, as the highest capacitance value also has the strongest DC-bias. For instance, when taking DC-bias into account, it might make more sense for a design to use two lower capacitance values instead of one higher capacitance MLCC to achieve the desired capacitance level.

While understanding the molecular properties of ceramics and the unique changes it experiences can be a challenge, adjusting for these changes does not have to be. With component design tools available from suppliers, engineers are just a few mouse clicks away from developing a more efficient and effective design process. The solution is educating the engineering community on the DC-bias effect and having them utilize suppliers' design tools to achieve an accurate representation of the unique behavior of MLCCs under DC-bias. This, in addition to advancements in ceramic technology, allow ceramics to continue to be an irreplaceable part of any advanced design. ■