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# Increasing Multilayer Ceramic Capacitor Lifetime with Bipolar Voltage Cycling

Kayla Y. Chuong, *Member, IEEE*, Jon A. Bock, *Member, IEEE*, Eric A. Patterson, *Member, IEEE*, Harlan J. Brown-Shaklee, *Member, IEEE*, Lukas Graber, *Member, IEEE*, Lauren M. Garten, *Member, IEEE*

**Abstract**—Enhancing the lifetime of multilayer ceramic capacitors (MLCCs) is critical in many aerospace, naval, or electrical grid applications where device failure could lead to catastrophic consequences. The migration of oxygen vacancies from the ceramic to the electrode interface under constant bias is known to reduce the lifetime of oxide based MLCCs. Bias cycling presents an opportunity to enhance MLCC lifetime by reducing oxygen vacancy migration. The ideal frequency range is expected to lie between frequencies low enough to avoid self-heating but high enough to avoid interfacial defect formation. However, the impact of low frequency bipolar voltage cycling (BVC) on MLCC degradation mechanisms has not been well studied. This work investigates the impact of periodic BVC on the degradation of MLCCs through highly accelerated lifetime testing (HALT) on X7R capacitors. HALT tests were conducted at 255 °C and 60 V using different switching frequencies: 0 (DC), 0.1, 2.5, and 10 Hz. BVC was found to improve the lifetime of MLCCs compared to DC test conditions. MLCCs tested at 10 Hz BVC showed a 311% increase in average time to failure compared to the DC case. Impedance spectroscopy shows that BVC decreases the rate of resistance degradation within MLCCs, indicating that oxygen vacancy migration to the electrodes is mitigated. The impedance spectra taken on BVC samples highlights how grain boundaries play a vital role in trapping oxygen vacancies. Periodic cycling causes oxygen vacancies to become trapped at grain boundaries, resulting in oxygen vacancies taking longer to reach the electrode interface and thus increasing MLCC lifetime. This work highlights not only how BVC can be used to increase MLCC lifetime but also how periodically cycling MLCCs could increase lifetime in extreme environments such as at elevated temperatures and electric fields.

**Index Terms**—AC reliability, dielectric reliability, high temperature capacitors, multilayer ceramic capacitors

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## I. INTRODUCTION

WHILE the dielectric layer thickness greatly increases the capacitive volumetric efficiency [1], [2], it can also increase the probability of device failure for multilayer ceramic capacitors (MLCCs) [2]–[5]. In aerospace, naval, or electrical grid applications, device longevity is critical. Premature failure of a MLCC can lead to catastrophic consequences, and this issue is only exacerbated in extreme operating environments such as increased temperature and humidity. Thus, there is a need to understand the underlying mechanisms that drive degradation to develop routes to improve the lifetime and reliability of MLCCs.

MLCCs are composed of alternating layers of base-metal electrodes (BME) and a barium titanate-based dielectric, which are sintered in a low oxygen partial pressure atmosphere in order to avoid oxidation of the electrodes [4], [6]. Unfortunately, this process introduces oxygen vacancies,  $V_{\delta}$ , in the dielectric layer [7]. Under an applied electric field,  $V_{\delta}$  stemming from the dielectric layer diffuse towards the negative electrode. The buildup of  $V_{\delta}$  at the interface causes physical changes in the crystal structure which lowers the potential barrier, resulting in a decrease of the insulation resistance of the MLCC [4], [8]–[10]. The result of this migration of  $V_{\delta}$  has previously been documented as the leading cause of degradation in oxide based MLCCs [8], [11]–[15].

Processing strategies can reduce the number of  $V_{\delta}$  present within the dielectric layer or reduce  $V_{\delta}$  migration. For example, using precious metal electrodes (PMEs) instead of BMEs allows for sintering processes that reduce the development of  $V_{\delta}$  [4]. However, the high price of PME makes this approach not cost effective for most applications, forcing manufacturers to resort to BME MLCCs, such as Fe, Cu, and Ni to reduce cost [2], [4], [7]. Other processing strategies include minimizing grain size, which increases the grain boundary area that can capture or hinder the migration of  $V_{\delta}$  [4], [16]. The  $V_{\delta}$

Kayla Y. Chuong, Lukas Graber, and Lauren M. Garten are with the Georgia Institute of Technology, Atlanta, GA 30332 USA (e-mail: [kchuong3@gatech.edu](mailto:kchuong3@gatech.edu); [lukas.graber@ece.gatech.edu](mailto:lukas.graber@ece.gatech.edu); [lauren.garten@mse.gatech.edu](mailto:lauren.garten@mse.gatech.edu)).

Jon A. Bock and Harlan J. Brown-Shaklee are with Sandia National Laboratories, Albuquerque, NM 87185 USA (e-mail: [jabock@sandia.gov](mailto:jabock@sandia.gov); [hjbrown@sandia.gov](mailto:hjbrown@sandia.gov)).

Eric Patterson is with the Materials Science and Technology Division of the U.S. Naval Research Laboratory, Washington D.C. 20375 USA (e-mail: [eric.patterson@nrl.navy.mil](mailto:eric.patterson@nrl.navy.mil)).

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concentration within fine grain samples is lower than that of coarse grain samples improving the degradation resistance by increasing the time it takes for a critical concentration of  $V_{\delta}$  to build up at the electrode interface [4], [17]. Decreasing the grain size also decreases the effective acceptor concentration in the grains as they tend to accumulate at the grain boundaries instead, which results in improved degradation resistance [4]. However, there is a practical limit to minimizing grain size, and thus other avenues need to be explored to extend MLCC lifetime.

Doping with trace amounts of elements is another approach that can decrease the concentration or mobility of  $V_{\delta}$ . Many dopants have been studied in efforts to reduce resistance degradation in MLCCs. Transition metal elements, such as Mn or Cr, are generally incorporated into the B-site of  $\text{BaTiO}_3$  and act as acceptors to create trap sites for the excess electrons generated by  $V_{\delta}$  [1], [4], [18]. The addition of rare earth oxides that preferentially incorporate near the grain boundary region, (specifically those with an effective ionic radius between 0.096 and 0.106Å) [19], has been shown to decrease the  $V_{\delta}$  concentration within the grains of  $\text{BaTiO}_3$ -based capacitors [4], [19], [20]. The decrease in  $V_{\delta}$  concentration is accomplished by charge compensation and the formation of defect complexes that also inhibit the migration of  $V_{\delta}$  [4], [18], [20]. Trivalent rare earth oxides such as Dy, Sm, Er, Y, Ho, or Yb are of particular interest due to their amphoteric nature -either acting as a donor in A-site doping or an acceptor in B-site doping [2], [4], [6], [18]–[21]. However, the addition of dopants and the associated processing changes are costly, and the introduction of acceptor impurities often leads to an increase in  $V_{\delta}$  concentration [22], [23]. As such, alternative routes are needed to increase the lifetime of any capacitor without physically changing the device itself.

When microstructure or doping control cannot provide the required lifetime improvements (or are not viable), it is advantageous to investigate external routes to enhance MLCC lifetime. Periodically cycling the MLCC device with reverse bias is proposed here as a route to improve lifetime compared to devices held under DC electric fields. Varying the field direction is hypothesized to delay or decrease the amount of  $V_{\delta}$  collected at either electrode. This bipolar voltage cycling (BVC) could be employed to improve MLCC lifetime by modifying the circuit architecture without needing to change the MLCC processing or composition. While there have been extensive studies on the DC degradation of MLCCs [8], [11], [21], [24]–[26], there are limited reports on the effectiveness of BVC on degradation. AC cycling at 60 Hz and upwards of 1.8 kV/cm was found to decrease MLCC lifetime due to self-heating and ripple currents [27]. Plotnikov et al showed that MLCCs AC cycled at 1 kHz with a rms voltage of 0-600 V failed after a sharp, local increase in temperature at the electrode interface, which was likely due to self-heating [28]. Using a lower cycling frequency of 50 Hz and a peak to peak voltage of -130 to 130 V in multilayer ceramic actuators still resulted in failure due to self-heating [29]. M. Samantaray investigated using reverse polarity on partially degraded

MLCCs to redistribute the built-up  $V_{\delta}$ , but it was found to be ineffective [30]. However, in this study the polarity was only switched after the parts already showed significant resistance degradation. Since oxygen vacancies form ordered defect complexes, which trap the  $V_{\delta}$  in place, switching after degradation is unlikely to be effective [31]. This suggests that if reverse bias at low cycling frequencies and voltages is applied before significant degradation occurs, then  $V_{\delta}$  redistribution may be possible and lifetimes of MLCCs can be extended. In this study, constant cycling at lower frequencies and voltages is tested to avoid failure as a result of self-heating and defect complex formation.

This work focuses on determining the impact of BVC on the reliability and lifetime of MLCCs using highly accelerated lifetime testing (HALT), IV measurements, and impedance spectroscopy. Clear increases in reliability with increasing cycling frequency reveal reverse biasing as a route to increase MLCC lifetime. Impedance spectroscopy shows that increased lifetime stems from limiting  $V_{\delta}$  migration to the electrodes. From these results, routes to increase MLCC lifetime using BVC are proposed.

## II. EXPERIMENTAL METHODS

Highly accelerated lifetime testing (HALT) was conducted on commercially available X7R capacitors (KEMET), rated to 0.1  $\mu\text{F}$  at 6.3 V from -55 to 125 °C. Voltages and temperatures beyond the capacitor rating were used during HALT experiments to expedite the time to degradation. A new capacitor was used for every measurement except where explicitly stated otherwise. Capacitors from multiple X7R batches produced from 2018-2021 were studied. No statistically significant differences were observed in the lifetime of MLCCs tested under bipolar voltage conditions at any frequency from different batches. However, there were variations in time to degradation for different batches under DC testing conditions which are discussed further in the following section. All subsequent figures include data only from a single batch. Voltage-current measurements were taken on a Keithley 6487 picoammeter to determine the range of voltages and temperatures to use during HALT testing. From these measurements, it was determined that HALT testing at 60 V and  $250 \pm 5$  °C was acceptable. These conditions were used for all subsequent BVC and DC HALT measurements. A Keithley 6487 picoammeter was used for DC HALT measurements. The test temperature was maintained using a Sun Systems furnace for all HALT tests. The temperature was monitored by a separate type-k thermocouple placed on the capacitor and read via a 3478A digital multimeter (HP) with a cold junction compensator (Omega, TAC-386-KC). Prior to running a HALT test, the samples were allowed to equilibrate for thirty minutes at temperature.

For bipolar voltage HALT measurements, a square waveform was applied with frequencies of either 0.1, 1, 2.5, or 10 Hz using a Keithley 2410 source-measure unit system to apply the voltage and measure the current response. BVC here refers to cycling between equivalent positive and negative voltages, but rather than being sinusoidal as in AC cycling, BVC is distinctly

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switched DC polarity using a square waveform. An applied voltage of 60 V was used in all tests. The use of the same applied voltage and square waveforms ensures that the maximum applied field experienced by a MLCC is the same in every test. Using a square wave reduces the difference in the time under applied field between the BVC and DC test cases. A leakage current threshold of 0.5 mA was set as the upper limit for device failure. This was an arbitrary limit set to be commensurate with the current limitations required in many high temperature dielectric applications [25]. A total of 12, 9, 5, and 4 samples were tested for 0, 0.1, 2.5, and 10 Hz respectively. The average time to degradation for a set of MLCCs tested under the same conditions at various frequencies was used to determine the impact of an alternating field on the lifetime of the capacitor.

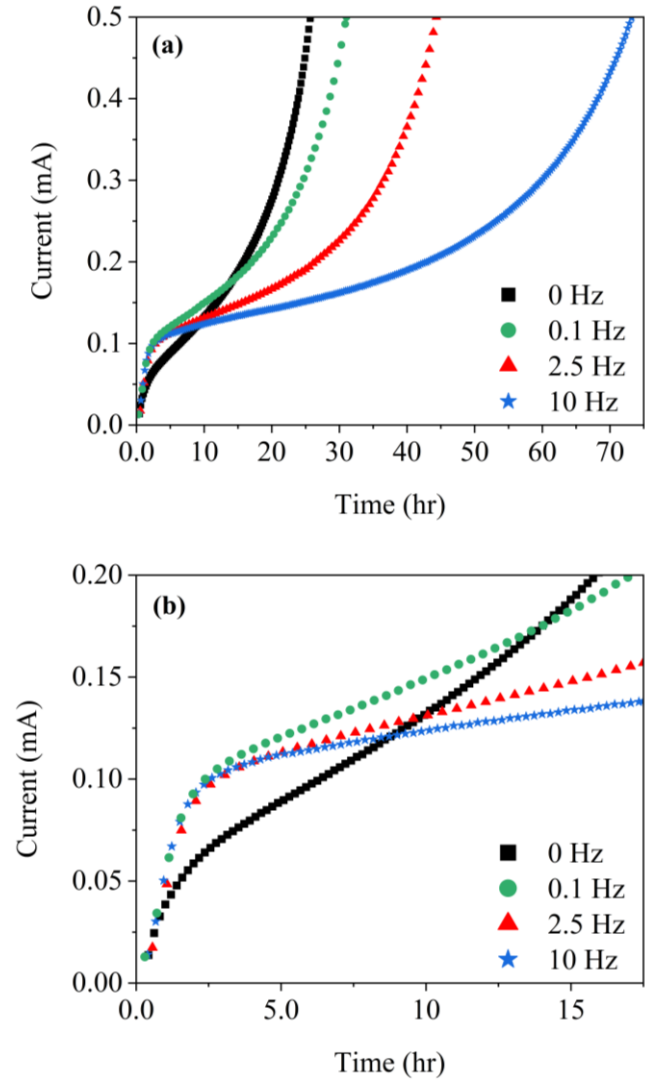
Impedance spectroscopy was measured with a ModuLabXM (Solartron Analytical) impedance analyzer. Impedance measurements were taken as a function of frequency over a range of static temperatures. The temperature control was managed through the same Sun Systems furnace system used for the current and HALT measurements. The capacitors were connected to the leads by stainless steel clamps. Open and short calibrations were run for the full length of the cabling. Impedance measurements taken after HALT testing were taken at  $235 \pm 5 \text{ }^\circ\text{C}$  and 100 mV from a frequency of 10 mHz to 1MHz. the impedance spectra was fitted to a 4RC equivalent circuit. The average layer thickness of the ceramic in the capacitor was determined by scanning electron microscopy (Zeiss Gemini 500).

### III. RESULTS AND DISCUSSION

The first step towards understanding the impact of electric field cycling on the degradation of MLCCs requires establishing the conditions for HALT testing. Ideal conditions for HALT testing should not cause instantaneous failure but should induce degradation by the same mechanism as if the MLCC was under normal operation. Preliminary current-voltage and current-temperature measurements were conducted to ensure that the dominant degradation mechanisms were consistent between typical standard operating conditions and the highly accelerated testing conditions used in this study. Fig. S1(a) displays the results from current measurements taken under a fixed voltage of either 6.3 (rated value), 12.6, 20, or 60 V over a range of temperatures from  $40 \text{ }^\circ\text{C}$  to  $290 \text{ }^\circ\text{C}$ . Fig. S1(b) shows current as a function of voltage where temperature was fixed at 40, 125 (rated value), and  $250 \text{ }^\circ\text{C}$ . While current increases with increasing temperature, it remains below 0.5 mA current threshold up to at least  $250 \text{ }^\circ\text{C}$  and 60 V. The current maintains a roughly linear response up to  $250 \text{ }^\circ\text{C}$  and at voltages greater than ten times the rated voltage without any indications of degradation or failure. Once the leakage current exceeds the noise floor of the measurement system, no other discontinuities or significant changes in slope occur. Even at the upper limit of temperature and voltage tested, there was no deviation in the slopes of either the current-voltage or current-temperature graph, indicating a consistent behavior across those voltage and temperature ranges. Therefore, the conditions for HALT testing were chosen to be  $250 \text{ }^\circ\text{C}$  and 60 V in order to expedite the

degradation of MLCCs. These testing conditions also provide insight into the functionality of these MLCCs at voltages and temperatures beyond the rated conditions.

Understanding the impact of cycling electric fields on MLCC lifetime requires accelerated testing under both DC and bipolar electric fields. Fig. 1(a) shows a comparison of the time dependent current measurements conducted at 0 Hz (DC), 0.1 Hz, 2.5 Hz, and 10 Hz (only the positive portions of the current are shown for the BVC capacitors). In all tests, the current exhibits a sharp initial step followed by a long period of slowly increasing leakage currents that gradually reach the maximum allowed leakage current. The spikes in current seen in higher frequency tests are attributed to regions where local electric field concentration leads to degradation but not complete device failure [32]. While MLCCs under AC cycling have also been shown to experience issues with self-heating and microcracking due to the effects of ripple current [28], [29], [33], [34], this usually occurs at higher switching frequencies than the ones used in this paper [35], [36]. Here, MLCCs are tested at low enough frequencies where self-heating is considered negligible.



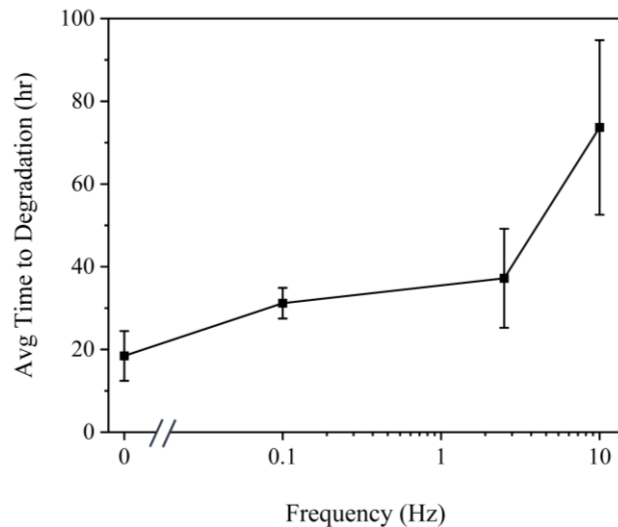
**Fig. 1.** Time dependent current changes for MLCCs cycled at 0, 0.1, 2.5, and 10 Hz (a); An expanded inset from the data in (a) showing the first 18 hours of HALT testing (b).

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During the initial stages of testing, there are clear differences between the current responses for samples undergoing BVC compared DC testing. Fig. 1(a) shows  $I(t)$  curves from representative capacitors tested at 0, 0.1, 2.5, and 10Hz. A change in the behavior of the curve is noted for times at less than 10 hours, highlighted in Fig. 1(b). All curves show an initial fast increase in leakage current during the first two hours. This behavior is increased in samples undergoing BVC. The DC sample shows a faster degradation rate after this initial period and ultimately fails first. Samples subjected to BVC only show differences after this initial period and, as expected, a significant decrease in degradation rate is seen with increasing switching frequency. After approximately 14 hours, the DC leakage current overtakes the leakage current rates for all of the BVC tests. For films cycled at 10 Hz, the time spent at the steady state period is 42.5 hours or approximately 2.4 times longer than the DC case. Most noticeably, the steady state period increases markedly with increasing frequency. Overall, increasing the testing frequency increases the time it takes for a device to fail, as was hypothesized. These results show that the time to degradation is heavily dependent on the cycling frequency. Increasing the testing frequency further could potentially add further improvements to MLCC lifetime.

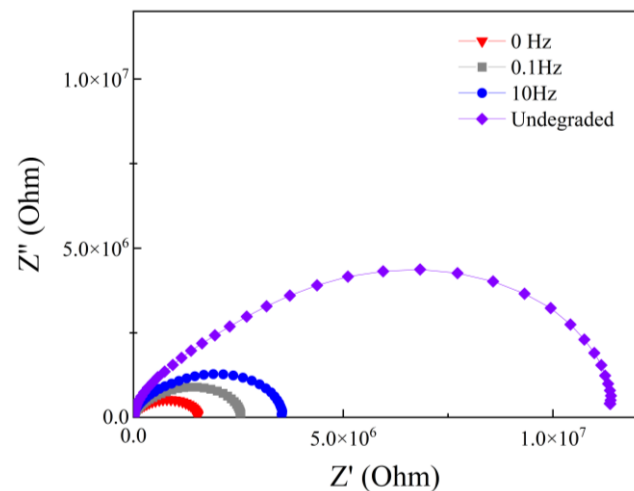
The median time to failure for a set of MLCCs measured at each frequency condition is shown in Fig. 2. With increasing frequency, the average time to degradation increases. These results are consistent with the individual sample results shown in Fig. 1. The average time to degradation at 10 Hz is significantly greater than that for DC measurements, approximately 74 hours compared to 18 hours respectively. Thus, testing at 10 Hz has an average increase in lifetime of 311%. Even a small increase in frequency, i.e. changing the operating frequency from DC (0 Hz) to 0.1 Hz, improves the average time to failure by an additional 13 hours (72%). This indicates that under standard operating conditions, applying BVC could significantly extend the lifetime of MLCCs. There is greater variability in the time for MLCCs to degrade with increasing testing frequency, as seen in the broader error bars at 10 Hz compared to lower frequencies. The increasing variability at higher frequencies likely stems from the time dependent probability of an  $V_{\delta}$  reaching the electrode interface, which will be discussed later. The results in Fig. 2 are consistent across multiple batches of X7R capacitors. The only significant difference observed between batches is the time to degradation under DC conditions, shown in Fig. S2. The variations in the time to degradation for the case of DC testing could stem from slight differences in chemical composition between production batches. Overall, BVC is found to significantly increase the lifetime of X7R MLCCs.

Impedance spectroscopy provides further insight into the potential mechanisms impacting MLCC degradation. Fig. 3 shows the complex impedance spectra for capacitors that had been degraded under 0 (DC), 0.1, and 10 Hz and undegraded capacitors all measured at  $235 \pm 5^\circ\text{C}$ . This temperature range is used so the full impedance response can be visualized on the undegraded capacitor. The impedance of the undegraded capacitors is consistent with previous reports of X7R Ni-BaTiO<sub>3</sub> capacitors [8], [37], [38]. The impedance response in X7R MLCCs is characterized by a highly distorted semicircle,



**Fig. 2.** Average time to degradation from the HALT testing of MLCCs as a function of frequency.

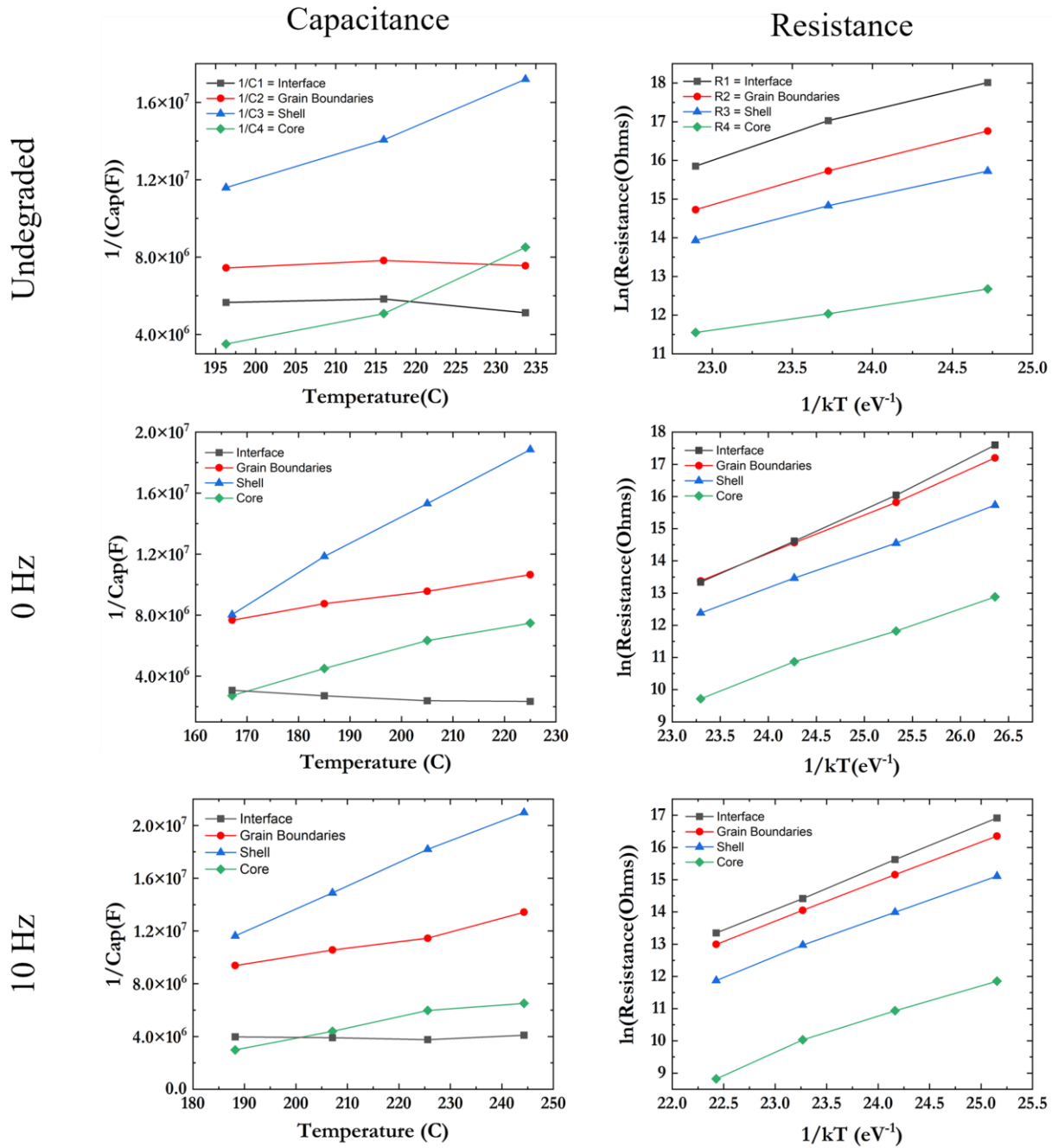
which has previously been modeled as a 3RC equivalent circuit with multiple overlapping contributions attributed to the grain, grain boundary, and ceramic-electrode interface [24], [38]. However, later investigations used a 4RC equivalent circuit to account for the presence of a shell region surrounding the core grains of the dielectric where certain dopants tend to congregate [4], [8], [39]–[41]. The impedance spectra in Fig. 3 are best fit to a 4-element RC (4RC) circuit diagram. The  $\chi^2$  goodness of fit  $p = .0007$  for the 4RC model as opposed  $p = .008$  for the 3RC model, and the exact fitting can be seen in Fig. S3. The four discrete circuit elements within the 4RC are attributed to the core, shell, grain boundary, and ceramic-electrode interface [8], [9]. Although the extent of the core-shell microstructure varies depending on the manufacturing process for X7R MLCCs, which are not publicly available, there is a precedent for a core-shell microstructure in these capacitors [8], [19], [37]–[39], [42]. Therefore, due to the superior fit and the precedent of X7R MLCCs having a core-shell microstructure, all following analyses will use the 4RC circuit model.



**Fig. 3.** Complex impedance spectra of undegraded and degraded MLCCs, measured at  $235 \pm 5^\circ\text{C}$ .



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**Fig 4.** Capacitance (a-c) and resistance (d-f) values extracted from the impedance spectra plotted as a function of measurement temperature.

The impedance spectra in Fig. 3 show a significant decrease in the resistance for both DC and BVC degraded MLCCs compared to the undegraded capacitor. There is a slight increase in the resistance degradation with decreasing frequency which could stem from differences in recovery between samples when reheated. Since all samples were HALT tested at  $255 \pm 5 \text{ }^\circ\text{C}$  while impedance analysis was conducted at  $235 \pm 5 \text{ }^\circ\text{C}$ , it is expected that resistances between samples are varied due to the difference in temperature dependent conductivity.

To investigate the microstructural aspects of degradation further, impedance spectra are taken over a range of temperatures for MLCCs degraded at varied frequencies. The

capacitance and resistance are extracted from the fitted 4RC equivalent circuit for each component. Fig. 4(a-c) shows the reciprocal capacitance for undegraded, DC and 10 Hz degraded MLCCs plotted as a function of measurement temperature. Fig. 4(d-f) shows the Arrhenius plots of resistance for the same samples. Next the four contributions can be correlated with components of the microstructure. Both  $1/C3$  and  $1/C4$  are linear, indicating a Curie-Weiss temperature dependence.  $1/C1$  and  $1/C2$  are temperature independent. This means that  $C3$  and  $C4$  must be stem from the crystal lattice; thus these contributions are attributed to the core or shell region [8], [40]. Given that  $C1$  is temperature independent and  $R1$  initially has

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the highest resistance value, the first RC element (R1-C1) is attributed to the Schottky barrier at the ceramic-electrode interface. The fourth element (R4-C4) is attributed to the core because it follows Curie-Weiss behavior. The activation energy extracted for this component is 0.62 eV, which likely corresponds to  $V_{\delta}$  diffusion [43], [44]. R3-C3 is then attributed to the shell region due to C3's corresponding Curie-Weiss behavior. This leaves the second element (R2-C2), represented by the grain boundaries. To summarize, each component of the 4RC circuit has been correlated with the microstructure: R1-C1 to the ceramic-electrode, R2-C2 to the grain boundaries, R3-C3 to the shell region, and R4-C4 to the core region. These results agree with Chazono et al's findings with X7R BaTiO<sub>3</sub> MLCCs [8].

Further analysis between undegraded, DC and BVC degraded samples reveals the impact of frequency on the degradation mechanism of MLCCs. After HALT testing, the resistances of both DC and BVC degraded MLCCs were found to have all decreased significantly, which can be seen in Fig. 4(d-f). The decrease in resistance is indicative of  $V_{\delta}$  migrating and reducing the height of the Schottky barrier at both the ceramic-electrode interface and the grain boundaries, resulting in the degradation of the MLCC [8], [32]. Samples degraded under DC conditions have a reduced ceramic-electrode interface resistance that is nearly the same value as the grain boundary resistance, averaging only a difference of 1.44  $\Omega$ , and at one point falling below the value of the grain boundary resistance. This is not seen in the BVC degraded samples. For samples degraded under BVC conditions, the resistance of the ceramic-electrode interface still decreases but not enough to match the values of the grain boundary resistance. An average difference of 2.76  $\Omega$  is maintained at all temperatures. These results indicate that the

extent of degradation at the ceramic-electrode interface is not as extreme under BVC. This suggests that in the BVC samples there is reduced migration of  $V_{\delta}$  to the ceramic-electrode interface and a slight increase in the  $V_{\delta}$  interactions with the grain boundaries. At the grain boundaries the  $V_{\delta}$  can either form complexes, thereby reducing resistance, or become temporarily trapped before migrating to the electrode. Multiple grain boundaries are encountered as the  $V_{\delta}$  travel towards the electrode, increasing the probability of recombination or trapping. After multiple cycles, the  $V_{\delta}$  could eventually reach the electrode, albeit at a delayed rate compared to DC testing [4], [8]–[10]. The slowed migration of  $V_{\delta}$  is further supported by the gradual increase in leakage current exhibited as the MLCC degrades over time. Because the Schottky barrier resistance does not decrease enough to equal the grain boundary resistance, BVC MLCC lifetime will have a greater dependence on grain boundaries compared to DC degradation [45].

Using the HALT data in conjunction with the insights garnered from impedance spectroscopy allows for the development of a model of degradation during BVC. The different effects of DC and BVC on  $V_{\delta}$  migration is shown schematically in Fig. 5. Rather than accumulating a high amount of  $V_{\delta}$  at the electrode interface, as in DC testing, bipolar voltage tested samples have a broader distribution of  $V_{\delta}$  throughout the sample. In this model, the grain boundaries play a more significant role in changing the electrical response of the device. If the  $V_{\delta}$  become temporarily trapped at the grain boundary or defects, then this would stagger the overall movement and distribution of the vacancies. This would not matter as much in the DC case as the constant bias will continue to drive  $V_{\delta}$  towards the electrode. However, under BVC, this staggered movement is more significant because the direction

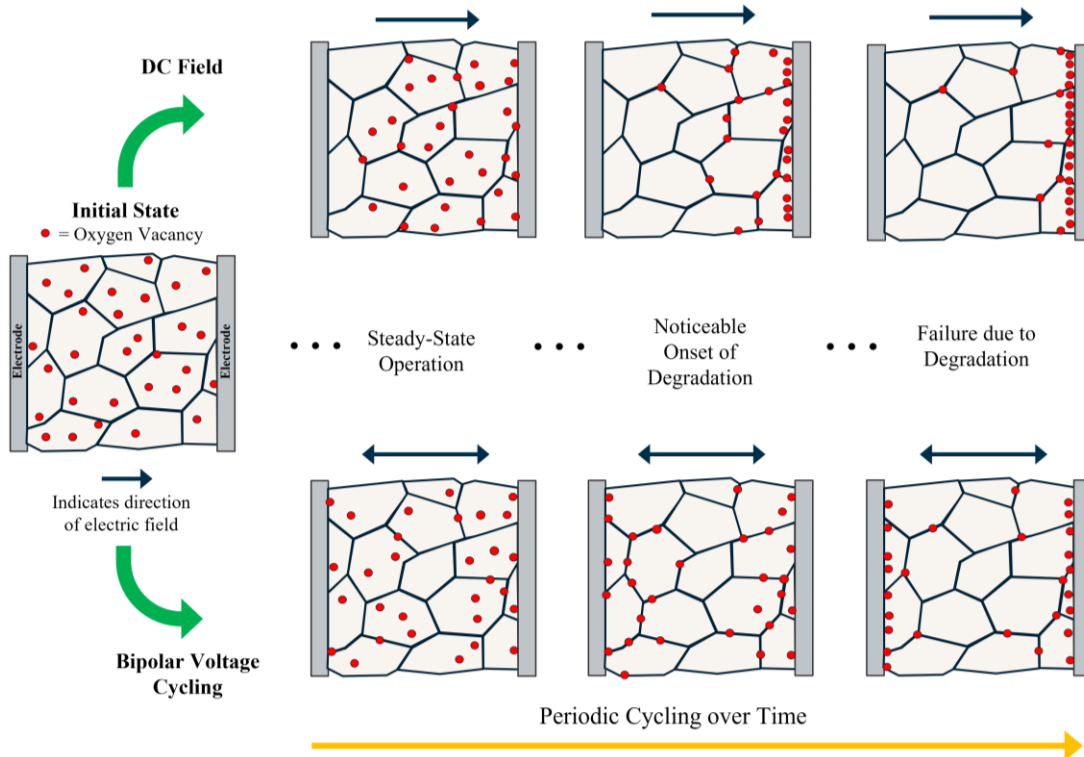
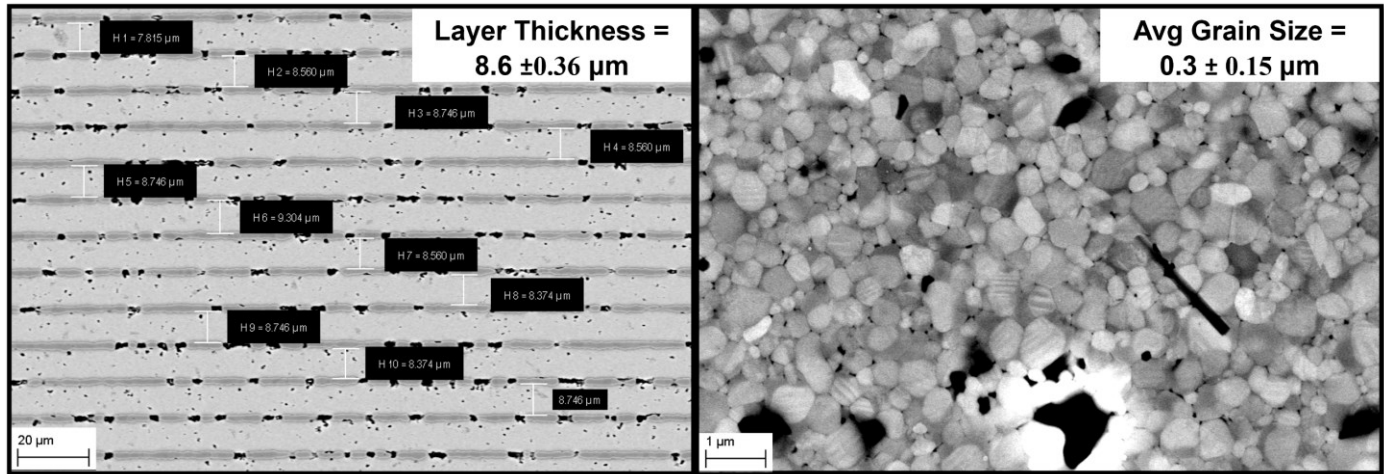


Fig. 5. Schematic of the proposed degradation mechanism for DC and BVC degraded MLCCs

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**Fig. 6.** Scanning electron micrograph (SEM) of the device cross section (a); SEM image of the grains of an X7R taken on an undegraded sample (b).

in which the  $V_{\dot{O}}$  travels is periodically reversed. Due to this staggered movement and the variable probability of trapping and detrapping for each cycle, whenever the electric field direction reverses, the mean distance traveled between cycles is no longer zero. And the  $V_{\dot{O}}$  could eventually reach the electrodes, but at a much slower rate than under a DC influence. Thus, increasing the frequency will limit the distance that a vacancy can travel per cycle, minimizing the probability of an  $V_{\dot{O}}$  making it to the grain boundaries to become trapped and leading to increases in lifetime with increasing frequency. The combination of the variable probability of  $V_{\dot{O}}$  getting caught at the grain boundary and the influence of BVC is thought to significantly increase the time it would take for the  $V_{\dot{O}}$  to reach either electrode, thus increasing MLCC lifetime. Furthermore, this model explains the broader distribution in time to degradation for BVC samples that is seen in Fig. 2, given that the time dependent probability of an  $V_{\dot{O}}$  migration plays a larger role in the overall probability of failure. As such, MLCCs operating under BVC conditions have significantly greater lifetimes than their DC counterparts, but there is also greater variability in how much lifetime is improved as frequency increases.

Now that the concept of using BVC to increase lifetime has been demonstrated, at least for the conditions used here, the next question to address is how far could the benefits of this method be pushed? In the case of an ideal single crystal, if the cycling frequency of the electric field is faster than the time it would take the oxygen to migrate to the electrodes based on ideal diffusion rate, then  $V_{\dot{O}}$  would not have the chance to migrate to the electrode before switching directions. The impact of frequency cycling on the degradation rate is then dependent on the layer thickness and grain size of the device. Fig. 6(a) and Fig. 6(b) show scanning electron micrographs (SEM) of the layer thickness and grain size respectively in an undegraded MLCC. The average layer thickness is  $8.6 \pm 0.36 \mu\text{m}$  and the grain size is  $0.3 \pm 0.15 \mu\text{m}$ . Given an  $V_{\dot{O}}$  mobility of  $1.0 \times 10^{-6} \text{ cm}^2/\text{Vs}$  at  $255 \text{ }^\circ\text{C}$  determined by H. Yoo et al [46] and an applied electric field of approximately  $7 \text{ kV/cm}$  to the MLCC, this would take an approximate cycling frequency of  $1.2 \text{ Hz}$  in a  $\text{BaTiO}_3$  film with a dielectric layer thickness of  $8.6 \mu\text{m}$  for an

$V_{\dot{O}}$  to move from one electrode to the other. However, degradation occurs in the samples tested in this study at a much faster rate indicating that there are additional factors to consider in estimating the impact of BVC on lifetime. The impedance spectroscopy indicates that while delayed,  $V_{\dot{O}}$  still move, and structural changes do still occur. Predicting the rate of degradation is then complicated by the variable probability that  $V_{\dot{O}}$  become temporarily trapped or detrapped at grain boundaries or defects. Further testing is required to calculate these probabilities in order to determine the minimum and maximum cycling frequencies that will decrease the rate of degradation and thus increase MLCC lifetime.

Therefore, if the circuit structure allows for it, BVC would significantly increase the lifetimes of X7R MLCCs. Operating under BVC conditions has been shown to increase the median time to failure of MLCCs, indicating increases in overall lifetime in comparison to when operating under DC conditions. BVC is thus a promising solution that does not involve changing the elemental composition or fabrication process of the MLCC to improve lifetime. Additionally, this work shows the impact of using this method at elevated temperatures and electric field conditions, showing the benefits of BVC in extreme conditions. However, there is a broader distribution in time to degradation for bipolar voltage testing, given that the time dependent probability of an  $V_{\dot{O}}$  migration plays a larger role in the overall probability of failure. As such, MLCCs operating under BVC conditions have significantly greater lifetimes than their DC counterparts, but there is also greater variability in how much lifetime is improved as frequency increases. Thus, further work is necessary to apply this method in applications where the accuracy of the expected lifetime is just as critical as to the actual lifetime of the MLCC itself, especially in high risk, harsh environmental applications where reliability is paramount.

#### IV. CONCLUSION

In summary, BVC is found to significantly increase the median time to failure of HALT tested X7R MLCCs compared to DC tested samples. The median time to failure consistently

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increases with increasing testing frequency. MLCCs tested under 10 Hz show a 311% increase in average time to failure compared to the DC case. Impedance spectroscopy shows that BVC decreases the rate of resistance degradation indicating that this approach increases the time it takes for the  $V_{\delta}$  to migrate to and accumulate at the electrodes. BVC is also shown as an effective route to increase device longevity for capacitors in extreme conditions such as elevated temperatures and electric fields. However, there is a broader distribution in time to degradation for bipolar voltage testing, due to the trapping and detrapping of  $V_{\delta}$  at the boundaries, staggering the mean distance travelled for each switching cycle. So, while lifetime is significantly increased for MLCCs operating under BVC conditions rather than DC conditions, how much lifetime has increased is much more variable due to the time dependent probability of the  $V_{\delta}$  migrating to the electrode. While proper estimates of the impact of BVC on MLCC lifetime require a deeper understanding of the underlying  $V_{\delta}$  motion, it is already clear that cycling increases lifetime and that further increases in frequency will likely lead to further enhancements in lifetime.

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