WHITEPAPER

Comparing High Temperature Capacitors for DC Link Buses

Today's advancements in power electronics are reaching all-new highs in performance. With the utilization of wide bandgap (WBG) semiconductor materials in high frequency switching devices, design engineers are creating smaller, faster, more reliable, and more efficient power conversion modules. These latest innovations stand to impact a wide range of industries – such as electric vehicles, aerospace, energy production, and test equipment.

However, improvements in semiconductor technology have a trickle-down effect that impact other crucial components in DC link buses and other power circuits. Fast switching in a tiny form factor means the devices run "hot" with high temperatures and high voltages. Therefore, capacitors and other passive parts surrounding the power semiconductors must also be capable of operating in harsh environments while keeping losses at a minimum. What alternatives exist today that can meet these requirements, and how do their characteristics compare with traditional capacitor options?

This whitepaper examines two capacitor technologies – lead lanthanum zirconate titanate (PLZT) and strontium bismuth ferrum titanate (SBFT) dielectrics – that are designed to meet the high voltage, high temperature needs in the power electronics industry. A performance analysis was conducted to investigate the effects of DC voltage bias and AC current on capacitance value and temperature rise for multilayer ceramic capacitors (MLCCs) using SBFT, PLZT, and traditional X7R materials.

KEEPING UP WITH THE LATEST POWER SEMICONDUCTORS

In order to increase the efficiency and power density of converters and inverters, manufacturers are looking at using WBG semiconductors, such as gallium nitride (GaN) and silicon carbide (SiC), for making metal-oxide semiconductor field-effect transistors (MOSFETs), metal-semiconductor field-effect transistors (MESFETs) and other devices. These materials are capable of operating at faster switching frequencies and higher temperatures – and therefore greater current and power – compared to traditional silicon-based materials. This higher temperature rating also allows the semiconductors to be used in hotter, harsher environments found in automotive, aerospace, and energy applications. However, unless the passive components around them (like DC link and snubber capacitors) are able to survive temperatures up to 125°C, engineers will be forced to design supplemental cooling systems that ultimately add complexity, weight, and cost to the power modules.

In the past, power systems were designed with electrolytic capacitors for their high capacitance density and low cost. Unfortunately, common problems included poor long-term performance and inability to handle high current applications. This led to the rise of large film capacitors because of their higher current ratings and improved reliability. However, according to the IEEE paper, DC Link Bus Design for High Frequency, High Temperature Converters, "It is common for a film or electrolytic capacitor to resonate around 10-15 kHz and be limited to temperatures below 105°C," which still limits their usage in high frequency and high temperature applications.

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> - IEEE Paper, DC Link Bus Design for High Frequency, High Temperature Converters

Nowadays ceramic capacitors or MLCCs are an attractive choice since they offer high energy density, high resonant frequencies, high current ratings, small footprint, and physical robustness. MLCCs are constructed with alternating layers of ceramic dielectric and metal electrodes (and can be capped by flexible termination for surface mount) that protects the ceramic from mechanical stresses and reduces the likelihood of catastrophic failure in the case of cracking.

Traditional ceramic capacitors, such as X7R Class II types, can withstand temperatures up to 125°C, but as a ferroelectric material, its dielectric constant and therefore capacitance value drops greatly as the DC bias increases. Also, X7R capacitors typically do not keep their optimal capacitance values at high voltages. To keep up with the advances in power electronics, new and improved capacitors must be developed with the following characteristics:

- **High capacitance values and performance**, even when operating at high temperatures (up to +125°C), high voltages (up to 1000 VDC), and high frequencies up to a few hundred kHz
- **High current rating** and low leakage current to handle more power
- **Low equivalent series resistance** (ESR) to minimize losses and noise from high frequency switching
- **Low equivalent series inductance** (ESL) to increase the capacitor's energy transfer speed for high frequency switching
- **Small size** to decrease the size and weight of power modules
- **High reliability** against mechanical stress, solder shock, and other industrial conditions

COMPARING THE LATEST HIGH TEMPERATURE, HIGH VOLTAGE CAPACITORS

Materials scientists are hard at work developing new formulations that accomplish these goals, and this article examines two currently available ceramic solutions: PLZT and SBFT dielectrics.

PLZT is a lead lanthanum zirconate titanate ceramic used in piezo actuators and capacitors. Unlike Class II ferroelectric materials, PLZT is an antiferroelectric formulation where the dielectric constant is reduced at low DC biases but peaks in value at the operating voltage rating. Typical PLZT capacitors range in capacitances from 0.25 to 1 µF, are rated for 500 to 900 VDC, and function in temperatures of -40 to +125°C. Designed for high frequency switching semiconductors up to several MHz, it boasts high capacitance density, low ESR and ESL, low leakage current, and long lifetime even in high heat conditions.

SBFT is a strontium bismuth ferrum titanate ceramic, branded under the name of Hiteca capacitors from Knowles Precision Devices. Compared to standard Class II materials like X7R, this low loss, semi-stable Class II dielectric features high capacitance at the maximum operating voltage, improved capacitance stability, low ESR and ESL, and 0% aging rate with no loss of capacitance over time. SBFT capacitors are made with 100pF to 2.2 µF capacitance range, 450 to 1000 VDC voltage ratings, and -55 to +125°F operating temperature. At 2.5 to 4 mm thickness, these components help enable the design of smaller, lighter power modules without the need for active cooling systems.

In order to best compare the performance metrics of X7R, PLZT, and Hiteca dielectrics, we conducted a series of experiments to study:

- Capacitance versus DC bias voltage
- Temperature rise due to self-heating
- ESR versus frequency
- Capacitance loss over time

CAPACITANCE VERSUS DC BIAS VOLTAGE

We used a standard capacitance bridge to measure capacitance value at different DC bias levels up to the rated voltage, as shown in Figure 1. As the bias voltage increased, the capacitance of X7R and Hiteca capacitors decreased because of their negative voltage coefficient of capacitance. However, Hiteca capacitance values lessened at a more gradual rate than the X7R's capacitance. In contrast, PLZT capacitors have a positive voltage coefficient, such that the capacitance increased to a maximum value at 400V (just below the rated voltage) and then decreased slightly when approaching the rated voltage.

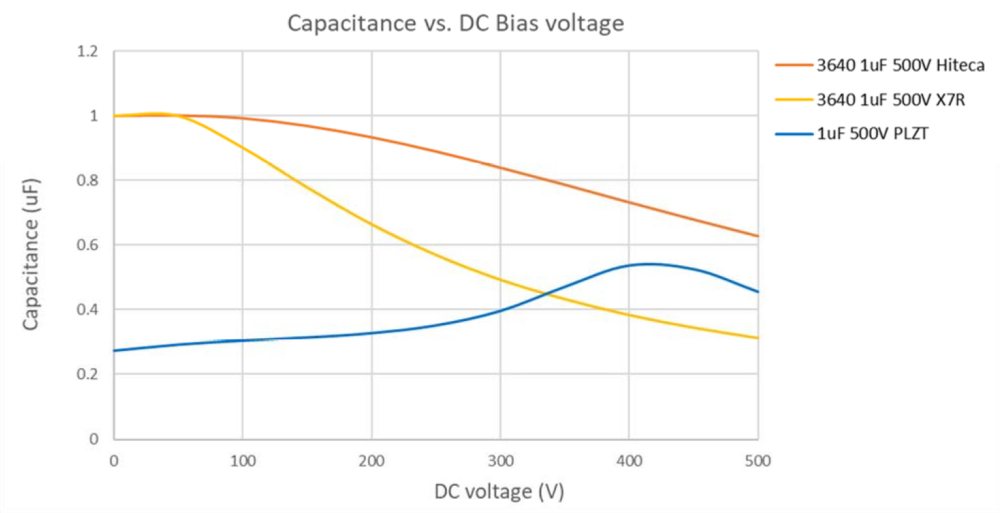

Figure 1. Capacitance versus DC bias voltage, measured at 1kHz using a capacitance bridge

As seen by their slopes, X7R had the greatest amount of capacitance change over the DC bias voltage range, with a 73% difference from its maximum value. In comparison, PLZT displayed a 49% change of maximum value and Hiteca showed a 31% change of maximum value.

Furthermore, Table 1 displays the maximum and minimum capacitance values measured and the bias voltage at which they were obtained. Both Hiteca and X7R parts reached their rated capacitance values, whereas the PLZT part reached less than 60% of its rated capacitance value.

Capacitance	**1uF 500V Hiteca**	**1uF 500V X7R**	**1uF 500V PLZT**
Maximum	1uF at 0V bias	1uF at 0V bias	0.54uF at 400V bias
Minimum	0.63uF at 500V bias	0.32uF at 500V bias	0.27uF at 0V bias

Table 1. Comparison of maximum and minimum capacitance values for Hiteca, X7R, and PLZT capacitors

In general, even though all three capacitors have a nominal capacitance value of 1 µF, Hiteca provided the highest capacitance at all DC bias voltages from 0V to the rated voltage of 500V. At higher frequencies, similar results were found while taking voltage and current readings during the temperature rise experiment at 1kHz, 10kHz, and 100kHz (see Figure 2).

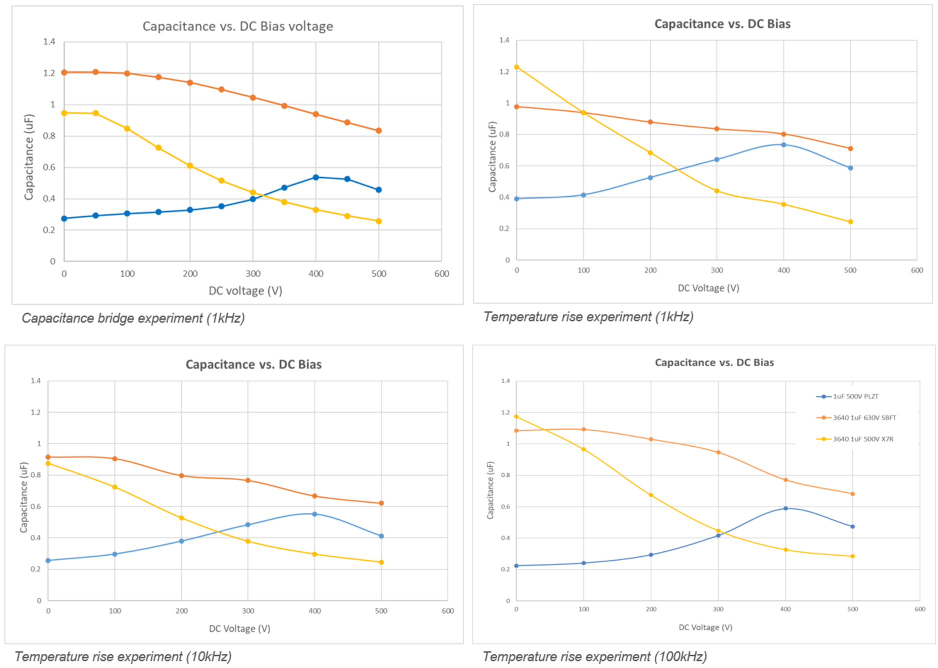

Figure 2. Capacitance versus DC bias voltage, measured at different frequencies

TEMPERATURE RISE DUE TO SELF-HEATING

Temperature rise in a capacitor is caused by multiple factors, including ripple current, ESR, and thermal resistance. Ripple current flowing through a capacitor causes energy losses, which raises the part's internal temperature and reduces the electrical efficiency of the circuit. As energy losses occur, the capacitor experiences self-heating and the dielectric begins to degrade, ultimately shortening its life span. Ideally, a capacitor should have minimal temperature rise in response to increasing ripple current. The following experiment uses AC current to simulate ripple current and study the capacitors' temperature reaction.

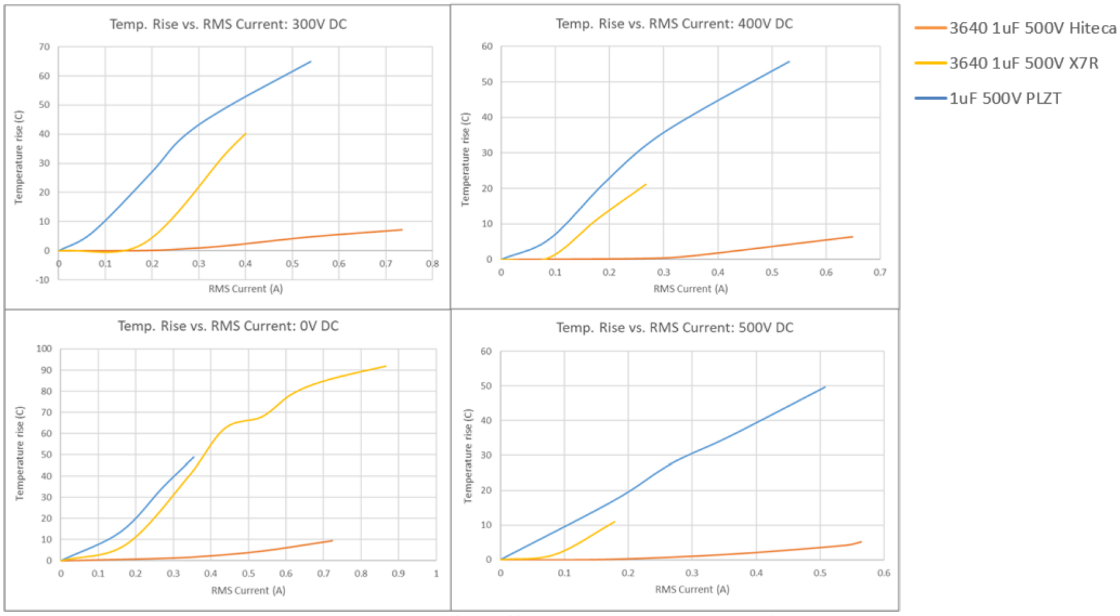

Figure 3a. Temperature rise versus RMS current for different DC bias voltages (at 1kHz frequency)

Figure 3a shows the measured temperature rise versus 1kHz AC current for Hiteca, X7R, and PLZT capacitors at DC bias voltages of 0V, 300V, 400V, and 500V. In all instances, the Hiteca capacitor produced the lowest temperature rise for all DC bias voltages and all AC currents at 1kHz frequency.

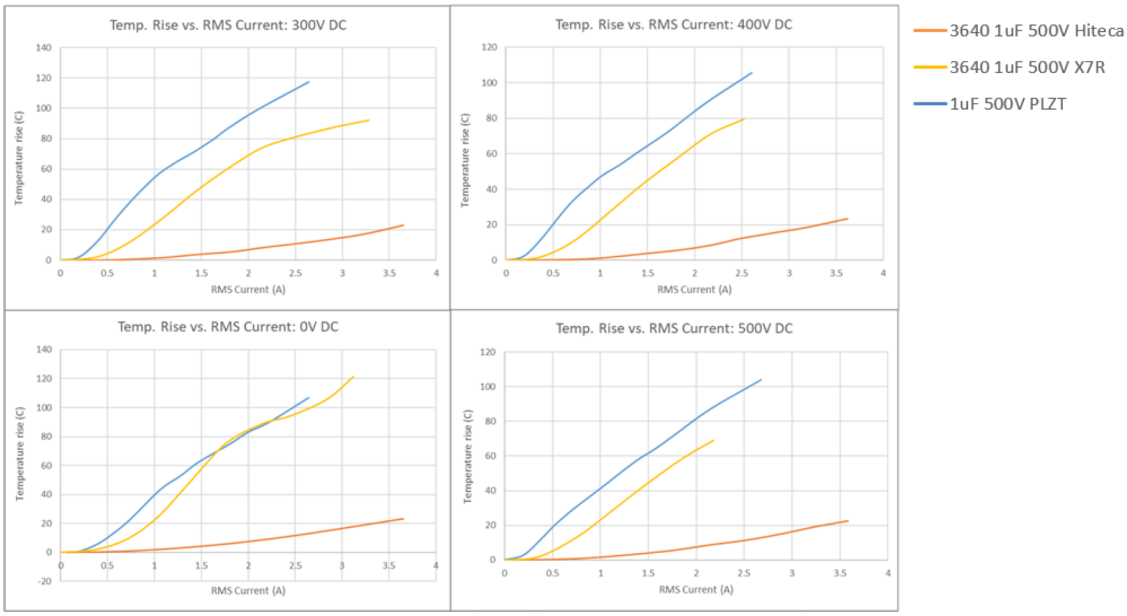

Figure 3b. Temperature rise versus RMS current for different DC bias voltages (at 10kHz frequency)

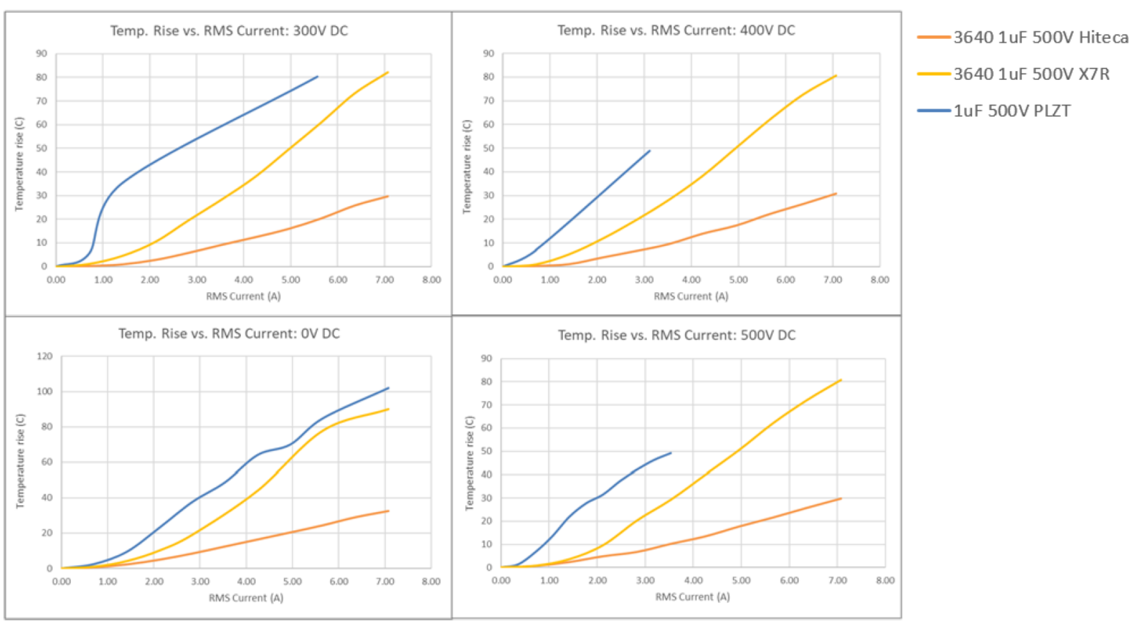

Figure 3c. Temperature rise versus RMS current for different DC bias voltages (at 100kHz frequency)

As the frequency increases, the temperature increases as well, making the capacitance more and more unstable. Therefore, the experiment was repeated at ripple frequencies of 10kHz and 100kHz, as seen in Figures 3b and 3c. These tests yielded similar outcomes, such that Hiteca consistently displayed the lowest operating temperatures compared to X7R and PLZT over a wide range of DC bias voltages, AC currents, and ripple frequencies. The temperature rise of X7R was also generally lower than PLZT. Hiteca's enhanced ability to tolerate increased ambient operating temperatures leads to longer capacitor lifetime, reduced cooling requirements, more efficient circuit design, and overall improved performance and reliability in power electronic applications.

ESR VERSUS FREQUENCY

As mentioned before, temperature rise is affected by ESR in capacitors, and capacitors with low ESR are able to withstand high ripple currents with minimal temperature rise. ESR itself is affected by the operating frequency and temperature, and therefore, an experiment was conducted to measure ESR versus frequency.

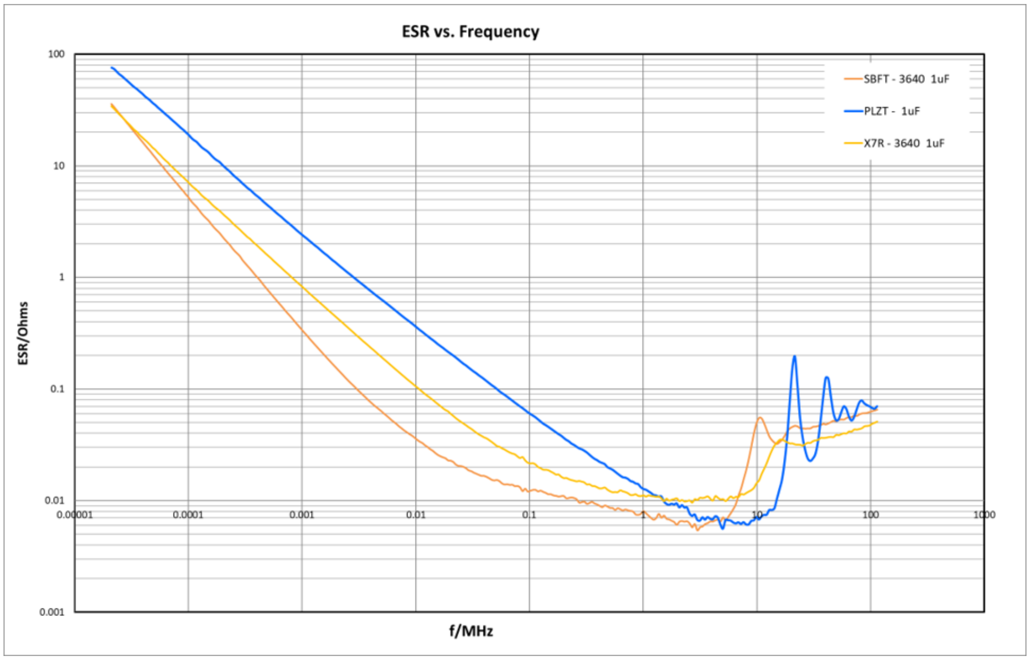

Figure 4. ESR versus frequency comparison

The temperature rise results are corroborated by the ESR results seen in Figure 4. For frequencies lower than 6 MHz, Hiteca had a consistently lower ESR than PLZT, and then ESR values widely varied between 6 to 100 MHz frequencies. Overall, Hiteca has lower self-heating properties and low losses that enables the capacitor to handle much higher ripple currents than conventional ceramic capacitors.

CAPACITANCE LOSS OVER TIME

Aging occurs when a decrease in capacitance is experienced over time. For example, ferroelectric capacitors exhibit aging when the ions in the crystal lattice shift and stabilize to positions of lower potential energy. This degradation of the domains of polarization causes a logarithmic aging of the dielectric constant, such that the majority of capacitance loss occurs in the first 10 hours of age.

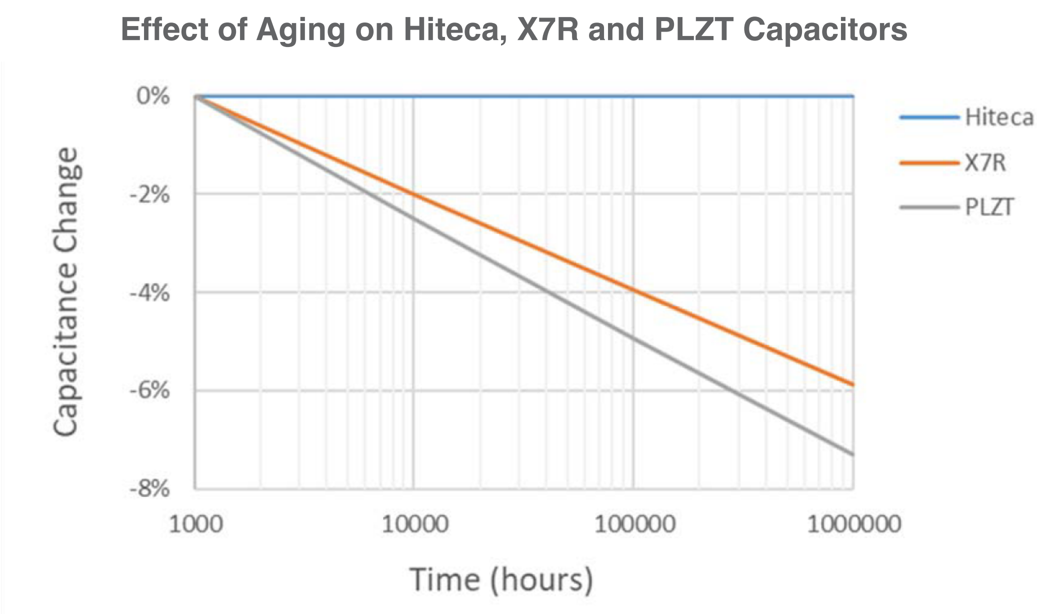

Figure 5. Capacitance aging over time

Figure 5 illustrates the effect of capacitor aging for all three capacitor types. X7R shows 2% aging per log decade in hours, whereas PLZT has 2.5% aging rate. Hiteca dielectric, on the other hand, experiences no loss of capacitance over time with 0% rate of aging, which gives engineers peace of mind that their designs will not be adversely affected by capacitance loss over time.

CONCLUSION

With the latest WBG semiconductor technology enabling more power in smaller packages, we need capacitors that can handle these new high temperature, high voltage requirements. Film capacitors are no longer feasible because they melt under increasing temperatures. X7R capacitors can operate under high heat, but don't display optimal capacitance values at high voltages. Both PLZT and Hiteca are designed to accommodate high frequency switching applications, but given the side-by-side test results, we believe Hiteca is the next viable step in capacitor technology because of its higher capacitance over DC bias voltages, lower temperature rise over AC currents, and long-term reliability with 0% aging rate. The need for enhanced performance in transportation, energy production, and other power applications will pave the way for increased usage of new dielectrics like Hiteca.

For more information about Hiteca capacitors, visit our website to download the Hiteca capacitor datasheet and contact us for help choosing the right component for you.

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