IMPACT OF CIRCUIT RESISTANCE ON THE BREAKDOWN VOLTAGE OF TANTALUM CHIP CAPACITORS

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ABSTRACT

Experiments are described in this paper whose results suggest a clear mathematical relationship between total circuit resistance (including the capacitor's ESR) and the voltage at which a capacitor is likely to break down. Specifically, the relationship defines how much each capacitor's (not precisely known) breakdown voltage is affected by changes in circuit resistance. Since a factor that strongly influences the reliability of a tantalum capacitor is the ratio of the capacitor's breakdown voltage to the applied voltage, if the impact of circuit resistance on breakdown voltage can be established, then, at least indirectly, the impact of circuit resistance on reliability can be inferred.

The breakdown voltages of individual capacitors, drawn from large randomized samples, were determined for different values of circuit resistance. These data were analyzed and found to fit a specific mathematical relationship with a high degree of confidence. The relationship was found to hold for different batches and part-types. The test methods employed to minimize statistical noise are described in the paper as is the resulting mathematical relationship. Implications of the relationship are explored and avenues of future research are suggested.

INTRODUCTION

It is almost universally accepted that the reliability of tantalum capacitors is influenced by circuit resistance. That is, higher circuit resistance leads to higher reliability. In the early days of tantalum capacitors, rules existed that suggested a "safe" level of circuit resistance. Perhaps the best known rule of the time was one that suggested that the designer provide at least 3 ohms-per-volt of circuit resistance at the operating voltage in order to insure adequate reliability. Process improvements, customer needs, and rigorous surge current testing by manufacturers have lead to new "rules" such as 0.1 ohms-per-volt of effective circuit resistance, and it is now common for tantalum capacitors to be used in low-impedance circuits. Clearly progress has been made, but a "missing link" in this evolutionary process has been a clearly defined relationship between circuit resistance and capacitor reliability. The objective of the work presented here is to clarify the relationship between circuit resistance and the likelihood of catastrophic failure when tantalum capacitors are rapidly charged to a given voltage.

The applicable experimental test methods are described as are various steps that were taken to verify test conditions and minimize experimental error. The resulting test data are presented, discussed, and fit to a mathematical model. The model and its reliability implications are discussed. Finally, suggestions are made to guide future research, and appropriate conclusions are drawn.

REVIEW OF SURGE CURRENT TEST METHODS

As was briefly mentioned above, surge current testing (screening) is a technique used to reduce the incidence of catastrophic failure in low-impedance circuits. Surge current testing is the rapid charging and discharging of capacitors to/from a given voltage through low circuit resistance (generally less than 1 Ω). When subjected to such testing, capacitors typically withstand the testing without detectable degradation of performance or fail catastrophically. The underlying assumption of the test is that if the capacitor survives such a test when done by the manufacturer under fairly harsh conditions, then it should easily survive future, less stressful surges in the customer's application. Real-world observations tend to support this assumption, but occasional failures still occur.

Theoretical aspects of surge current testing and the impact of high inrush currents on the reliability of tantalum capacitors are discussed in some depth by Reed[1]. He argues that the magnitude of the inrush current is not a significant factor in the likelihood of catastrophic turn-on failures as long as the integrity (insulating quality) of the capacitor's dielectric is not compromised. Stated another way, as long as the rising voltage of the capacitor does not exceed the threshold of dielectric breakdown, even very high inrush currents are not inherently harmful, and do

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not progressively degrade capacitor reliability, even after millions or billions of charge/discharge cycles.

Reed further indicates that if the dielectric does become compromised during charging (that is, breakdown occurs at a fault site), the high available fault current of low-resistance circuits can defeat the natural "self-healing" properties of tantalum capacitors. In this case, catastrophic failure is likely even for relatively small dielectric faults. On the other hand, for circuits with moderately high series resistance, the natural self-healing property of the MnO_2 solid electrolyte can effectively isolate small breakdown sites from the rest of the circuit before intense localized breakdown current expands the region of damage to the point where catastrophic breakdown is inevitable. So, high current in the presence of a peak voltage that does not approach the breakdown strength of the dielectric does not appear to initiate dielectric breakdown. But if a breakdown does occur for whatever reason, the high current associated with low resistance circuits certainly favors catastrophic failure over self-healing.

Marshall and Prymak[2] expand on this important idea that failures in high inrush current applications are not initiated by the presence of high current, but rather by failure of the dielectric to withstand the electric field stress as the capacitor's voltage rises. They describe how self-healing is accomplished in tantalum capacitors and how this mechanism becomes ineffective in high-current, low resistance circuits. They also explain that the surge-current screening done by capacitor manufacturers may not be fool-proof because, subsequent to surge-current screening, thermomechanical stresses generated by the customer's reflow mounting process and/or exposure to excessive humidity can compromise the dielectric's insulating properties and generate new fault sites.

Moreover, they introduce a powerful new test method (Surge Step Stress Testing – SSST) that identifies the threshold voltage where a capacitor's dielectric fails during rapid charging. The SSST method involves successively increasing the peak voltage of high-current rectangular voltage pulses until a capacitor catastrophically fails. The pulse voltages are routinely in excess of the rated voltage of the capacitor and occasionally approach the formation voltage of the dielectric. Making use of the SSST method, one can identify the statistical distribution of these breakdown threshold voltages in a batch of capacitors by testing to destruction a representative sample of the capacitors.

Once the underlying distribution of breakdown voltages is approximated, it is possible to estimate the likelihood of catastrophic failure of the capacitors in the remainder of the batch as a function of the peak voltage they see upon exposure to current surges. For example, the actual distribution of breakdown voltages of a test sample might indicate that roughly 5% of the sample capacitors fail when they are rapidly charged to 1.5 times their rated voltage. One would reasonably expect that if a random, statistically significant test sample behaved this way, capacitors randomly drawn from the remainder of the batch would behave similarly.

Moreover, if the distribution of failures in the test sample precisely fits a known statistical distribution, such as the Weibull distribution, one might be willing to extrapolate expected performance mathematically from the known distribution. Such extrapolations might be quite accurate, even if the number of experimental data points collected in the neighborhood of the voltage of interest is fairly small. As Marshall and Prymak report, this technique has lead to predictions of 100 ppm failure levels in applications that involve less than rated voltage. These predictions have proven quite accurate in spite of the fact that they are based on 100 piece test samples where the first breakdown occurred above rated voltage. In contrast, if one were to employ brute-force methods, at least 10,000 capacitors would have to be tested at the voltage of interest to begin to predict or verify a 100 ppm failure rate.

EXPERIMENTAL OBJECTIVE AND TEST STRATEGY

The SSST test method described above also allows one to answer the question of whether or not circuit resistance influences the threshold breakdown voltage of a capacitor, and if so, how much. Specifically, a random sample of capacitors can be drawn from a batch and subjected to the SSST test. The result of the SSST test is a statistical distribution of breakdown voltages. If one were to repeat the test with the same series resistance, he would expect to observe the same statistical distribution of breakdowns within the limits of experimental error and the statistical "noise" or variability caused by small sample size. Now, assuming a link between series resistance and threshold breakdown voltage, if another random sample were tested with different series resistance, the statistical distribution of the breakdown voltages should change. Specifically, it might be reasonably expected that higher series resistance should lead to generally higher breakdown voltages.

This logic suggests an experiment wherein several statistically significant test samples are drawn from a large, randomized population of capacitors. Each test sample is tested with progressively-larger series resistance, and the resulting statistical distributions are plotted on a common graph. Upon observation of the curves, one could judge whether there is an effect from changing series resistance, how large the effect is, and how reliable (or "noisy") the test data appear. Indeed, this is the strategy employed for the present investigation.

In the event such an effect is observed, it is well to quantify the magnitude of the effect. Statistical distributions lend themselves easily to such quantification. Specifically, the Weibull distribution has a parameter, which, in the case of SSST data, has been called the characteristic breakdown voltage. This is the stress voltage where 63.2 % of the test samples have catastrophically failed. For the experiment described above, the characteristic breakdown voltage of the statistical distribution corresponding to each level of series resistance can be plotted versus series resistance and fit to a mathematical model. Once the model has been proposed, data from an additional, similar experiment can be used to validate the model.

TEST METHOD DETAILS

The surge current test apparatus used for this evaluation has the following characteristics: (1) each capacitor is tested with an independent charge/discharge circuit. (2) Each charge/discharge circuit has its own 11,000 uF aluminum electrolytic capacitor as a charge reservoir. (3) Switching is performed with FETs having low "on" resistance. (4) Wiring is optimized to minimize inductance and series resistance. (5) Minimum series resistance is 0.11 ohms.

A preliminary test was performed at 35 V to establish the accuracy of the current measurement system and, ultimately, to verify the minimum series resistance of the test station. The test device consisted of 20 separate 22 uF/35 V tantalum chip capacitors connected in parallel. This device was found to have 120 Hz capacitance of 456 uF and 100 kHz ESR of 8 mΩ. The time history of the resulting charge current pulse appears in Figure 1.

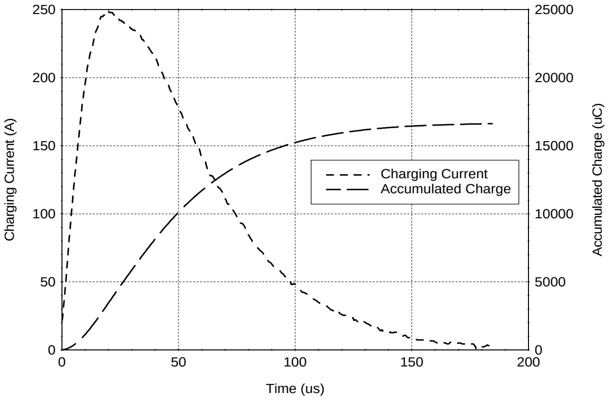

Figure 1. Current and Total Accumulated Charge for a 456uF, 8mΩ Test Capacitor Charged to 35V.

Also seen in this figure is the integral of this current pulse which is the total accumulated charge in microcoulombs. The integral curve provides an indirect method to verify current measurement accuracy. Both curves used together provide enough data to estimate the tester's circuit resistance. Calculations of the accuracy of the current measurement and of the tester's circuit resistance follow.

Electrical theory (Q = CV) predicts that a 456 uF capacitor charged to 35 volts should require 15,960 µC to achieve full charge. The current integral curve in Figure 1 peaks at roughly 16,600 µC. This implies that the current measurement circuitry measures about 4 % high. This is within the +/- 5 % accuracy of the current probe. The point of peak current (247A / 1.04 = 238 A) occurs at about 20 us. At this time, about 3,200 µC of charge has entered the capacitor, raising its voltage to about 7 volts. So the peak current of 238 A occurs with a voltage difference of 35 – 7 = 28 V across the system's total resistance which includes the test sample's 8 mΩ. Thus, Ohm's law predicts the total resistance to be 28 V / 238 A = 0.118 Ω. Discounting the test sample's 8 mΩ, the series resistance of the test circuit alone is 0.110 Ω, which is consistent with the value mentioned above. Since one hesitates to assume accuracy better than +/- 10 mΩ because of variable contact resistances, the series resistance is stated as 0.11 Ω.

The minimum series resistance of the tester was augmented with separate, high-power, metal-film resistors. The values of these resistors were chosen to roughly double circuit resistance for each successive test sample group.

The test fixture was designed to physically isolate each capacitor from its neighbors. This is done to block heat and debris of failing capacitors from affecting nearby healthy test samples. It must be emphasized that there is nothing subtle about the failure mode of these devices.

Much effort was spent to minimize experimental and statistical errors. Each population (batch) of capacitors was thoroughly randomized by mixing them in a container prior to board mounting. Test samples between 200 and 300 pieces were randomly drawn from each population, depending on the population's size. These samples were mounted on test cards according to a precisely defined test method to insure that all devices were treated similarly within the limits of practicality. Also, the time between mounting and testing was controlled to minimize any influence of this variable.

In spite of these precautions, some irregularities did occur. The biggest problem was that some devices ignited and were violently disconnected from the test fixture before the test circuit was able to detect that a failure had occurred. In these cases, the offending test device was mathematically removed from the test population in subsequent determinations of statistical distributions. Empirical observation indicated that the occurrence of such events was relatively infrequent, random, and independent of test voltage. It is not thought that the study is significantly impacted by these irregularities.

TEST RESULTS

A population of 220 uF, 10 V capacitors was randomly divided into five test samples of approximately 230 devices each. The sample groups were tested with external circuit resistances of 0.11, 0.29, 0.63, 1.31, and 2.51 Ω, respectively. Since these capacitors have 100 kHz ESR of about 60 mΩ, the total charging resistance for each of the sample groups (including the capacitor's ESR) was 0.17, 0.35, 0.69, 1.37, and 2.57 Ω, respectively.

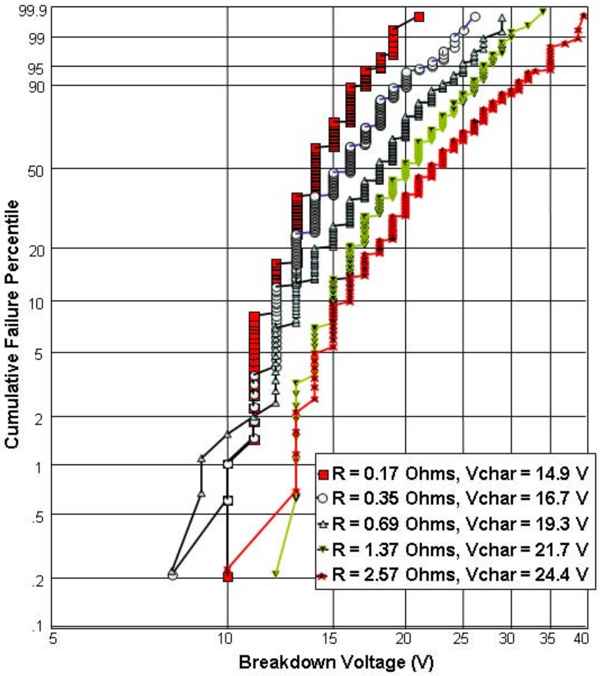

Figure 2. Weibull Plot of Cumulative Failure Percentile versus Breakdown Voltage at 0.17, 0.35, 0.69, 1.37, and 2.57 Ω for 220uF, 10V Tantalum Capacitors.

Figure 2 is a Weibull plot of the resulting breakdown distributions. The total charging resistance and the characteristic breakdown voltage for each sample group appears in the legend of the figure. It is clear from the data that the distributions of breakdown voltages do depend on the total circuit resistance. Moreover, there is high likelihood that this dependence can be modeled mathematically because of the similar shape of the distributions and their uniform spacing. Some evidence of experimental variation and sampling error are evident, but it is also clear that the precautions taken against error during the test process were quite effective.

A second population of capacitors was also randomly divided into five test samples. These capacitors were 330 uF, 10 V devices which had 100 kHz ESR of about 50 mΩ. Each of the five random samples contained 300 pieces. For these sample groups, the total charging resistances were 0.16, 0.34, 0.68, 1.36, and 2.56 Ω, respectively. The resulting breakdown voltage distributions appear in Figure 3. The total charging resistance and the characteristic breakdown voltage for each sample group appears in the legend of the figure.

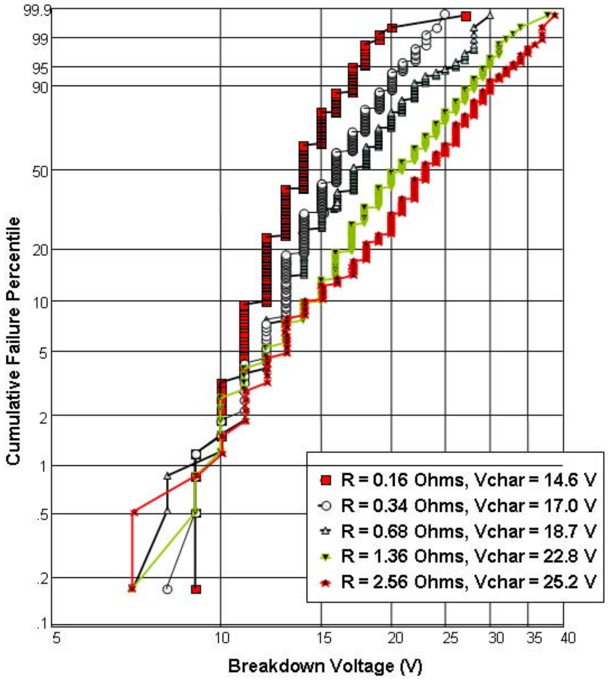

Figure 3. Weibull Plot of Cumulative Failure Percentile versus Breakdown Voltage at 0.16, 0.34, 0.68, 1.36, and 2.56 Ω for 330uF, 10V Tantalum Capacitors.

There is much similarity between Figures 2 and 3 which leads one to believe that that the overall behavior exhibited therein is characteristic of tantalum capacitors in general, not just these devices in particular, especially since the devices were selected from different part types that were manufactured on different dates. Some irregular behavior occurs in the curves at the lower voltages. Here the curves have a tendency to cross over each other and not maintain their regular spacing. Some comments on this behavior are appropriate.

It should be noted that there are relatively few data points in the region of irregular behavior -- typically about 2% of each test sample. It is believed that statistical sampling error is the primary cause of this effect. Very few devices in the total population are destined (by random variation in the manufacturing process) to fail at the first few test voltages. Thus, it is not statistically likely that these few "weakest" devices will be as evenly spread among the five test sample groups as are the devices that make up the heart of the distribution around the 60th percentile. By the same logic, the very "strongest" few devices (again around 2% of the population) should not be as evenly spread among the five test samples as are those from the heart of the distribution. Indeed, the data of Figures 2 and 3 bear out this prediction of irregular behavior at the highest percentiles as well.

Statistical methods exist to quantify this kind of sampling error, but precise mathematical treatment of the topic is beyond the scope of this paper. However, some informal discussion of the issue follows.

The difficulty of obtaining adequate statistical representation for the devices that occupy the fringes of a distribution is illustrated in the following example. Consider an imaginary experiment wherein 1,500 white table-tennis balls are poured into a large bowl. 30 balls are removed, painted red, and returned to the bowl. They represent the "weakest" devices. Likewise, 30 balls are colored blue and returned to the bowl. They represent the "strongest" devices. A blind man is asked to stir the balls until he thinks they are randomized, and then randomly select balls to create five samples of 300 balls each.

Consider the likelihood that each sample will get exactly 6 red or blue balls. One is likely to conclude that the probability is quite low, and that it is more likely that some samples will get 7 or 8 red or blue balls while other sample groups will only get 4 or 5. Were there only 5 red balls in the bowl at the start of the drawing, it should be clear that it is extremely unlikely that each sample would get exactly one red ball. Thus, the likelihood of adequate statistical sampling falls as one observes devices progressively further out on the tails of the distribution.

Finally, all will conclude that the white balls will be almost evenly distributed among the five samples, simply because there are so many of them. That is why the distributions in Figures 2 and 3 look so "well behaved" between the 20th and 80th percentiles – each breakdown voltage is well represented. Likewise, heavy statistical representation makes the characteristic breakdown voltage (identified at the 63rd percentile) a robust statistic to identify the typical behavior in a Weibull distribution, just as the mean (or average) robustly describes the most likely expected behavior in a normal distribution. Indeed, it is the characteristic breakdown voltage that is used in the next section to fit the breakdown data of Figures 2 and 3 to a mathematical model.

BREAKDOWN MODEL

The characteristic breakdown voltages of Figures 2 and 3 and lines fit to these data are plotted as a function of total charging resistance in Figure 4. Both the x and y axes are chosen to be logarithmic since the data best fit a power law model of the form $y=ax^b$. In this model, y is the resulting characteristic breakdown voltage, a is the characteristic breakdown voltage with 1 Ω of charging resistance, x is the chosen charging resistance in ohms, and b is the exponent that defines how much the characteristic breakdown voltage changes as the total charging resistance is varied.

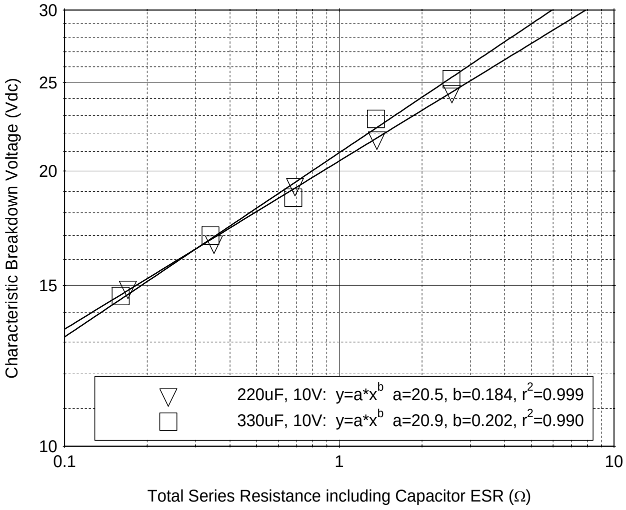

Figure 4. Characteristic Breakdown Voltage as a Function of Total Series Resistance, and Associated Best-Fit Approximations.

The fit of the lines to the data is exceptional with $r^2=0.99$ or better. The characteristic breakdown voltages with $R_{total}=1\ \Omega$ are 20.5 and 20.9 V, or about 2.1 times the capacitors' rated voltage of 10 V. However, it is expected that these characteristic breakdown voltages at 1 Ω are more closely tied to the formation voltages of the capacitors, purity of the raw materials, and optimization of the manufacturing process than they are tied to the capacitors' rated voltage. Thus, the characteristic breakdown voltage is not expected to hold constant from manufacturer to manufacturer, and certainly will be different for capacitors of different rated voltage.

On the other hand, the exponents b=0.184 and b=0.202, which relate changes in the characteristic breakdown voltage to changes in total charging resistance, are expected to be fairly consistent for all tantalum chip capacitors. This is because they describe how the dielectric strength of tantalum pentoxide is modified by changes in the rate of application of electric field stress. Specifically, the b exponent predicts that the ultimate breakdown voltage of tantalum pentoxide will change by roughly a factor of $2^{0.19}$=1.14 every time the total charging resistance is doubled or $0.5^{0.19}$=0.88 every time the total charging resistance is halved.

DISCUSSION OF THE MODEL

A mathematical expression that relates changes in tantalum pentoxide breakdown voltage to the total charging resistance (or, viewed alternatively, to the peak charging current) is the most important product of the present investigation. This model indicates that as total circuit resistance (including the capacitor's ESR) is altered by a factor of two, the voltage necessary to achieve dielectric breakdown will be altered by roughly 13%. Also, it is significant that the relationship appears to hold over a wide range of charging resistances.

One is reluctant to cite this relationship as a constant of nature, because some variation in the b exponent is expected to result from doping of the substrate tantalum during manufacture (e.g., tantalum nitride) or doping of the tantalum pentoxide during formation (e.g., phosphorous doping due to phosphate containing electrolytes). Considerable variation exists among the materials and processes used by different manufacturers. Since these materials and methods change the oxide into a material that is inherently different from pure tantalum pentoxide (the doping is done to achieve various beneficial effects), some variation in the magnitude of the exponent b is to be expected. However, since many other observed electrical properties are not greatly affected by such material and process variation, it is not expected that the b exponent will vary greatly.

It is not a novel concept that there might exist a link between charge rate (the effect of changing the charging resistance) and the ultimate breakdown voltage of a dielectric. Indeed, other investigators have observed that the results of UVBD (ultimate voltage breakdown) testing of insulators are affected by the rate of rise of the testing voltage, and that this variable must be controlled to achieve reproducible test results. Nonetheless, quantifying this effect for tantalum capacitors over a wide range of series resistances is of value.

Hypotheses have been offered that explain why fast charging reduces dielectric strength. The most common theme is that the atomic-level physical distortions which occur upon application of electric field stress are delayed in time from the field stress that induces them. The polarization that results from these physical distortions is necessary to produce a usefully high dielectric constant. During the time it takes the polarization to catch up to the applied field stress, atomic bonds in the dielectric are subject to forces that exceed the forces due to the applied electric field stress alone.

As the rate of application of electric field stress increases, the instantaneous discrepancy between the applied stress and resulting polarization increases. If the electric field stress approaches the level where atomic bonds are likely to be broken, the additional forces caused by the time delay between the applied field and the resulting polarization may be sufficient to achieve dielectric breakdown. However, had the same level of applied field stress been approached more gradually, the forces resulting from the stress-polarization delay would be much smaller, and the dielectric would not break down.

A final observation is in order. The self-healing properties of tantalum capacitors will ultimately limit the upper range of circuit resistances over which the model presented here will hold. As was discussed earlier, when externally supplied fault currents are limited, small faults in the dielectric of a tantalum capacitor can be isolated from the circuit before concentrated current can lead to catastrophic failure. We know that very low circuit resistance defeats this self-healing property because the dielectric degradation process outruns the self-healing process. However, when the series resistance of a circuit approaches roughly 100-1000 Ω, the self-healing process begins to dominate. Thus one would expect that the model will lose accuracy as circuit resistance approaches 100 Ω because of the introduction of this new "anti-failure" mechanism.

LIKELY RELIABILITY EFFECTS

All should agree that the reliability of tantalum capacitors is directly related to the breakdown strength of a capacitor's dielectric. More precisely, reliability is directly related to the difference between the applied electric field stress and the breakdown strength of the weakest, or most compromised, site in the dielectric. The validity of the concept of voltage acceleration factors and the related wisdom of de-rating the application voltage of a capacitor to achieve enhanced reliability are the result of indisputable empirical evidence. Clearly, less voltage stress leads to enhanced dielectric reliability in the absence of other degradation mechanisms.

The present investigation demonstrates that charging a capacitor through lowered series resistance lowers the strength of the capacitor's dielectric, making breakdown more likely at a given peak voltage and time of life. So reliability in applications where capacitors are rapidly charged to voltages that closely approach the breakdown strength of their dielectric can be very sensitive to changes in circuit resistance. This is because the safety margin between the dielectric strength and the actual circuit voltage is reduced in dynamic circuits when the circuit resistance is reduced. It is clear that a small number of the capacitors in the distributions of Figures 2 and 3 could be susceptible to breakdown if they were rapidly charged to voltages close to their rated voltage (10V) through resistances less than 1 Ω.

On the other hand, prudent circuit design dictates a substantial margin between a capacitor's dielectric strength and the application voltage. If this safety margin (or degree of voltage de-rating) is large (50% de-rating is very common in low-resistance circuits), the 12% downward shift in the dielectric strength that results from cutting circuit resistance in half may not have much observable effect. Indeed, even the weakest capacitors in the distributions of Figures 2 and 3 would probably survive rapid charging to 5V (half rated voltage), even through essentially zero external circuit resistance, which would leave only their own ESR of 50 or 60 mΩ.

FUTURE OPPORTUNITIES

Many questions still remain. Does the b exponent indeed stay close to 0.19 for capacitors with different formation voltages? Does doping of the dielectric have much impact on the breakdown model? Does variation from manufacturer to manufacturer affect the model? Does use of polymer counter-electrode material affect the model? Does the b exponent change much with temperature? Finally, how much is the model affected by use of alternative materials such as niobium and aluminum? Many opportunities exist to validate, clarify, and extend the present work.

CONCLUSIONS

Catastrophic failure of tantalum capacitors in high inrush applications is the result of voltage-driven dielectric failure rather than simply high inrush current. However, the threshold of dielectric breakdown is sensitive to the total circuit resistance and, thus, the peak magnitude of the charging current. Thus, albeit indirectly, the likelihood of catastrophic failure of tantalum capacitors can be increased by high inrush current in cases where the peak charging voltage approaches the now-reduced breakdown strength of the capacitor.

However, in cases where there is a wide safety margin between the peak charging voltage and the capacitor's breakdown voltage, reduced circuit resistance will not have much effect on likelihood of failure. This observation is not inconsistent with Reed's previous conclusion that high inrush current doesn't appear to significantly impact the reliability of tantalum chip capacitors having uncompromised dielectric.

The conclusion that a wide safety margin between application voltage and breakdown voltage minimizes the influence of series resistance on the likelihood of catastrophic failure strongly reinforces the value of appropriate voltage de-rating in low-resistance, high-current circuits. There is always the chance that a few capacitors may be compromised after manufacture by the stress of re-flow mounting and other environmental threats. Appropriate voltage de-rating can provide the needed safety margin for these devices in high inrush current applications.

The model proposed here indicates that doubling or halving the circuit resistance in high-current circuits will either increase or decrease, respectively, the breakdown threshold voltage of a tantalum capacitor by roughly 13%. Again, the significance of this shift is directly related to how much safety margin exists between this new breakdown voltage and the application voltage. For large safety margins (application at one-half rated voltage), the significance of this effect should be small, as indicated above.

Finally, the SSST test method described by Marshall and Prymak provides a new and powerful tool to explore the dielectric breakdown behavior and reliability of tantalum capacitors.

REFERENCES

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[2] J. Marshall and J. Prymak, "Surge Step Stress Testing (SSST) of Tantalum Capacitors," CARTS '01 Proceedings of the 21st Capacitor and Resistor Technology Symposium (2001).