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CAPACITOR DEVELOPMENT FOR RELIABLE HIGH TEMPERATURE OPERATION IN INVERTER APPLICATIONS

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Advanced inverters based on wide band gap (WBG) semiconductors are attractive for increased efficiency and power handling capabilities over their Si-based counterparts. In addition, WBG materials can function at significantly elevated temperatures, which would allow the simplification or even elimination of bulky, costly, and complex cooling systems for associated inverters and other power electronics modules. Present inverter designs are limited by capacitors as much as (or in many cases, more than) the active semiconductor material because presently available capacitors do not simultaneously meet every requirement associated with capacitance, volume, equivalent series resistance (ESR), operating temperature, and cost. We have developed inverter-scale multilayer ceramic capacitors using scalable low cost manufacturing techniques that can operate reliably at temperatures in excess of 300°C. This work focuses on the materials advances associated with this development and resulting performance of these capacitors as related to integration into inverters for high operating temperature power electronics applications.

Keywords: capacitors, power electronics, ceramic, reliability

INTRODUCTION

Motivation

Next-generation power electronics modules, specifically those based on gallium nitride (GaN) or silicon carbide (SiC), can operate at significantly higher powers and higher temperatures than currently-available Si-based electronics. These capabilities make them attractive not only for greater operating efficiency, but also because of the potential for reduction or elimination of active cooling systems. Active cooling systems occupy a large percentage of the volume and contribute to disturbingly high numbers of failures in power electronics modules. Deployment of containerized transportable storage systems increases the need for high density ancillary systems in order to maximize the volume available within the fixed-size container for active storage modules further intensifying the drive to eliminate—or at least minimize—active cooling systems. For economic viability, such systems must also meet strict reliability requirements.

For simplicity, we focus our discussion on inverters, but the overall conclusions remain valid in a qualitative sense regardless of the particular module or system characteristics. The primary target application of the capacitors from this work is power electronics for transportable storage. These modular systems are highly volume constrained because they fit within a standard shipping container. Their needs for a combination of high operating temperatures, high power handling, small volume, and high reliability provide a challenging overall environment that serves as a sort of worst case scenario for component selection and integration, but improved capacitors will have an impact across the grid, anywhere that power needs to be stored, switched, or regulated. Some conceptual examples appear in the artistic rendering of Figure 1. Furthermore, the capacitors developed here have characteristics that make them attractive for automotive, military, and other moderate voltage, high power applications.

Application requirements

In many present-day inverter modules, the active cooling system required by the Si-based electronics takes up roughly half of the entire system volume and commonly accounts for a large majority of the maintenance expense. Of the remaining system, it is common for nearly half of the volume to be occupied by capacitors, whether they are more traditional aluminum or tantalum electrolytic parts or more recent polymer film capacitors. While the polymer film capacitors typically provide a moderate reduction in capacitance density vs. electrolytic capacitors, they offer a significantly lower equivalent series resistance (ESR) than their electrolytic counterparts.

ESR is a critical parameter for power electronics capacitors because it represents the resistance to charge flow during each charging and discharging cycle. A large ESR leads not only to self heating because of the resistive dissipation of power, but it also increases the RC time constant of the capacitor, increasing the amount of time required to reach a given state of charge. In order to compensate for the large ESR values inherent to electrolytic capacitors, modules are often designed with much larger capacitance values than would actually be required for baseline performance. The converse of this, of course, is that reducing the ESR of the capacitors used in a design can actually reduce the total capacitance requirements. Further, reduced ESR translates into greater efficiency because of reduced resistive losses as well as the ability to operate at higher switching frequencies. This is one of the drivers for today's trend of replacing electrolytic capacitors with polymer film capacitors.

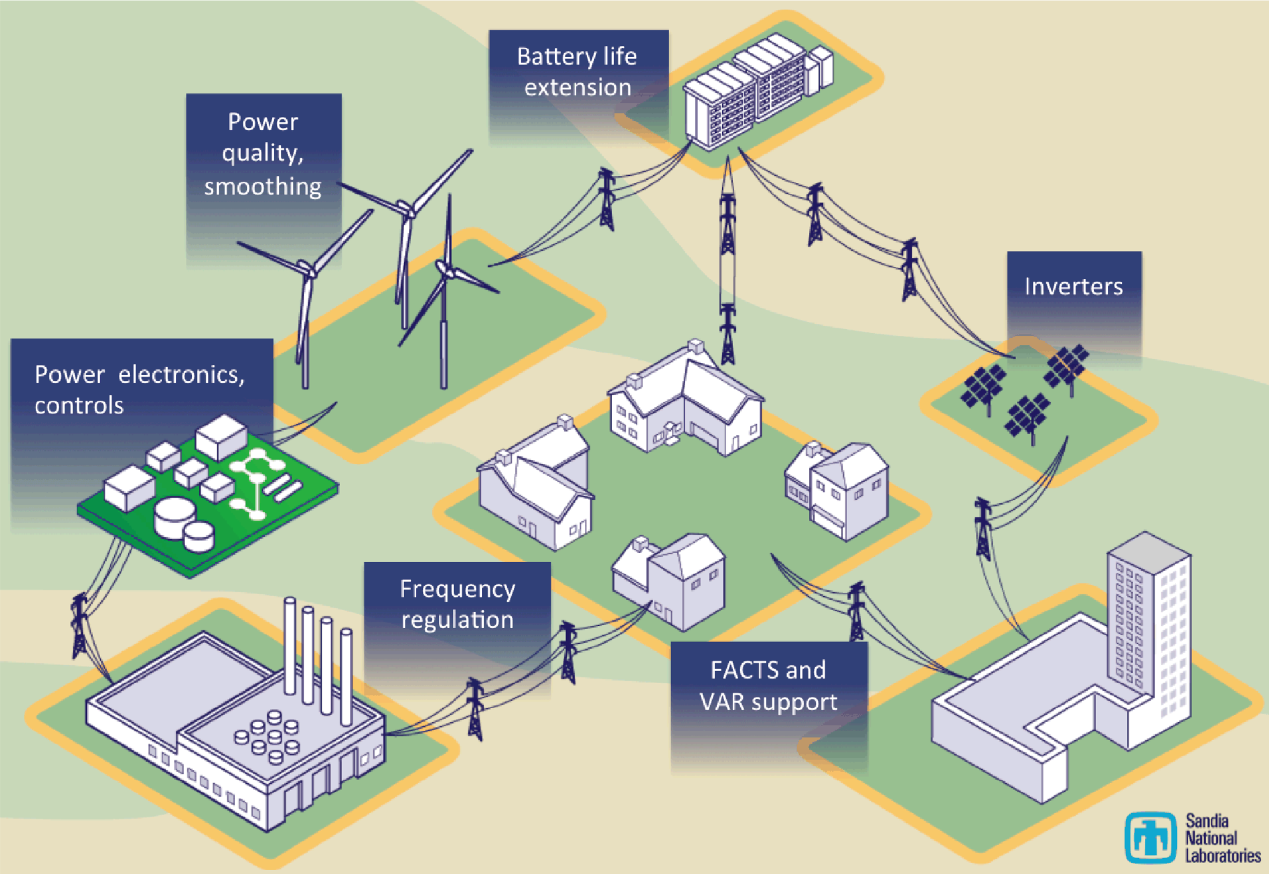


Figure 1 – Artist's depiction of some of the potential roles of improved capacitors and associated improvements in power electronics systems in grid-tied applications.

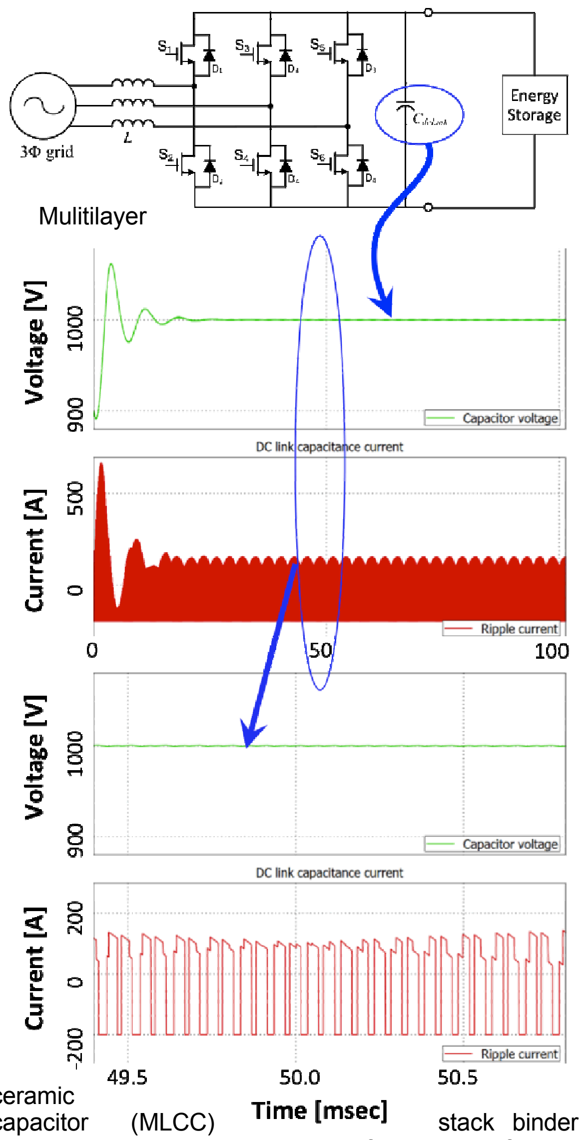
The ESR consideration is also the primary reason that carbon-based double layer capacitors (often referred to as supercapacitors), which can have significantly higher capacitance density values than even electrolytic capacitors, are not used extensively in power electronics systems. The enormous surface area that results in high capacitance values also presents long and tortuous paths for the electrons during charging and discharging, and thus high ESR values relative to other capacitor technologies. The plots shown in Figure 2 provide a generic example of the operating conditions of a grid-tied dc link capacitor. In this example, the capacitor experiences a 1000 V bias baseline with >300 A transient currents on microsecond or faster time scales. Next-generation power electronics based on SiC and GaN can (and will need to) operate under ambient temperatures >200°C; because of self-heating and power dissipation from other components, having capacitors rated for operation up to at least 300°C is desired.

Though there are some notable exceptions, the vast majority of electrolytic and polymer film capacitors have a very difficult time operating continuously at 125°C ambient (many are rated to only 85°C, and even then with power restrictions). Since they are able to operate at higher temperatures in the first place and dissipate significantly less heat because of their lower ESR values, ceramic capacitors offer a lot of potential advantages for high power applications. Figure 3 provides a qualitative visual comparison of the tradeoffs associated with some of the general classes of electrostatic capacitors. However, use of ceramic capacitors in power electronics modules today is relatively rare. The reasons for this boil down to volume, reliability, and—by extension—cost; the current work systematically breaks down these factors and presents a demonstration of multilayer capacitors that show promise for high operating temperature inverter and related power electronics applications.

CAPACITOR FABRICATION

$Bi(Zn_{0.5}Ti_{0.5})O_3$ – $BaTiO_3$ (BZT-BT) dielectrics were synthesized using conventional solid state ceramic techniques from Bi_2O_3, ZnO, $BaCO_3$, and TiO_2 precursor powders ball milled in ethanol for 24 hours. Solvent was removed by rotary evaporation to reduce particle segregation. Dried powders were lightly ground in a mortar and pestle, sieved, and calcined at 950°C for 12 hours in air using a covered Al_2O_3 crucible. Single phase calcined powders were ball milled in ethanol to reduce particle size. Disc capacitors were produced by dry pressing BZT-BT powders containing 3 wt.% polyvinyl butyryl (PVB) binder at 35 MPa followed by isostatic pressing at 200 MPa.

Tape casting slurry containing nominally 60 vol.% BZT-BT dielectric powder was produced using a commercial binder system (B-73305, Ferro Electronic Materials). Milled BZT-BT powders were dispersed in the PVB binder system by slow ball milling for 24 hours. Slurries were vacuum deaired until no visible bubbles were released. Deaired slurry was then cast onto silicone coated mylar from a twin doctor blade on a heated bed. After drying, green tapes were cut and electrodes were applied by screen printing Pt cofire ink (9894 Pt Ink, DuPont). Printed dielectric tapes were collated to produce 6 active layers with buried electrodes and 2 support tape layers. Collated stacks were laminated and then singulated by CNC laser machining and hot knife dicing.



ceramic capacitor (MLCC) stack binder removal was carried out in a tube furnace in a flowing O_2 atmosphere and was monitored by in situ residual gas analysis (RGA). In situ RGA was also used to monitor the gases evolved during sintering in an Al_2O_3 tube furnace. Analysis of RGA data was then used to optimize the binder removal and sintering profiles to

Figure 2 – Schematic diagram of a dc-link capacitor in a grid-tied energy storage module and simulation results of the voltage and current associated with the capacitor in such a setup (simulation provided by Stan Atcitty, SNL)

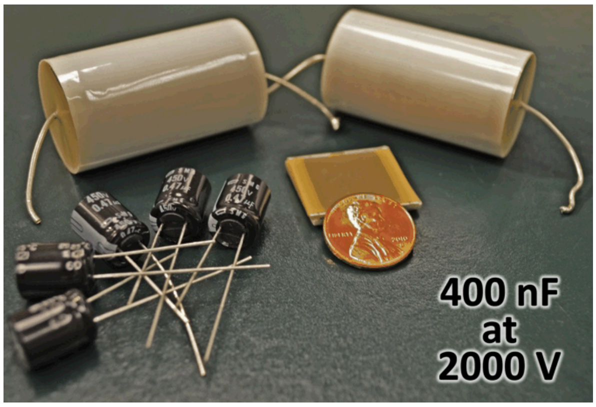


Figure 4 – Each group of capacitors above represents 400 nF at 2000 V operation.

prevent the formation of blister defects associated with entrapped gases. After sintering, the same Pt ink used for screen printing was applied by hand to capacitor ends to form active electrode terminations. The end result of this processing is shown in both Figures 3 and 4: MLCCs with active areas slightly larger than a U.S. dime (the light-colored regions in the pictures are margins that could be trimmed for reduced volume of non-active area) and dielectric layer thicknesses of approximately 100 µm. Each MLCC has a capacitance of 200 nF and was designed for operation at 2000 V.

PROPERTIES AND PERFORMANCE

The primary parameter of importance for capacitors is, not surprisingly, capacitance, but this is only one of many important properties to consider. Capacitance (for a simple parallel plate configuration which is appropriate for a planar MLCC) is related to the intrinsic materials properties by the equation

$$C = \frac{KA\varepsilon_0}{t} \qquad (1)$$

where C is capacitance (in Farads, or more commonly

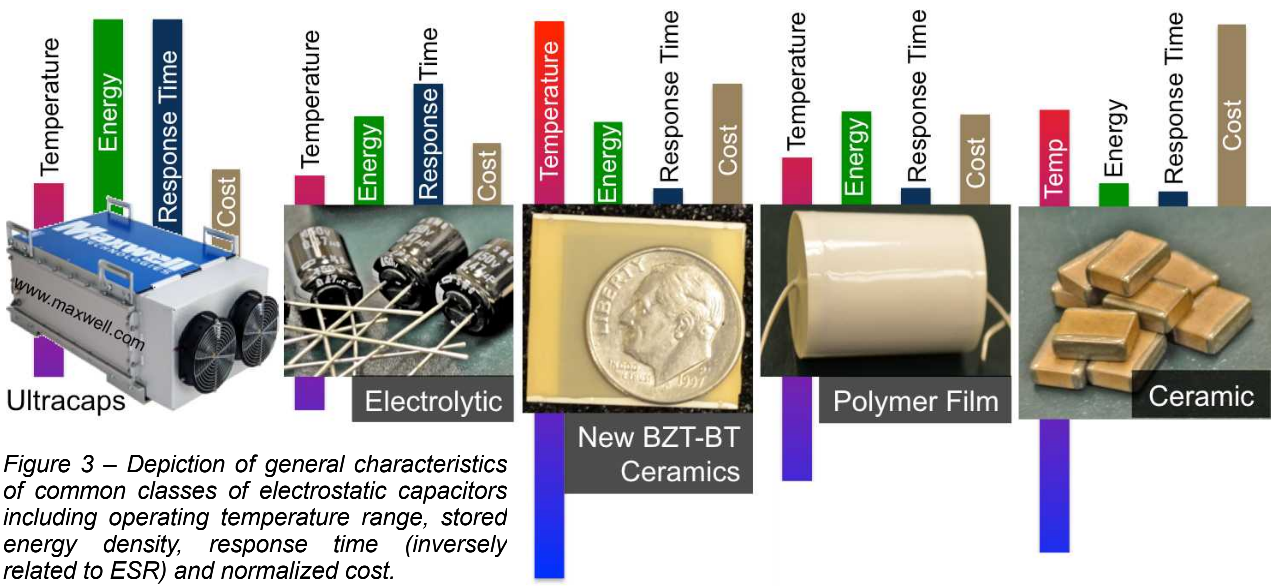


Figure 3 – Depiction of general characteristics of common classes of electrostatic capacitors including operating temperature range, stored energy density, response time (inversely related to ESR) and normalized cost.

nF), K is relative permittivity (dielectric constant), A is active dielectric area, ε_0 is the permittivity of free space (8.854E-12 F/m), and t is the thickness of the dielectric (electrode separation distance). This equation highlights the importance of having large active areas and small thicknesses in order to achieve large capacitance values, but it hides the dependence of relative permittivity on applied electric field.

Supercapacitors and electrolytic capacitors both achieve extremely large areas and thin layers, but this increase brings with it large ESR values because of the often thin and tortuous electrodes. These kinds of capacitors also utilize dielectric materials that have low or moderate relative permittivity values (e.g., $K_{Ta2O5} \approx 27$), but importantly, these values are stable with applied electric field. Most MLCCs based on ferroelectric materials, on the other hand, exhibit extremely large relative permittivity values (e.g., >3,000 for traditional $BaTiO_3$-based X7R dielectrics, >50,000 for some Pb-based relaxor dielectrics), but these large permittivity values are highly field-dependent, typically dropping below 300 under fields of ~100 kV/cm as demonstrated in Figure 5. This behavior is of minimal concern for applications that require high capacitance density at relatively low operating fields, but for a dc link capacitor and other high field applications, this behavior is highly undesirable.

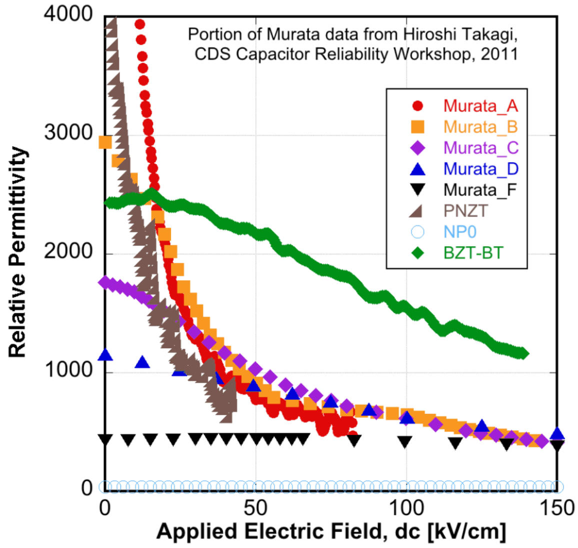


Figure 5 – Electric field dependence of relative permittivity for BZT-BT ceramics compared to some other representative dielectric ceramics.

Energy Density

In some applications, dc link capacitors being one example, both capacitance density and energy density are of high importance. The energy stored in an electrostatic capacitor can be expressed as

$$J = \int_0^V CV\,dV \Rightarrow \tfrac{1}{2}CV^2 \qquad (2)$$

where J refers to energy (typically in J or scaled to volume as J/cm^3), V is voltage, and C is capacitance which can have a voltage dependence; the simplification to $J = 0.5CV^2$ is only strictly valid for linear capacitors which show no field dependence. Translating this into intrinsic properties, stored energy varies directly with relative permittivity but with the square of the electric field; this means that maintaining a large permittivity *under large electric fields* is important for achieving large energy densities. From the data in Figure 5 (after smoothing and knowing from other measurements that hysteretic losses in these materials are quite small), we can plot the energy density stored and available for discharge for each of these dielectrics (Figure 6) and it becomes apparent

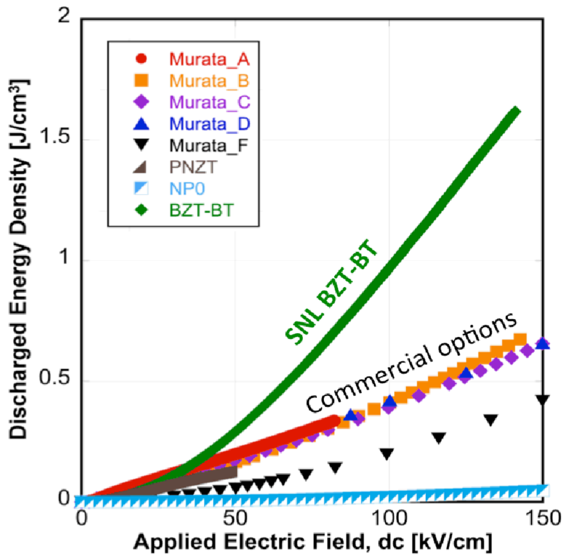


Figure 6 – Energy densities from BZT-BT and other common ceramic dielectrics.

that though the low-field permittivity of our BZT-BT materials is not as high as some of the other dielectrics, the fact that it maintains a large relative permittivity at high fields corresponds to much greater energy densities. It should be noted here that we have used data from Murata capacitors because they are representative of the current state of the art in ferroelectric-based MLCCs.

High Temperature Operation

The primary drive behind this project was to develop new dielectrics and capacitors capable of operating reliably and with high energy and high capacitance densities at ambient temperatures in excess of 200°C. Pure $BaTiO_3$ undergoes a phase transition associated with its Curie Temperature (T_C) near 125°C, and much of the success of the MLCC industry is a direct consequence of technologies that chemically shift and broaden this phase transition in a way that provides relatively stable low-field permittivity values across the temperature range between -55°C and 125°C. Materials which offer stable dielectric response at higher temperatures are almost exclusively those with low relative permittivities. However, $Ba(Zn_{0.5}Ti_{0.5})O_3$ additions to $BaTiO_3$ flatten the permittivity response above T_C and result in a dispersive relaxor-like response below T_C [1-4].

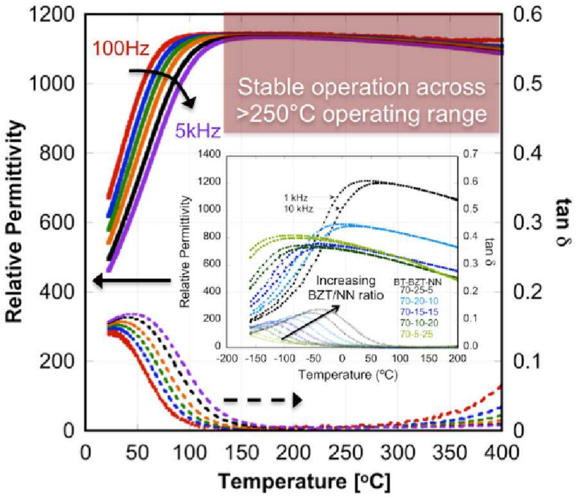


Figure 7 – $BaTiO_3$ modified with appropriate Bi-based perovskite additions exhibits relaxor dielectric behavior with remarkably stable temperature performance above T_C. The inset shows reductions in T_C with other perovskite additions.

Additional doping with $BiScO_3$ results in remarkable temperature stability of permittivity above T_C (Figure 7) but retains the relaxor response near room temperature [5]. For applications which require operation to lower temperatures as well, we have shown that $SrTiO_3$, $NaNbO_3$ and other additives can effectively shift T_C to temperatures well below 0°C [6].

Resistivity

Capacitor failures have been shown to account for roughly half of the failures in photovoltaic inverter systems [7], so testing the degradation and failure mechanisms of these new dielectrics in order to get an indication of their reliability is a high priority. Accelerated lifetime tests [8] are ongoing, so full analysis of the results will be presented in future work. Electrical resistivity and associated activation energy measurements, however, can provide a preliminary indicator of high operating temperature reliability. Figure 6 shows the temperature dependent resistivity and corresponding activation energy values from measurements on BZT-BT dielectrics as well as comparisons to other typical dielectric ceramics. The significantly higher resistivity and much larger activation energy values both suggest that BZT-BT dielectrics are promising materials for reliable long-life operation at elevated temperatures [9].

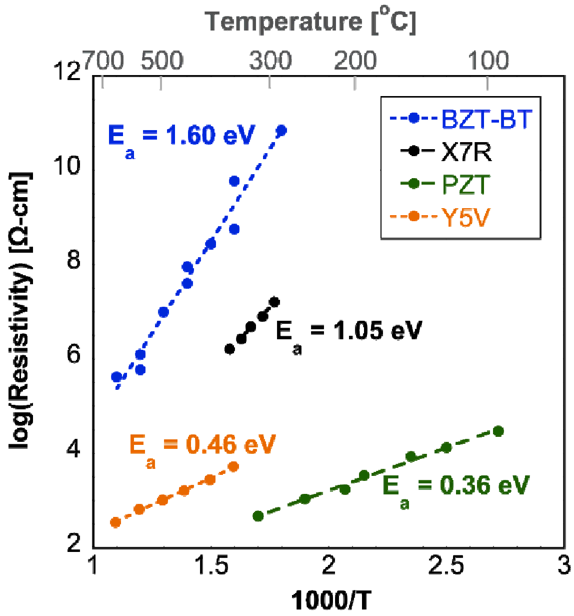


Figure 8 – Electrical resistivity and associated activation energies for conduction for BZT-BT and other common ferroelectric-based dielectrics.

SUMMARY

Multilayer ceramic capacitors based on recently-developed $Bi(Zn_{0.5}Ti_{0.5})O_3$-$BaTiO_3$ dielectrics have been fabricated in sizes relevant to integration with wide band gap power electronics. The large permittivity values can be made stable with both voltage and temperature; combined with the low equivalent series resistance typical of ceramic capacitors, these characteristics make the materials extremely attractive for high operating temperature inverter applications. In addition, the high resistivity values and large activation energies provide encouraging early indicators of potential reliability while accelerated lifetime testing is ongoing.

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