Scintillation Breakdowns in Tantalum Capacitors

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Abstract:

Scintillations in tantalum capacitors are momentarily local breakdowns terminated by a self-healing, or conversion of the manganese oxide used as a cathode to a high-resistive mode. Similar breakdown events are often considered as nuisances, rather than failures. The author argues that a time-dependent sustained scintillation breakdown can be considered as a major reason of failures during steady-state operation of the capacitors. Analysis of distributions of scintillation breakdown voltages and assessment of the safety margins are critical to assure high quality and reliability of tantalum capacitors.

INTRODUCTION

Scintillations in solid tantalum capacitors are momentarily local breakdowns terminated by a self-healing or conversion to a high-resistive state of the manganese oxide cathode. This conversion effectively caps the defective area of the tantalum pentoxide dielectric and prevents short-circuit failures. Typically, this type of breakdown has no immediate catastrophic consequences and is often considered as nuisance rather than a failure. Scintillation breakdowns likely do not affect failures of parts under surge current conditions [1], and so-called "proofing" of tantalum chip capacitors, which is a controllable exposure of the part after soldering to voltages slightly higher than the operating voltage to verify that possible scintillations are self-healed, has been shown to improve the quality of the parts [2]. However, no in-depth studies of the effect of scintillations on reliability of tantalum capacitors have been performed so far. KEMET is using scintillation breakdown testing as a tool for assessing process improvements and to compare quality of different manufacturing lots. Nevertheless, the relationship between failures and scintillation breakdowns is not clear, and this test is not considered as suitable for lot acceptance testing [3].

Military documents and manufacturers' data sheets do not specify breakdown voltages of tantalum capacitors, but it is assumed that the rated voltage, VR, is chosen to be far below the breakdown range. Typically, VR is a portion of maximum formation voltage, VF, which determines the thickness of anodically grown Ta_2O_5 dielectrics and their electrical strength. It is often assumed that VF corresponds to the maximum electrical strength of the part [4], and, respectively, the formation ratio, n = VF/VR, indicates the margin for the operating conditions. However, the value of n varies from manufacturer to manufacturer; depends on the materials and processes used; and steadily decreases over the years, reducing from 4 for parts manufactured more than 20 years ago to ~ 2.5 for parts manufactured in 2005 [5]. This might be partially due to improvements in the quality of the dielectric, but the wish of manufacturers to increase performance of their product by squeezing the margin is also possible. In any case, the result is uncertainty of the significance of VR, which is likely determined differently for similar parts manufactured by different vendors and even for different part types manufactured by the same vendor. This difference in defining VR might explain the fact that in spite of using similar materials and processes, different manufacturers of tantalum capacitors are using different models to predict reliability of their product.

Quality and reliability of tantalum capacitors strongly depends on the safety margin between the operating and breakdown voltages. It has been shown that screening out parts with potentially low VBR results in significant reduction of life test failures [6]. Uncertainty in the meaning of VR and its relation to VBR casts some doubt upon the results of reliability estimations. This also reduces the effectiveness of derating, which might be excessive in some cases and insufficient in others. Obviously there is a need in evaluation of breakdown characteristics of tantalum capacitors to assure their quality, especially for high-reliability applications.

Failures of tantalum capacitors at steady-state conditions can be considered as a result of field and temperature accelerated degradation of the electrical strength of the Ta_2O_5 dielectric, and as a time-dependent dielectric breakdown, TDDB. When a local breakdown occurs, it might create a spike in power supply lines and thus cause a fault signal in sensitive detecting systems. In low-impedance applications, the scintillation can be sustained by the

power supply, thus preventing self-healing and resulting in a catastrophic failure of the part. TDDB in Ta_2O_5 has been studied using MIM and MIS structures for DRAM applications [7-10] and has been demonstrated for tantalum capacitors [11, 12]. However, the TDDB model has not been used yet to predict failures in chip tantalum capacitors.

In this work, scintillation breakdowns in different military-grade and commercial tantalum capacitors were characterized and related to the rated voltages and to life test failures. A model for assessment of times to failure, based on distributions of breakdown voltages, and accelerating factors of life testing are discussed.

TECHNIQUES

Two methods can be used to determine scintillation breakdown voltages in tantalum capacitors. One is based on application of a constant current stress (CCS) while the voltage across the part is monitored. This method has been described in several publications by J. Primak and co-authors, KEMET, and is referred to below as V-t technique. During scintillation, the capacitor discharges momentarily and a voltage drop is observed on the V-t curve. The scintillation breakdown voltage, VBR, is determined as amplitude of the voltage spike.

Another method, which is essentially a step-stress technique, is based on application of a constant, incrementally increasing voltage and monitoring leakage current during a certain period of time. The scintillation event manifests as a current spike on the I-t curve, and VBR is the voltage at which the first current spike is detected. This method is referred below as I-t technique. Details of these techniques, their benefits and drawbacks, are described below.

V-t technique

When a charging current, I_{ch}, is applied to a capacitor C, having a leakage current I_L, the voltage across the part increases with time:

$$V(t)=\frac{1}{C}\times\int_0^t\left[I_{ch}-I_L(t)\right]\times dt \qquad (1)$$

When $I_{ch} >> I_L$, V(t) is a linear function of time: $V(t) = I_{ch}\times t/C$ and the slope of the V-t curve can be used to calculate the value of capacitance C. When charging current is comparable with the leakage current, the V-t curve became sublinear and leakage current can be estimated as:

$$I_L(t)=I_{ch}-C\times\frac{dV(t)}{dt} \qquad (2)$$

Figure 1a shows typical results of V-t testing for parts having multiple scintillations during the test. For a 15 µF/10 V capacitor, a secondary scintillation occurs at a higher voltage than the first one, Vsc2 > Vsc1, and the electrical strength of the dielectric as a result of the first scintillation has increased. For a 100 µF/16 V capacitor, the secondary scintillation occurs at a lower voltage, Vsc2 < Vsc1, and the part apparently degrades after the first scintillation. As no catastrophic failures occur, both parts manifest self-healing, although of different degrees. In the second case the part remained damaged, self-healing was not complete, and the secondary breakdown obviously developed at the same site as the first one.

It should be noted that even when Vsc2 > Vsc1, it is conceivable that the secondary scintillation occurred at the same site as the first one because other sites of the dielectric might have breakdown voltages even greater than Vsc2. In this case, the first scintillation should be considered also as damaging. However, for practical purposes it is important to discriminate these cases and in the following analysis such scintillations are considered as non-degrading.

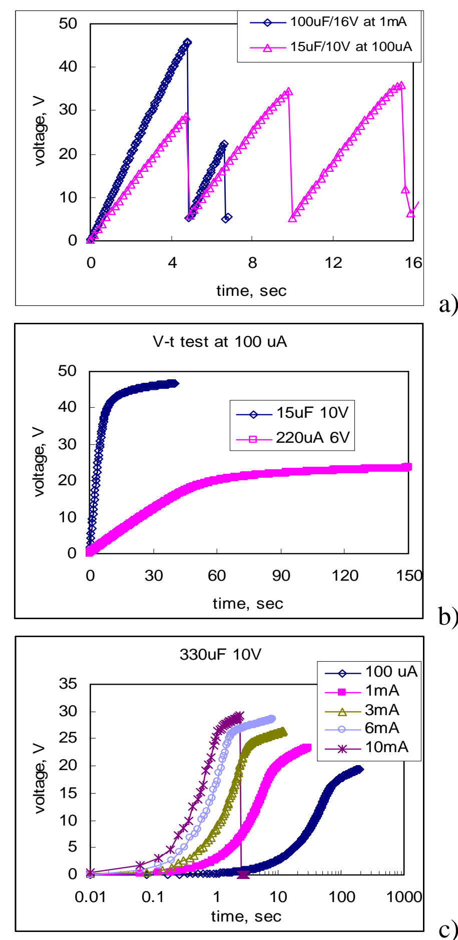

Fig. 1. Examples of V-t scintillation breakdown testing. Two cases of multiple scintillations, one (15 µF/10 V) with increasing VBR (non-degrading oscillations), and another (100 µF/16 V) with decreasing VBR (degrading oscillations), are illustrated in Figure a). Figure b) shows two parts where scintillations were not observed because the charging current (100 µA) was close to the leakage currents of the parts. Figure c) shows that in high-leakage capacitors the breakdown conditions can be eventually reached with increased charging currents.

If the charging current is not sufficient, breakdown does not occur, and the voltage stabilizes at a certain level as shown in Figure 1b. In this case $I_L(t) = I_{ch}$, $dV/dt = 0$, and the voltage does not increase with time. By carrying out this test at increased charging currents, the breakdown can be reached eventually as shown in Figure 1c.

Capacitance calculated as a slope of V-t curve exceeds the value measured using AC signals typically on 10% to 20%, and the leakage current calculated per Eq. (2) can be much greater than the one measured after 5 minutes at VR (DCL) as required per military specifications. Figure 2 shows correlation between AC and DC measurements of capacitance for 33 µF/10 V and 15 µF/10 V parts and an increase in capacitance of 22 µF/35 V parts as the rate of charging decreases from 300 µA DC to 10 µA DC.

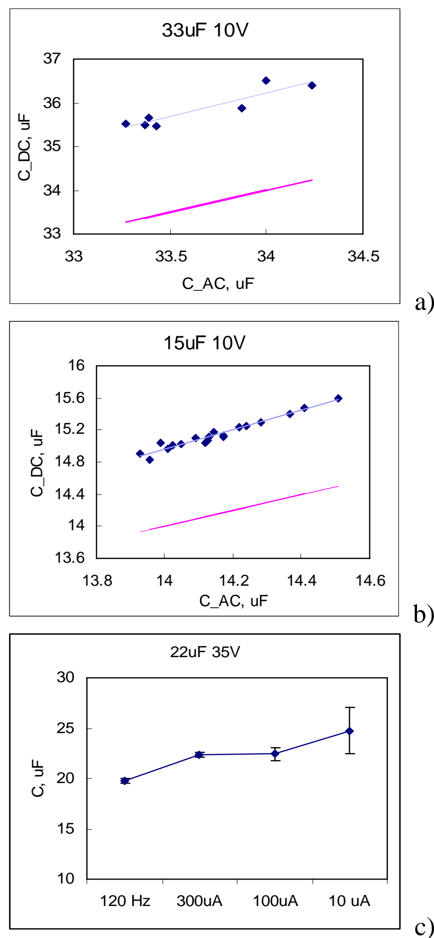

Fig. 2. Correlation between AC (120 Hz) and DC measurements for 33 µF/10 V (a) and 15 µF/10 V (b) parts. Lines in Figures a) and b) indicate no-change values. Figure c) shows variations of capacitance with charging current for 22 µF/35 V parts compared to measurements at 120 Hz.

An increase of capacitance and DCL obtained during V-t measurements compared to the standard methods is due to a substantial amount of charge absorbing on electron traps inside the Ta2O5 dielectric. Measurements of polarization/depolarization currents showed that the concentration of traps is very high, ~ 1E19 cm^{-3}. The difference between C_AC and C_DC and between DCL and the current calculated per Eq. (2) can be also used for rough estimations of the concentration of electron traps and their characteristic times.

I-t technique

Typical results of I-t measurements are shown in Figure 3. During these tests the voltage increased typically in 2 V or 3 V increments every 100 seconds. As a rule, breakdown does not occur right after voltage application, and it takes from a few seconds to a few dozen seconds for the scintillation to develop. Note that in the case shown in Figure 3a the currents almost completely recovered after the scintillation spikes, whereas in the case shown in Figure 3b the current remained higher. This indicates a full recovery of the part in the first case and remaining damage in the second case.

Obviously, this technique is more time consuming compared to the V-t technique and has worse voltage resolution; however, it is more sensitive to possible scintillation-induced damage and degradation. Besides, the necessity to vary charging currents depending on the value of capacitance and leakage current for V-t technique might complicate comparison of test results for different part types.

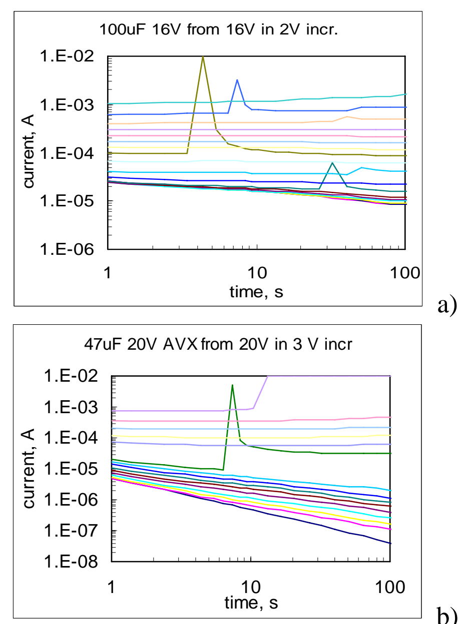

Fig. 3. Examples of scintillation I-t testing for 100 µF/16 V (a) and 47 µF/20 V (b) parts. I-t variations were recorded during 100 seconds starting VR with 2 V (a) and 3 V (b) increments. The first scintillation (current spike) is observed at 34 V after 32 sec. in case a) and at 50 V after 8 sec. in case b).

Comparison of V-t and I-t techniques

Groups of 10 to 42 samples of four different part types were tested using both V-t and I-t techniques. Weibull distributions of the breakdown voltages are shown in Figure 4 and indicate that both methods produce similar results. However, on average, VBR determined using the I-t method were slightly lower (on 3% to 10%) compared to the V-t method. This might be explained considering that the scintillation breakdowns in tantalum capacitors are time dependent. A typical time to breakdown during V-t tests (seconds) is approximately 10 times less than during I-t testing.

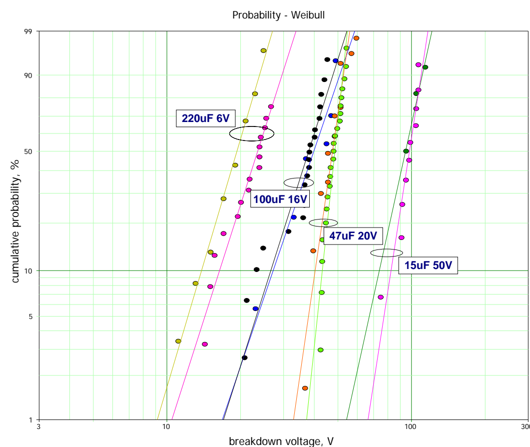

Fig. 4. Weibull distributions of first scintillations for four part types obtained using V-t and I-t techniques.

DISTRIBUTIONS OF VBR FOR DIFFERENT PART TYPES

Scintillation breakdowns were measured on 16 different types of commercial (seven types) and military-graded (nine types) solid chip tantalum capacitors. Note that all high-CV parts were commercial products. One part type, CWR11FH156KB, a 15 μF/15 V capacitor, was presented by three lots with different date codes, thus allowing evaluation of the lot-to-lot reproducibility of VBR. In most cases two-parameter Weibull distributions were used to characterize scintillation breakdowns in the parts, as shown in a probability plot in Figure 5. However, in some cases bi-modal distributions provided a better fit to experimental data.

Table 1 displays major statistical characteristics of the distributions, the shape factor, β, characteristic breakdown voltage, η, the rated characteristic breakdown voltage, η /VR, and the probability of failure at VR, P_{VR}. The value of P_{VR} varies in a wide range from 0.12% to less than 10^{-11} %. It is reasonable to assume that $P_{VR} > 10^{-3}$ % corresponds to poor-quality lots and should not be used in high-reliability applications.

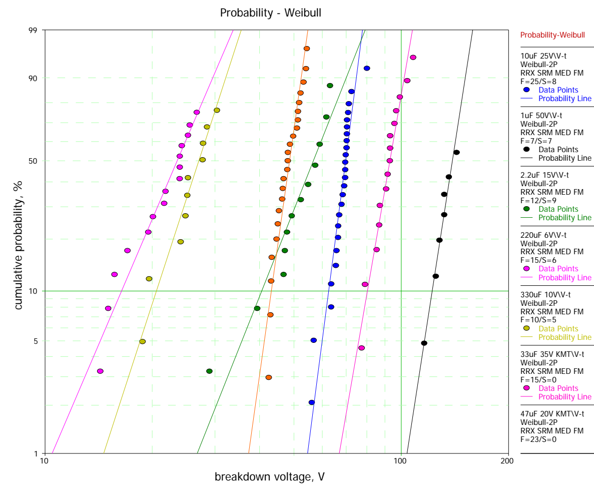

Fig. 5. Weibull distributions of first scintillation breakdowns for seven different part types.

Based on these distributions, another important parameter, breakdown margin, M, can be calculated. This parameter indicates a relative safety margin between the rated voltage and the minimum breakdown voltage of the population. For practical purposes it can be assumed that VBR_{min} corresponds to 0.1% of the distribution. In this case $M = (V_{0.1} - VR)/VR \times 100$, where $V_{0.1}$ is the breakdown voltage at probability 0.1%.

Tab. 1. Statistical characteristics of scintillation breakdowns in capacitors.

Part	Type	QTY	β	η	M, %
10uF 25V	CWR09	33	17.25	71.28	91
100uF 16V	commercial	39	5.57	39.65	2.9
15uF 50V	commercial	10	10.84	101.49	7.4
1uF 50V M. V	CWR06	14	8.07	154.46	31.3
1uF 50V M. A	CWR09	12	31	149	105.3
2.2uF 15V	CWR06	21	5.65	60.44	18.6
220uF 6V	commercial	21	20.8	15.43	86.7
22uF 6V	CWR11	15	6.7	29.25	73.8
22uF 20V	CWR09	16	19.5	57.66	101.3
3.3uF 10V	CWR09	33	14.73	30.01	87.8
330uF 10V	commercial	15	6.89	28.5	4.5
33uF 10V	CWR11	15	8.98	53.68	148.8
33uF 35V	commercial	15	12.96	95.57	60.3
22uF 35V	commercial	34	11.21	90.74	39.9
47uF 20V	commercial	23	15.98	49.72	61.4
15uF 10V DC0017	CWR11	25	5.82	31.73	51.7
15uF 10V DC0026	CWR11	23	9.41	35.48	70.3
15uF 10V DC0038	CWR11	31	10.91	49.65	163.6

The characteristic breakdown voltage exceeds VR in 3.4 times on average, and there is a trend of decreasing this ratio with VR as shown in Figure 6a.

However, the spread of η/VR is high, from 2 to 5.4, and the margin varies from 2.9% to more than 160%. This indicates that generally VR is not a reliable indicator of the electrical strength of tantalum capacitors, and each lot should be characterized to assess the electrical strength of the parts. Interestingly, some lots had a significant proportion of parts exceeding the rated voltage in more than 4 times, thus indicating that breakdown voltages might exceed the formation voltage of solid tantalum capacitors.

An average margin for military-grade parts (87.8%) is substantially greater than for commercial parts (37.2%), and both have a trend of decreasing with VR as shown in Figure 6b. This indicates a higher overall quality of military parts compared to commercial parts. However, a relative spread of this parameter is also greater for military parts (standard deviation 47.4% compared to 38.3% for commercial parts). Due to a large spread of the data, some commercial lots might have quality even higher than the military parts. Note also that high-CV capacitors are not available in a military-graded version, so this comparison might be not accurate.

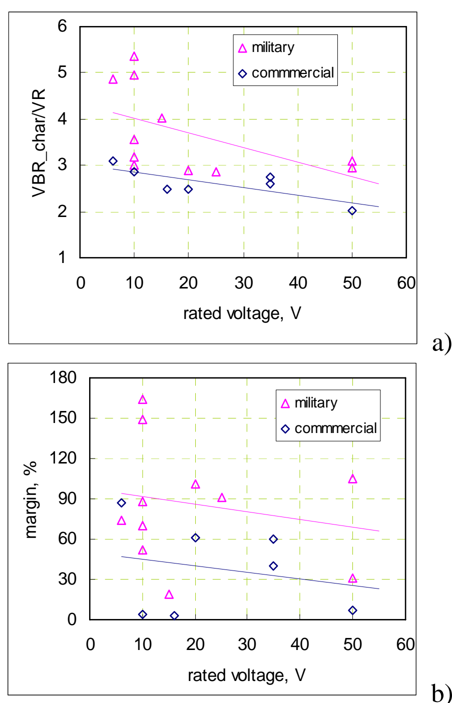

Fig. 6. Variations of the ratio of the characteristics breakdown voltage to VR (a) and margin (b) with the rated voltages for different commercial and military-graded parts.

Having a distribution of VBR for a given lot of parts, the rated voltage can be determined as the voltage at which the margin exceeds a certain acceptable level. Considering the range of M variations for different lots, it is reasonable to accept a 50% safety margin as a standard value. In this case, VR = $V_{0.1}/1.5$, and the probability of failure at VR will be several orders of magnitude lower than 0.1%.

Figure 7 shows substantial lot-to-lot variation of the electrical strength for CWR11FH156KB capacitors. The characteristic values of VBR in these lots varied from 31.7 V to 49.6 V. Although VBR in all parts exceeded VR, the margin varied more than three times, from 51% to 163%, thus indicating substantial variations in the quality and reliability of the parts from different batches.

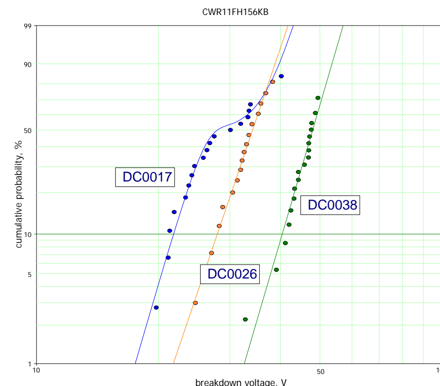

Fig. 7. Weibull distributions of breakdown voltages for three different lots of CWR11FH156KB capacitors. Note that the lot with DC0017 had a bimodal distribution, thus indicating the presence of two subgroups in this batch.

The data presented above describe distributions of the first scintillation breakdowns. An important question regarding the scintillations is whether they result in complete self-healing or whether some damage remains in the part, resulting in degradation of its electrical strength and reliability. By continuing V-t measurements after the first scintillation occurred, the breakdown voltages of the secondary scintillations, V_{sc2} were measured for some parts. The quantity of parts tested to multiple scintillations and the proportion of parts with damaging scintillations, P_{ds} (proportion of parts with $V_{sc2} < V_{sc1}$), are shown in Table 2.

On average, the first scintillation was damaging in approximately one-third of the cases, P_{ds} = 29.4%, and there was no significant difference between commercial parts and military parts. The spread of this proportion varied from 0 to almost 60%, suggesting that in many cases the self-healing was not complete and electrical strength of the parts had degraded. For this reason, a scintillation event should be considered as an indicator of potential failure, and a distribution of scintillation breakdown voltages can be used to characterize quality of the lot. Note also, that experiments showed that scintillations in high-CV parts migh cause explosion and ignition of the capacitors due to high energy stored in the part and released fastly during scintillation. In these cases failures are similar to the surge current events.

Tab. 2. Proportion of damaging scintillations.

Part	QTY	P_{ds}, %
10uF 25V	12	25.0
100uF 16V	14	35.7
15uF 50V	10	40.0
1uF 50V Mfr. V	7	57.1
2.2uF 15V	12	41.7
220uF 6V	17	35.3
22uF 6V	14	14.3
3.3uF 10V	10	20.0
330uF 10V	10	*
33uF 10V	7	28.6
33uF 35V	15	0.0
47uF 20V	20	15.0
15uF 10V DC0017	25	36.0
15uF 10V DC0026	7	14.3
15uF 10V DC0038	17	58.8
1uF 50V Mfr. A	12	*
22uF 20V	8	25
22uF 35V	29	24.1

* all parts failed catastrophically

SCINTILLATION BREAKDOWNS DURING LONG-TERM TESTING

As mentioned before, scintillations require some time to develop, and during I-t testing they often occur after a few seconds following application of the breakdown voltage. To prove that similar events might happen even after long-term operation under bias, monitoring of leakage currents were carried out on parts at room temperature and 125 ^{o}C at voltages varying from 1.5×VR to 3×VR.

Figure 8 shows examples of long-term current variations in 47 μF/20 V, 2.2 μF/15 V, and 100 μF/16 V capacitors. In all cases the breakdown appeared as a sharp current spike occurring with time ranging from seconds to dozens of hours. Note that one 47 μF/20 V and one 100 μF/16 V capacitor shown in Figures 8 a) and b) had two scintillations. The repeat scintillation occurred after a few hours of operation, thus confirming that parts experiencing scintillations have a higher probability of failure with time. Figure 8 d) shows variations of leakage currents in four 100 μF/16 V parts having scintillations after 6 to 20 hours of operation at 125 oC, 24 V. Here one of the four parts had also a repeat scintillation.

In the experiments described above, leakage currents were recorded every 20 seconds by measuring voltage across limiting 1 kOhm resistors. This allows only relatively powerful and damaging scintillations resulting in increased leakage currents to be observed. Obviously, scintillations not causing a substantial increase in the leakage current could be easily skipped because their duration is typically in the millisecond range. Also, the presence of resistors might limit the available current and energy of scintillations, thus limiting damage to the dielectric.

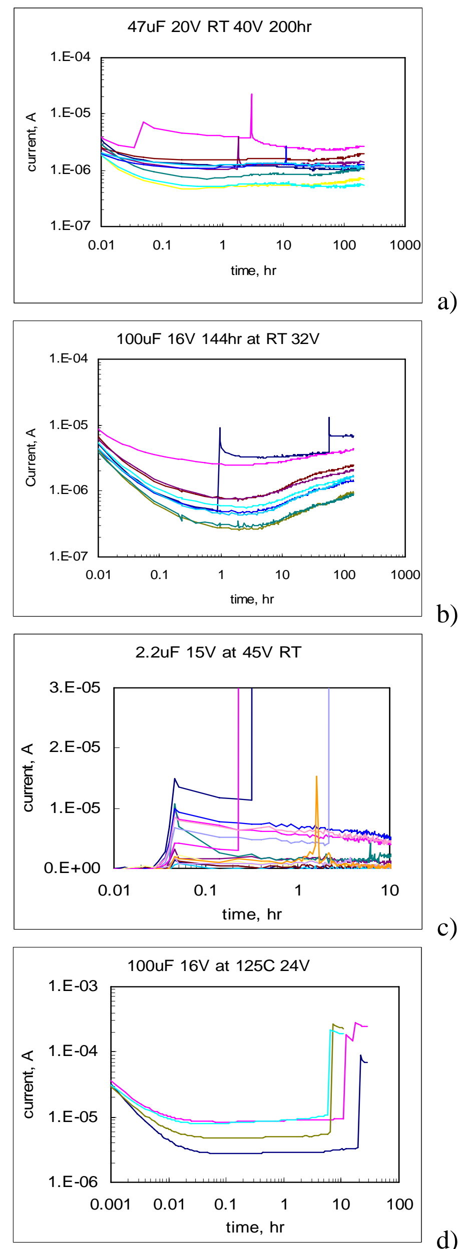

Fig. 8. Examples of scintillations observed during long-term I-t measurements in 47 μF/20 V (a), 100 μF/16 V (b, d), and 2.2 μF/15 V (c) capacitors at room temperature (a – c) and 125 ^{o}C (d). Parts presented in Figures a), b), and d) were tested with 1 kOhm resistors connected in series. Parts in Figure c) were tested with 1 Ohm 125 mA fuses. For this testing the voltage was gradually increased from 0 to 45 V during first 5 minutes, resulting in increased currents at the beginning of the test. A sharp increase of currents to more than 3.5E-5 A corresponds to fuse blowing.

Replacing limiting resistors with fast-acting fuses potentially allows all scintillations to be revealed, and by recording time to fuse blowing, a distribution of times to failure can be obtained. Figure 8 c) shows results of experiments with 20 capacitors, 2.2

μF/15 V, stressed at room temperature and 45 V for more than 10 hours. All parts had 125 mA fuses connected in series. The cold resistance of the fuses was 1.7 Ohms, and measurements of voltages across the fuses allowed for estimations of the leakage currents in capacitors (starting from a few microamperes) and detection of the times to failure. Three failures, ranging from 0.2 hour to 2 hours, were recorded during these experiments, but in two cases the scintillations without blowing the fuses were also observed. This indicates that even relatively low-current fuses might be insufficient for detecting all scintillation events in tantalum capacitors, and more sophisticated electronic systems are required.

Failures during Weibull grading testing can be also considered as caused by time-dependent scintillation breakdowns. During this testing, high-current fuses (from 1 A to 2 A) are required per MIL-PRF-55365, and to blow this fuse the part should experience a current spike of dozens of amperes during a few milliseconds. These powerful current spikes will likely be destructive in most cases. However, it is possible that relatively low-current scintillations would remain undetected. In this case, the reliability of the part might be degraded, but if the post-Weibull-grading leakage current is within the specified limits, the part with electrically weakened strength would not be screened out. Note that typically the specified DCL limits are two to three orders of magnitude greater than the real currents. In this situation, parts with increased leakage currents might pass the screening.

During highly accelerated life testing described in [1], five different lots of commercial capacitors were tested at 125 °C for 100 to 200 hours at 1.5VR. To reveal failures, 125 mA fuses were connected in sequence to each of the parts. Electrical measurements after life testing showed that out of 63 life test failures (parts with blown fuses), only three had high leakage currents exceeding the specified limits. This behavior can be explained considering that in most cases scintillations do not degrade the part to the level at which they exceed the specified limits of DCL.

DISCUSSION

According to the thermochemical model developed by McPherson and co-workers [8, 13], electrical breakdown in oxides occurs when local electrical field weakens polar molecular bonds to the level when thermal energy is sufficient to cause the breakage. This model also predicts that the time dependent dielectric breakdown follows E-model, so the time to failure can be expressed as:

$$TF = t_o \times \exp\left(-\gamma E + \frac{\Delta H}{kT}\right), \quad (3)$$

where ΔH is the activation energy required for displacement of ions from their normal bonding environment, γ is the field acceleration parameter, and t_o is a constant. For Ta_2O_5 dielectric ΔH is in the range from 1.7 eV to 2 eV.

Equation (3) is a special case of a more general Eyring E-model that is often used to describe time-dependent breakdown when the effective activation energy depends on the applied field. Similar equations were used by Goudswaard and Driesness from Phillips [12], Loh from Hughes Aircraft [14] and Khanin from Positron, Russia, [15] to describe voltage and temperature dependencies of times to failure for solid tantalum capacitors. However, their estimations of the activation energy were lower, 1.2 eV in [12] and 1.45 eV in [15]. This difference is possibly due to the presence of a high concentration of electron traps in anodic Ta2O5 films, which might substantially change internal electrical fields in the film. In spite of the differences in ΔH, empirical data confirm the applicability of the E-model to commercially manufactured capacitors.

The McPherson's model predicts that the breakdown field, EBR, decreases with the dielectric constant as $\varepsilon^{0.5}$, and the field acceleration parameter increases with ε so that their product does not depend on ε and can be presented as:

$$\gamma \times E_{BR} = \frac{\Delta H}{kT} \quad (4)$$

When (3) is used in conjunction with (4), it can be expressed via the breakdown voltage:

$$TF = t_o \times \exp\left(\frac{\Delta H}{kT}\right) \times \exp\left(-\frac{\Delta H}{kT} \times \frac{V}{V_{BR}}\right) = t_o \times \exp\left[\frac{\Delta H}{kT} \times \left(1 - \frac{V}{V_{BR}}\right)\right] \quad (5)$$

Assuming that VBR is related to the rated voltage and corresponds to the forming voltage of the dielectric, then VBR = n×VR, where n = (2.5 - 3.5) is the formation ratio, and Eq. (5) can be expressed via VR:

$$TF = t_o \times \exp\left(\frac{\Delta H}{kT} \times \left(1 - \frac{V}{n \times V_R}\right)\right) \quad (6)$$

A voltage accelerating factor at constant temperature, T, can be presented as follows:

$$AF_V = \frac{TF(V_R)}{TF(V)} = \exp\left(\frac{\Delta H}{nkT} \times \left(\frac{V}{V_R} - 1\right)\right) = \exp\left(-\frac{\Delta H}{nkT}\right) \times \exp\left(\frac{\Delta H}{nkT} \times \frac{V}{V_R}\right) = A \times \exp\left(B \times \frac{V}{V_R}\right), \quad (7)$$

where A = exp(-B) and B = ΔH/nkT.

The accelerating factor, which is used for Weibull grading test in MIL-PRF-55365, also varies exponentially with voltage:

$$AF = 7.03\times10^{-9}\times\exp\left(18.77\frac{V}{V_R}\right) \qquad (8)$$

Note that $AF(VR) = 1$ and $exp(-18.77) = 7.05\times10{-9}$. This means that expressions (7) and (8) are identical if parameter B = 18.77. According to the E-model, the voltage accelerating factor depends on temperature, and the applicability of Eq. (8) should be limited to a certain temperature range only, most likely around 85 °C, which is the temperature of the Weibull grading test.

Figure 9 shows temperature variations of parameter B for ΔH in the range from 1.5 eV to 2 eV and the formation ratio of 2.5 and 3.5. For military-graded parts the Ta2O5 dielectric is likely formed at relatively high voltages, so n = 3.5. At 1.75 eV < ΔH < 2 eV the agreement between the value of B calculated using the thermochemical model and the value used in MIL-PRF-55365, which was obtained based on empirical data of extensive life testing of tantalum capacitors, is reasonably good at temperatures between 60 °C and 100 °C. However, variations of n and ΔH might cause substantial variations of B and AF resulting in erroneous reliability estimations.

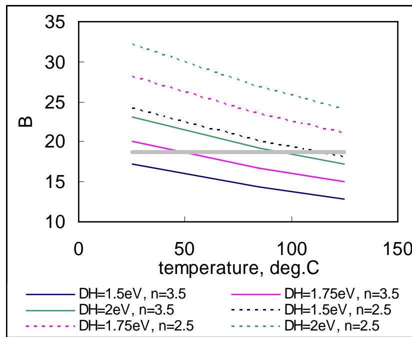

Fig. 9. Variations of parameter B with temperature for n = 2.5 and 3.5 and activation energies ΔH = 1.5 eV, 1.75 eV, and 2 eV. A horizontal line corresponds to the value of B used in MIL-PRF-55365.

Considering that for a given lot, the distribution of breakdown voltages can be described using a Weibull function with a characteristic breakdown voltage η and shape parameter β, the breakdown voltage can be expressed via the probability, p, of the part to have a certain level of VBR:

$$V_{BR} = \eta\times\left[-\ln(1-p)\right]^{1/\beta}, \qquad (9)$$

Using Eq. (5) and (9), the corresponding times to failure can be calculated, thus allowing numerical modeling (Monte Carlo simulation) of life testing. Table 3 shows results of simulation of life testing performed for three part types for T = 125 °C and V= 1.5VR.

Tab. 3. Parameters of VBR distributions and time-to-failure model per Eq.(5).

Parameters		100 uF 16 V	47 uF 20 V	33 uF 35 V
VBR distribution	η, V	40.2	49.1	94.8
	β	5.8	10.1	12.5
Life model	ΔH, eV	1	1	2.5
	t_0, hr	1E-3	1.5E-3	2E-12
Simulated TF	η, hr	86.6	241	5562
	β	0.25	0.49	0.29

Figure 10 shows comparison of experimental and calculated per Eq. (5) and Eq. (9) distributions of times-to-failure during highly accelerated life testing (HALT) for three types of capacitors. By adjusting parameters ΔH (in the range from 1 eV to 2.5 eV) and t_0 (from 1E-3 to 2E-12 hr) experimental data can be adequately enough approximated by Eq. (5). Note also, that in all cases the shape factor of the time-to-failure distributions, β, was below 1 suggesting infant mortality (IM) failures. Typically, similar failures are associated with manufacturing defects, occur during early stages of operation, and convert with time into wear-out failures. However, for tantalum capacitors IM period continues even when more that 50% of the parts failed. This indicates that most of the failures in tantalum capacitors are caused by defects (sites with low electrical strength) in the Ta2O5 dielectric. These defects are likely due to a large and irregular surface area of the oxide that is electrochemically grown on pellets made of sintered tantalum powder and can be considered as intrinsic for this technology.

The time-to-failure model allows also for demonstration of the significance of the rated voltage and safety margin. Assuming that parts are tested at a rated voltage and VBR at p = 0.1% is $V_{0.1}$, the minimum time to failure can be calculated as:

$$TF_{\min} = t_o\times\exp\left[\frac{\Delta H}{kT}\times\left(1-\frac{VR}{V_{0.1}}\right)\right] = t_o\times\exp\left[\frac{\Delta H}{kT}\times\left(\frac{M}{M+1}\right)\right] \qquad (10)$$

At relatively small M, Eq. (10) predicts exponential increase of time to failure with the safety margin. Based on results of life testing at 125 °C presented in [1], Figure 11 displays relationship between the time to failure and margin for four lots of tantalum capacitors. Experimental data show a sharp, exponential dependence of TF on the margin, which is in agreement with the model.

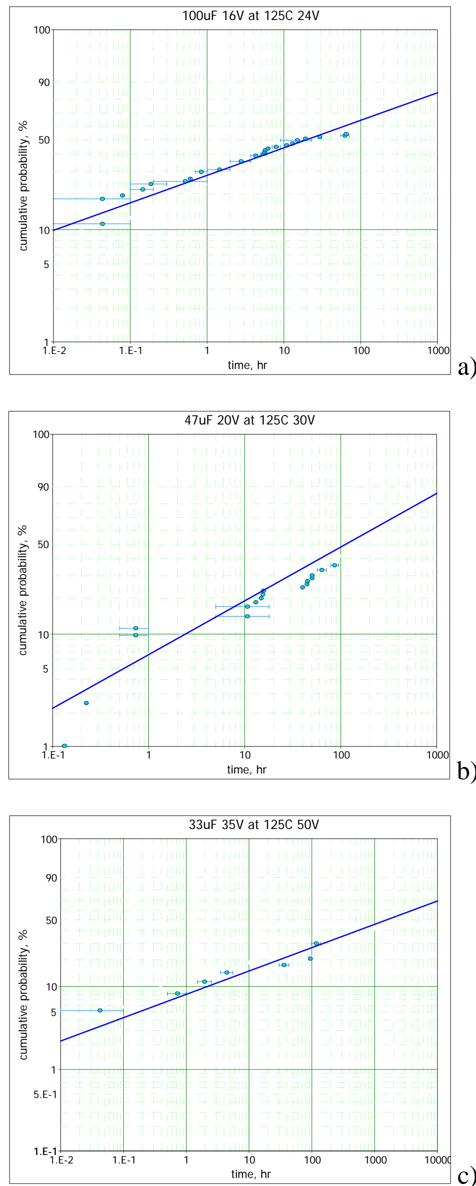

Figure 10. Experimental (marks) and calculated (lines) distributions of times to failure during HALT at 125 °C and 1.5VR for three part types.

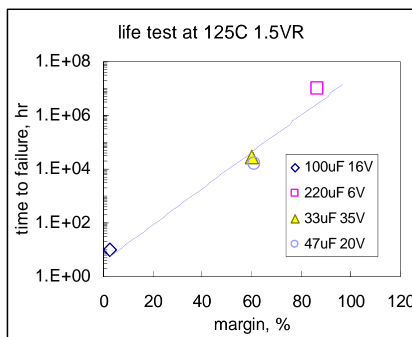

Fig. 11. Variations of the characteristics time to failure obtained during highly accelerated testing of four part types at 125 °C, 1.5 VR with the safety margin.

CONCLUSION

1. Scintillation breakdowns in solid chip tantalum capacitors have been characterized using V-t and I-t techniques. Both techniques gave similar results.
2. Measurements of breakdown voltages in 16 commercial and military-grade part types show poor correlation between VBR and rated voltage. This means that VR is not a reliable indicator of the electrical strength of the parts and their safety margin. Also, the effect of derating on reliability of tantalum capacitors might be significantly different even for lots with the same VR.
3. Analysis of distributions of scintillation breakdown voltages shows that the safety margin for different part types varies in a wide range from 3% to 164%, and there is a trend of decreasing margin with the rated voltage.
4. Scintillation breakdowns were found damaging (reducing electrical strength of capacitors) on average in 30% of cases and up to 60% in some lots, and for this reason they should be considered as a reliability hazard.
5. Failures of tantalum capacitors operating at steady-state conditions can be considered as time-dependent breakdowns. The electrochemical model of TDDB predicts a sharp decrease of the time to failure for parts with low safety margin, which is in agreement with the results of highly accelerated life testing.
6. Measurements of scintillation breakdowns provide important information regarding quality and reliability of tantalum capacitors, allow for assessment of the safety margin, and should be used to qualify parts for high-reliability applications.

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