

# High Temperature Multilayer Ceramic Capacitors

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## ABSTRACT

High temperature power electronics have become a vital aspect of future designs of compact power converters for applications including power conditioning and distributed motor/actuator controls. However, the development of high temperature capacitors had lagged far behind other system components (e.g. semiconductor switches and that can operate at temperature  $>200^{\circ}\text{C}$ ). The performance of these systems would benefit significantly from components and packaging designed and optimized for high temperature ( $200^{\circ}\text{C}$  to  $400^{\circ}\text{C}$ ) under generally harsh environmental conditions.

In this paper it will be demonstrated that high temperature materials can be successfully fabricated into multilayer ceramic capacitors (MLCC). The properties of various capacitors having application range  $200\sim 500^{\circ}\text{C}$  will be presented. It will include NPO type material with capacitance range  $10\text{pF}\sim 50\text{nF}$  useful up to  $500^{\circ}\text{C}$  and high Curie temperature Perovskite materials with a capacitance range  $10\text{nF}\sim 50\mu\text{F}$  at working temperature of  $200\sim 450^{\circ}\text{C}$ . The properties variations of MLCCs with respect temperature and reliability data will also be presented.

## INTRODUCTION

A new family of high volumetric efficiency, high temperature dielectrics have been developed based on high Curie temperature relaxor-ferroelectric ceramics. The dielectrics operate at temperatures far beyond conventional X7R and X8R formulations ( $125^{\circ}\text{C}$  to  $150^{\circ}\text{C}$ ). These new higher temperature ( $>300^{\circ}\text{C}$ ) materials are suited for advanced power electronics based on emerging solid state switching technologies

such as IGBT's and SiC. Capacitors used in these circuits must operate at high frequency (10's to 100 kHz) with voltages ranging from 200 to 600V. They must also be able of handling high AC ripple currents, implying the need for low dielectric loss, low equivalent series resistance (ESR), and high insulation resistance. For applications on spacecraft, electric automobiles, supersonic aircraft, and ships the capacitors must have a high volumetric efficiency to minimize volume and weight and, therefore, a high dielectric constant and/or very low dielectric layer thickness.

High temperature capacitors have been a small, highly specialized market based on low permittivity materials (mica, Teflon, re-rated NPO and X7R ceramics). However, the emerging, high power density solid state switching technologies represent substantially larger markets that, particularly for spacecraft and vehicles, are poorly served by existing capacitors. Thus, the development of high permittivity, high temperature dielectric with excellent power handling capability is a breakthrough that will enable development and commercialization of advanced power electronics.

Our goal was to develop a dielectric optimized for use with SiC-based electronics that had a high permittivity and low dielectric loss at  $300^{\circ}\text{C}$ . This was accomplished by developing one of the highest temperature ferroelectric relaxor dielectrics ever reported. Normal ferroelectrics are characterized by very sharp peaks in their dielectric constant vs. temperature curves that correspond to ferroelectric-to-paraelectric phase transitions (i.e. the Curie temperature). Below the Curie temperature these materials are ferroelectric and often have dielectric constants on the order of 500 to 5000 over a broad temperature range. However, ferroelectrics often exhibit very high losses under AC driving conditions due to reorientation of the ferroelectric

domains. On the other hand, relaxor ferroelectrics have broad, diffuse ferroelectric-to-paraelectric transitions. Near the transition temperature, the ferroelectric domains are nano-sized with unstable polarization and low loss under high AC driving conditions. Thus, our strategy was to take a normal high-temperature ferroelectric composition and modify it into a relaxor ferroelectric for high temperature power capacitors.

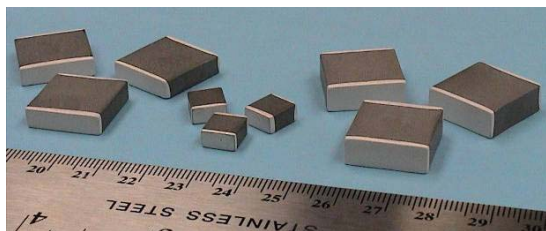


Figure 1. Prototype HT-300 capacitors: 500V components, left to right, 1.5 $\mu$ F, 100nF, and 2 $\mu$ F.

In general, a material that is initially ferroelectric can be modified into a relaxor by doping with cations that perturb the translational symmetry of the lattice. Dopants can have larger sizes, different valences, or create associated ionic vacancies on either the cation or anion sites. If the local strain or electric fields associated with these point defects are sufficiently strong they interact with the spontaneous dipolar polarization of the ferroelectrics and fundamentally alter the polarization mechanism.

The long-range dipolar ordering that characterizes the normal ferroelectric material, and produces domains with a specific crystallographic relationship, is broken down by these local interactions, and frustrated dipolar microregions exist instead. Along with this radical change in polarization distribution, dynamic fluctuations in the orientations of these microregions are also introduced. The net result in terms of properties, and highly attractive to capacitor applications, is a broad or 'diffuse' transition, that has a frequency dependence to what is now called the Curie maximum ( $T_{\max}$ ).

The performance of this new dielectric (referred to as HT-300) was demonstrated in the form of prototype multilayer ceramic capacitors (MLCCs). The basic properties of HT-300 material such as temperature dependence of capacitance, pyroelectric coefficient, and polarization behavior at various temperatures are shown in Figure 2 and 3. The prototypes designed to be rated at 200-500V with values ranging from 100nF to 10 $\mu$ F at 300°C, including: 0.1 $\mu$ F/500V, 1.5 $\mu$ F/500V, 1 $\mu$ F/200V, and 10 $\mu$ F/200V. This paper will describe our work to characterize the performance and lifetime of these components. Standard lifetime testing and highly accelerated lifetime testing [HALT] were used to modify the device designs to maximize lifetime. Newly developed NPO type capacitors (referred as WT-2) with 10pF~50nF capacitance and application temperature from cryo condition and up to 500°C will be demonstrated as well as high  $T_c$  material with

10nF~50 $\mu$ F at 360°C and application temperature 200~450°C (referred as WT-3).

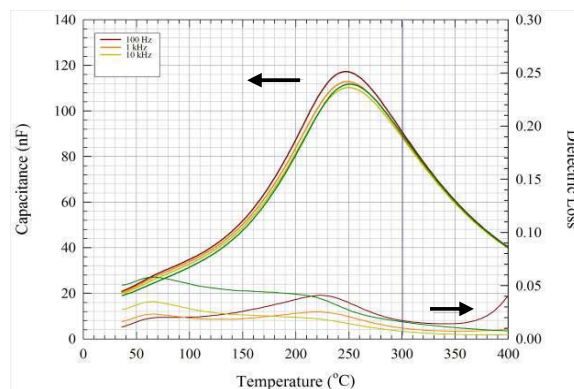


Figure 2. Temperature dependence of the capacitance and loss for 500V MLCC 100nF

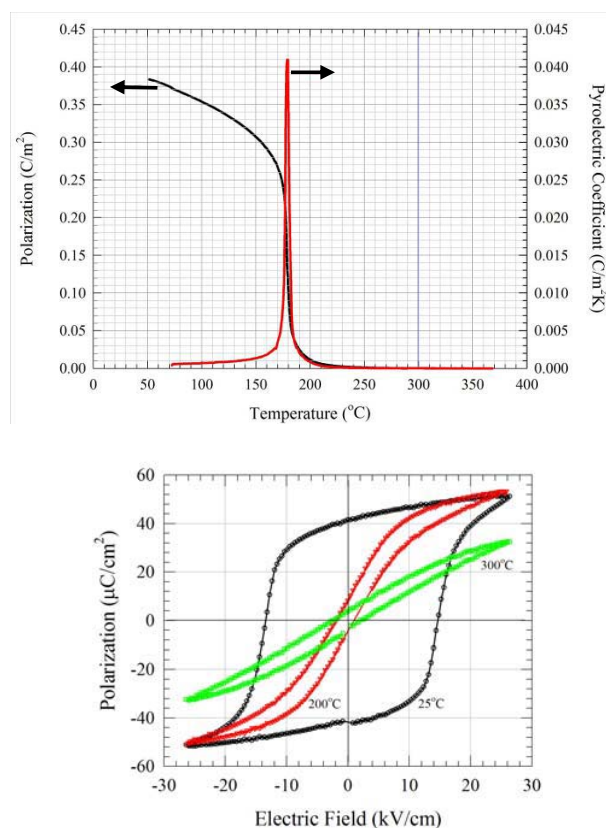


Figure 3. Temperature dependence of the polarization for HT-300 capacitors. (top) remnant polarization and pyroelectric coefficient, and (bottom) P-E hysteresis loops for 25°C, 200°C, and 300°C ( $\pm 600$ V).

## Experimental

Several pieces of equipment have been built or modified to accommodate testing of these high temperature dielectrics. Most of the high temperature electrical