

TECHNICAL PAPER

Low-Voltage Performance of Multilayer Ceramic Capacitors

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Abstract

Extensive experiments and detailed analyses of the performance of multilayer ceramic capacitors used for decoupling and in other low-voltage, low-impedance applications discloses no degradation of insulation resistance in components without physical flaws. Capacitors with physical flaws show similar loss of performance at both low and high voltages.



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Introduction

Several investigators¹⁻⁴ have reported failures of multilayer ceramic (MLC) capacitors in low-voltage applications. However, previous reports have all concentrated on their use in low-voltage, high-impedance circuits while most MLC capacitors are used in low-voltage, low-impedance circuits such as for decoupling. Since these applications are at low voltages, some users have attempted to examine all low-voltage applications in terms of the high-impedance performance. The mechanism postulated for failures in low-voltage, high-impedance applications is low insulation resistance (IR) resulting from the formation of a conducting path in physical defects such as cracks or voids in the capacitor dielectric. The conducting paths are formed by electrochemically deposited electrode material under high humidity and low applied DC bias.⁵ These types of failures are usually rare and lot-related.

This paper examines the low-voltage failure mechanisms under low-impedance conditions and finds that the failure mechanisms at low voltages are the same as for those at higher voltages in low-impedance applications. It was found that MLCs which do not have physical flaws do not show any degradation of IR at either low or high voltages. Parts with physical flaws show a degradation mechanism which is similar at low and high voltages for low-impedance applications; the mechanism for low-voltage, high-impedance IR failure is not applicable to low impedance applications.

Experimental Results and Discussion

Experiments and analyses were carried out to determine the performance of MLC capacitors in low-voltage, low-impedance applications and these are described below.

Low-Voltage, Low-Impedance Life Test

Six groups of sample capacitors, two each from NP0, X7R/BX and Z5U dielectric types, were chosen for the low-voltage, life-test experiments. Each group consisted of 250 samples and for each dielectric low and high-capacitance values were chosen.

Samples from each group were carefully examined using standard destructive physical analysis (DPA) techniques to confirm the absence of flaws such as delaminations or cracks. They were further examined with a scanning electron microscope (SEM) for grain size, and morphology studies were conducted to confirm that the samples were similar to the normal production. Electrical properties, such as capacitance and dissipation factor (DF), were as expected. The IR values at 5, 10, 15 and 50 VDC were well above the 1000 megohm- μ fd required value at room temperature. The breakdown voltages were also comparable to the nominal values.

These 1500 parts were then placed on life test for 4000 hours at 5, 10, 15 and 50 VDC and temperatures of 85 and 125°C. No degradation of IR was observed over this time period for any of the samples. Additional samples were also tested at 5 VDC in the 85°C/85% relative humidity environment without showing any degradation of IR.

Low-Voltage, High-Current Pulse Test

In order to simulate a decoupling application, the circuit shown in Figure 1(a) was used to apply low-voltage, high-current pulses to another set of capacitors. Several groups of X7R/BX and Z5U dielectric capacitors were studied using this procedure. Several hundred parts were tested in each group, after samples from each group were examined to assure the absence of physical flaws, such as cracks and voids.

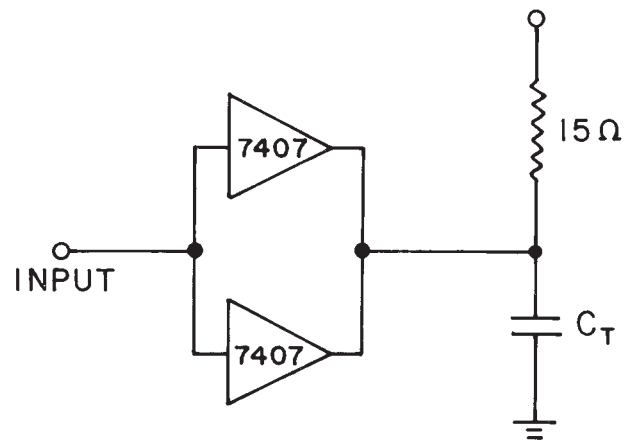


Figure 1(a). Low-Voltage, High-Current Pulse Test Circuit

A square-wave generator was employed to trigger the switches. The pulse width used was 100-ns with a 10-ns rise time at a frequency of 1 MHz. As an example, voltage across a 0.1 μF test capacitor was about 4 V and current was about 0.75 A. (See waveforms in Figure 1(b).) Each capacitor was subjected to about 3.6 billion pulses for the test (1 hour on test).

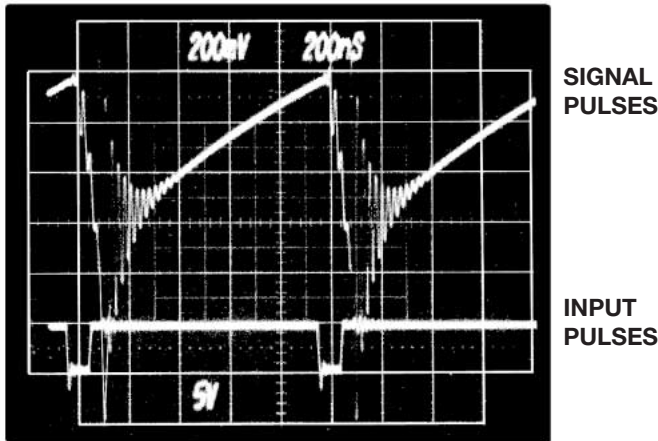


Figure 1(b). A typical test signal from the Current-Pulse Test (example for 0.1 μF capacitor)

A two-minute IR measurement at 2 VDC was performed for each capacitor before and after the current-pulse test. An electrometer was used and the output was applied to a strip-chart recorder (Figure 2). These parts were then subjected to a 2-minute IR measurement at 50 VDC and another two-minute IR measurement at 2 VDC. The purpose of these measurements was to first study any possible degradation of IR (and therefore the intrinsic behavior of the capacitor) due to the current-pulse test, and then to compare the low-voltage IR to the IR at the rated voltage of the capacitor.

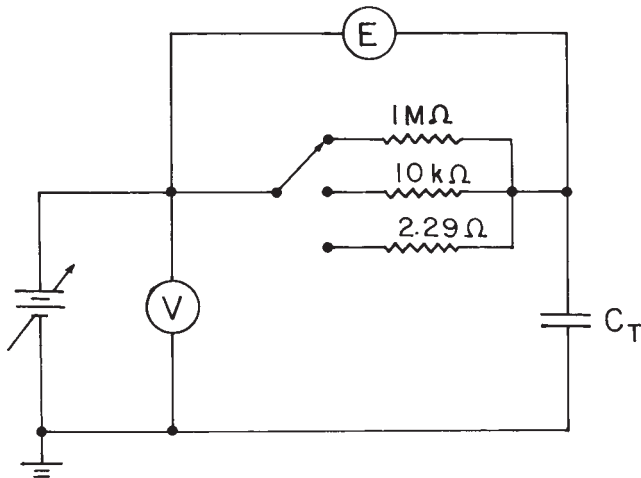


Figure 2. Test Circuit for IR and I-V Measurements

Of the 2000 capacitors analyzed, no degradation of IR was found. The IR at 2 VDC was comparable to that at 50

VDC (aside from the normal differences expected due to the intrinsic dielectric absorption characteristics of the ceramic dielectrics). There was no low-voltage degradation of IR in any part. Several samples were subjected to a hundred times the number of pulses with similar results.

Induced Failures Test Results

Several experimental groups were then prepared in which the capacitors had physical flaws purposely induced. This was accomplished by subjecting the parts to severe thermal and mechanical shock so as to induce microcracks and/or macrocracks. The subjected shock treatment far exceeded any likely to be encountered in normal handling of these capacitors. Most of the parts in these experimental groups had lower average IRs but some had IRs which were several orders of magnitude higher due to discontinuous electrodes. Other types of flaws were also investigated including experimental groups with significantly higher porosity compared to the nominal.

In an experimental group of 1000 of these parts, 40 capacitors were found to have significantly lower or unstable IR compared to the nominal values. (Unstable IR is a random change in this parameter by more than a factor of two when measured at different time intervals. Instability of IR in itself indicates the presence of flaws.)

All 1000 capacitors with experimentally induced cracks were then subjected to the current-pulse test and a two-minute IR measurement at 2 VDC. The 40 parts with erratic IRs continued to show lower or unstable IR after the pulse test while the remaining 960 components showed no detectable change in IR. These results demonstrate that the pulse test does not produce any further degradation of IR, even for capacitors with physical flaws; the variation of IR is due to the physical flaws and not due to the decoupling application itself.

As a second part of this study, the 1000 capacitors were then subjected to a two-minute IR measurement at 50 VDC followed by another two-minute IR measurement at 2 VDC. Comparable IR values were obtained for the 960 capacitors mentioned above. However, the 40 parts with unstable IR gave generally lower values at 50 VDC. This demonstrated that the higher voltage degraded the IR for these components more than the low voltage application.

Current-Voltage Characteristics of the Capacitors

The I-V characteristics of some of the 40 unstable capacitors mentioned above and parts from other control groups showing variations in IR were determined using the circuit in Figure 2. The selectable series resistors provide the signal current and limit current flow should capacitor breakdown occur during the voltage increment.

As an example, curve 1 in Figure 3 shows that IR decreases by as much as three orders of magnitude with increase of voltage. The most rapid degradation of more than two orders of magnitude occurred between 35 and 50 VDC again indicating the greater effect of higher voltages.

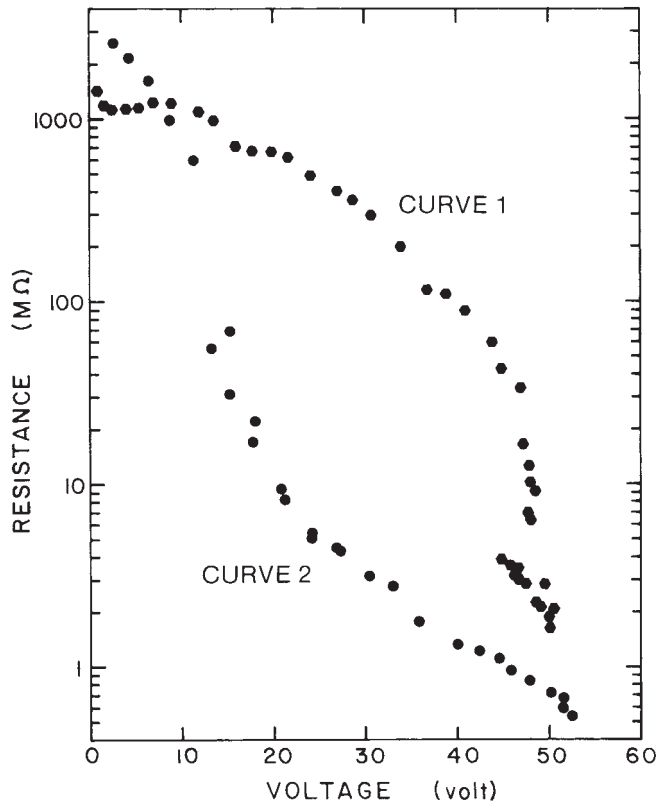


Figure 3. Variation of IR as a Function of Applied Voltage

Next, the voltage was increased to 53 volts and then reduced to zero. When the IR measurements were carried out again, curve 2 in Figure 3 results. This shows the higher voltage did more damage to the IR than the lower voltage. For these capacitors, IR degradation in the 0 to 5 VDC range was minimal, if any. (The ohmic heat dissipation is less than 1 nW at 1 V and 5 mW at 53 V.)

The I-V characteristics of two low-IR capacitors are shown in Figure 4. Curve (a) shows the non-ohmic behavior found in various parts with the approximate relationship:

$$I \propto V^n, \text{ where } 1 < n \leq 4.$$

In this particular case, the curve can be described by $I \approx 1.4 V^2 (\mu A)$. Curve (b) shows the unstable IR behavior where the behavior is unpredictable.

With repeated cycling, the IR is reduced further by several orders of magnitude due to the voltage degradation. As an example, Figure 5 shows typical I-V characteristic curves for three such components. Experimental data shows that about 10 watts are required for a capacitor to heat up and trigger thermal runaway failure. In a low-voltage, high-impedance application, where the current is less than 1 mA, the circuit does not have the capability to maintain this power level. In a low-impedance circuit, on the other hand, there is no current limitation to stop the heating process once it begins and thermal runaway can result. However, this mechanism is not unique to the low-voltage performance; in fact, it has already been shown that higher voltages actually do more damage.

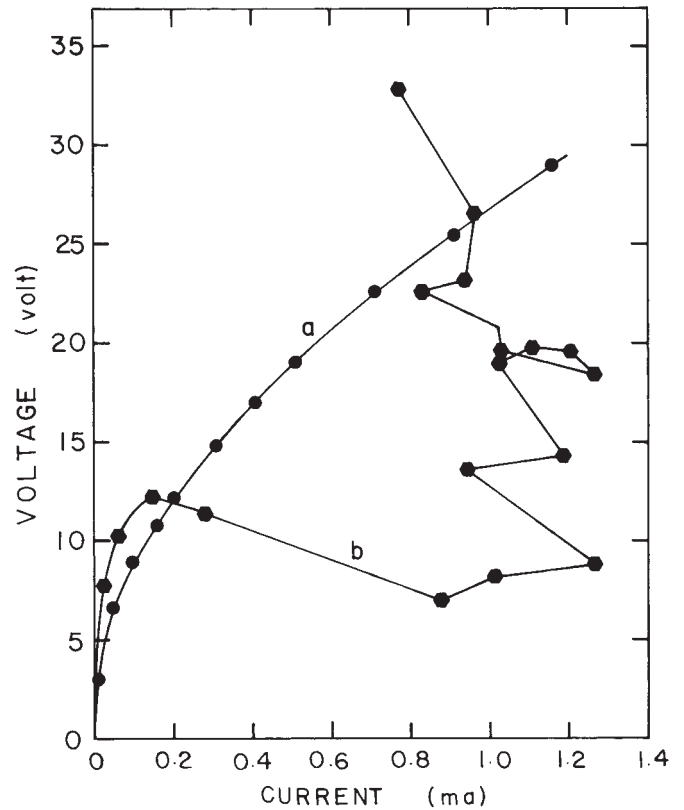


Figure 4. Two Typical I-V Characteristics of Low IR Parts with Physical Flaws

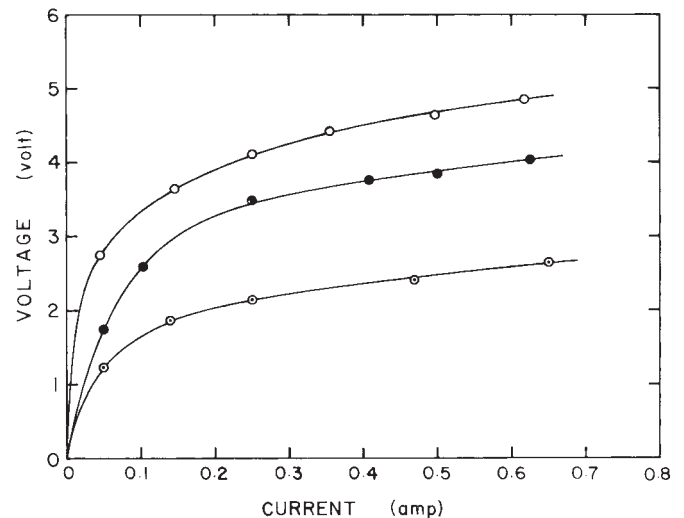


Figure 5. I-V Characteristics of Three Control Parts with Their IR Degraded by Voltage

Finally, selected groups of capacitors with unstable IR due to physical flaws were analyzed in the 85°C/85% RH environment at 5 VDC without current limiting. These parts showed a similar degradation of IR at higher voltages.

Conclusions

Characteristics of MLC capacitors used in low-voltage, low-impedance applications were evaluated with the following results:

1. Capacitors placed on life test in a circuit simulating low-voltage, low-impedance applications do not show degradation of IR at low voltages.
2. The high-current pulse test developed to simulate this application indicates no degradation of capacitor performance.
3. Flaw-free parts do not show any reduction of IR or unstable IR for this application at test voltage.
4. Capacitors which were intentionally flawed show unstable IR but no further degradation occurs after the current-pulse test. The degradation of IR increases more at higher voltages than at lower voltages.

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