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Testing the effects of temperature cycling on tantalum capacitors

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ABSTRACT

This study focused on the reliability testing of tantalum capacitors. The objective was to develop efficient tests to examine the effects of temperature cycling on capacitor maximum voltage. A test according to the standard JESD22-A104D overlooks the fact that temperature changes often occur while the voltage is on. Capacitors were first tested according to the standard without voltage; the test was then repeated with added 15 V and 30 V. Second, short cycling tests were run at different temperatures to detect any changes in capacitor characteristics. After the cycling tests, capacitors were tested for voltage, which was slowly increased from 0 V to 90 V, provided no failure occurred. Results suggest that a temperature cycling effect can be achieved in a much shorter time than in standard tests. Temperature cycling can also be accelerated by adding voltage. Possible reasons are discussed in the paper.

1. Introduction

Components can be stored, or they can operate at very high and/or very low temperatures. Temperature may often vary between these extremes, and such cycling can weaken the characteristics of a component. Accelerated temperature cycling tests have been deemed an effective acceleration technique for thermal cycling [1]. Accelerated testing is used to study the reliability of electronic components, especially certain dominant failure mechanisms under normal operating conditions. Alternatively, accelerated tests can be designed to induce failure mechanisms other than those occurring under normal operating conditions in the field [2].

Temperature cycling, according to the standard JESD22-A104D, “is conducted to determine the ability of components and solder interconnects to withstand mechanical stresses induced by alternating high- and low-temperature extremes. Permanent changes in electrical and/or physical characteristics can result from these mechanical stresses [3].” This standard test does not take into account the fact that an applied bias voltage often occurs during temperature changes. In addition, because of its required 500 or 1000 cycles, this standard test is a time-consuming way to examine possible effects of temperature changes and thus less than ideal for detecting failures in components such as surface mount solid tantalum capacitors.

Nowadays, electronics design makes wide use of tantalum capacitors because of their high capacity density, size, and achievable levels of capacitance. We used the standard temperature cycling (−40/85 °C) test and developed new accelerated cycling tests for surface mount tantalum capacitors. Thus, in this paper, simultaneous temperature cycling and added voltage are studied in a case of a tantalum capacitor, and a novel accelerated failure detection method is proposed.

2. Tantalum capacitors

Fig. 1 shows the structure of a surface mount solid tantalum capacitor. The reliability of these capacitors is greatly affected by environmental conditions. In addition, strong ripple currents and mechanical stresses can cause failures. This section focuses on possible failure mechanisms caused by temperature and changes in it.

Temperature varies the rates of many physical and chemical reactions. Failure mechanisms are basically physical/chemical processes and temperature is often used in reliability testing as an accelerating parameter. However, at high temperatures, new failure mechanisms (previously dormant because of their high activation energy) may be activated. If a test is run at these temperatures, failure can occur because of a mechanism that is unlikely during normal operating conditions [4]. Heat, whether generated externally or internally, degrades the performance and reliability of tantalum chip capacitors [5]. The use of tantalum capacitors at high temperatures has been studied, and manufacturing tantalum capacitors for critical, such as high temperature, applications, is challenging [6].

Some publications indicate that mechanical stresses related to the soldering of chip tantalum capacitors affect their performance and reliability and account for turn-on breakdowns in the parts. In addition, thermomechanical stresses can generate new fault sites in the components. A tantalum capacitor package may undergo material expansions at different rates depending on thermal

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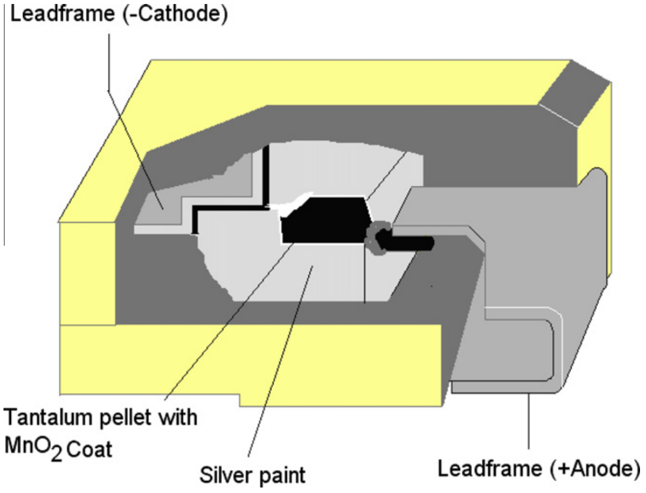

Fig. 1. Structure of a tantalum capacitor.

expansion and suffer from tensile forces on the pellet structure; its elements may shrink while cooling and not fit together as they did before the expansion. Furthermore, compressive forces may appear on the pellet structure and produce fractures along tiny sections of its edges and corners [7–9]. Such phenomena may also occur in a cycling test.

Temperature cycling of tantalum capacitors has been studied before [10] with capacitors subjected to temperature cycling in a range from −65 °C to +125 °C and −65 °C to +150 °C. Results indicate that tantalum chip capacitors are capable of withstanding up to 500 cycles of temperature ranging from −65 °C to +150 °C. However, different lots show different robustness under cycling conditions, and though parts may not fail formally by exceeding specified limits, a significant degradation in the leakage current and breakdown voltages indicates an increased propensity of some lots to failure after temperature cycling. Cracking in the tantalum pentoxide dielectric, which develops during temperature cycling, results not only in increased leakage current, but also increases the probability of scintillation breakdowns [10]. The standard temperature cycling test is also widely used by manufacturers to test the reliability of capacitors, but in this study reliability was tested using applied bias voltage.

3. Measurements

We examined the effects of temperature cycling on the characteristics of tantalum capacitors and used solid tantalum chip capacitors of a maximum voltage of 50 V, a capacitance of 10 μF, and an operating and non-operating temperature of −55 °C to +125 °C (cross-section of a tested capacitor shown in Fig. 2). A tantalum capacitor is typically built with three to four times the dielectric thickness required for its rated voltage. It is tested and exposed to voltages that are at least 132% of the rated voltage and usually used at application voltages below its rating.

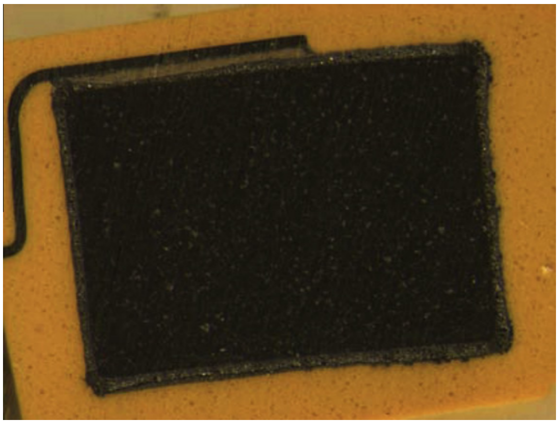

Fig. 2. Cross-section of a tantalum capacitor.

Table 1
Conditions in test 1.

Test	Test 1a	Test 1b	Test 1c
Stresses	0 V, 85 °C, −40 °C	15 V, 85 °C, −40 °C	30 V, 85 °C, −40 °C
One cycle	0.5 h	0.5 h	0.5 h
N cycles	500	500	500

Our testing was divided into two parts, hereafter called test 1 and test 2. Aimed at studying the effects of temperature cycling on tantalum capacitors, test 1 consisted of a standard cycling test and a standard cycling test with added voltages. The test was further divided into three specific tests: 1a, 1b, and 1c, depending on the applied voltage. Test 2 was an attempt to test the effects of temperature cycling on tantalum capacitors more efficiently than standard cycling tests. It was divided into four subtests: 2a, 2b, 2c, and 2d, depending on the upper temperature.

In test 1, the temperature changed between −40 °C and 85 °C, and one cycle lasted for 0.5 h. Test 1a was a standard temperature cycling test and lasted for 500 cycles [3]. In test 1b, lasting also for 500 cycles, 15 V were added to the standard test. Test 1c was similar to test 1b, but an added 30 V were used. In all tests, 18 capacitors were tested.

In test 2a, capacitors were first held for 30 min at 85 °C and after that for 30 min at −40 °C. The test was repeated five times over 5 h. Tests 2b, 2c, and 2d were similar to test 2a, but the upper temperature was 100 °C, 125 °C, and 150 °C, respectively. In all tests, 18 capacitors were tested (test conditions 1 and 2 shown in Tables 1 and 2).

After reliability testing, capacitors were tested for voltage, which was slowly increased from 0 V to 90 V, provided no failure occurred. Because the capacitors were rated for an operating and non-operating temperature of −55 °C to +125 °C, they were tested here within their operating limits, except for the upper temperature in test 2d.

4. Results and discussion

Table 3 shows failure voltages for capacitors without testing and in tests 1 and 2. Accordingly, capacitors not submitted to temperature cycling did not fail at voltages below 90 V. This means that the capacitors can be expected to withstand voltages of over 90 V. Figs. 3 and 4 show failures and corresponding voltages in tests 1 and 2, respectively.

The results of test 1 show that added voltage increased the stress effect of temperature cycling. However, no difference was evident at added 15 V or 30 V. There were only four failures after standard test, whereas in tests 1b and 1c, nine out of the 18 tested capacitors failed. Standard temperature cycling can definitely be accelerated with added voltage, and the voltage does not need to be high. A standard test may not be enough to detect failures while the component is being used in an environment with radically changing temperature with the voltage on. In these conditions, this new test with added voltage should be used instead. However, tests with higher voltages should be tried, since these capacitors have a maximum voltage of 50 V. Tests with different maximum and minimum temperatures should also be tried with added voltages.

Table 2
Conditions in test 2.

Test	Test 2a	Test 2b	Test 2c	Test 2d
Stresses	0 V, 85 °C, −40 °C	0 V, 100 °C, −40 °C	0 V, 125 °C, −40 °C	0 V, 150 °C, −40 °C
One cycle	1 h	1 h	1 h	1 h
N cycles	5	5	5	5

Table 3
Failure voltages in tests 1 and 2.

No test	Test 1a	Test 1b	Test 1c	Test 2a	Test 2b	Test 2c	Test 2d
>90	50	68	57	>90	39	*30*	23
>90	79	69	69	>90	79	*80*	30
>90	81	70	70	>90	90	*85*	41
>90	84	70	75	>90	>90	*85*	60
>90	>90	71	77	>90	>90	*90*	70
>90	>90	75	79	>90	>90	>90	73
>90	>90	78	80	>90	>90	>90	80
>90	>90	80	81	>90	>90	>90	>90
>90	>90	86	87	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90
>90	>90	>90	>90	>90	>90	>90	>90

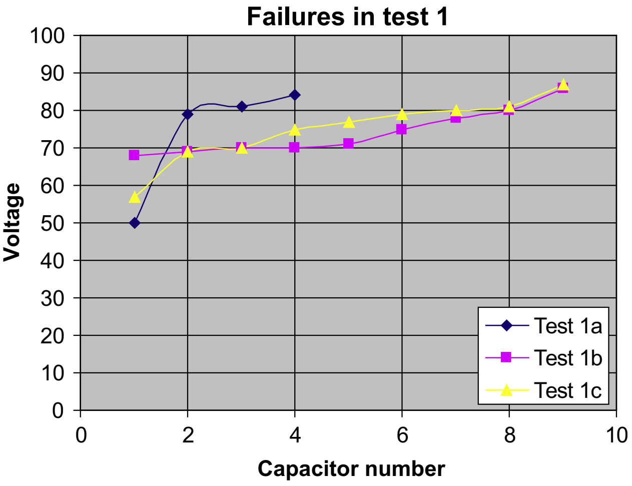

Fig. 3. Failure voltages in test 1.

The results of test 2 show that those five cycles at −40 °C and 85 °C (2a) were not enough to change the maximum voltages of these capacitors. In test 2b, in which temperatures changed between −40 °C and 100 °C, three failures occurred at under 90 V. In test 2c with an upper temperature of 125 °C, five failures occurred at below 90 V, and in test 2d with an upper temperature of 150 °C, seven failures. This means that even such short temperature cycling affected these tantalum capacitors, weakened their characteristics, and lowered their maximum voltage. The results indicate that a test shorter than the standard JESD22-A104D could be used for tantalum capacitors if their upper temperature is increased. However, more research should be done on appropriate testing times and temperatures and tests with different maximum and minimum temperatures should be tried, with and without voltage.

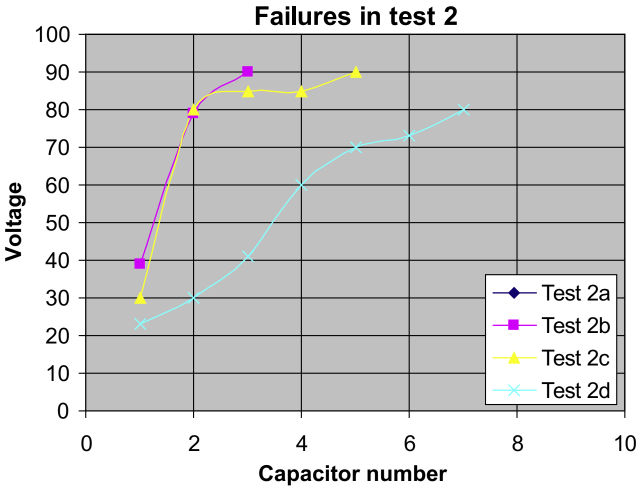

Fig. 4. Failure voltages in test 2.

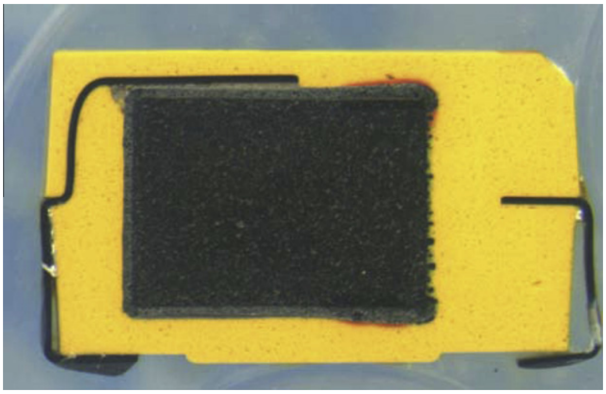

Fig. 5. A cross-section of a failed capacitor.

Failed components were further examined. They were cross-sectioned and analyzed for failure by optical microscopy (shown in Fig. 5). Cross-sectioning of all the failed tantalum capacitors (from tests 1 and 2) showed redness in corners where overheating had burned the capacitors' internal materials and molding. However, no clear physical reason could be found leading to their failure.

Faults may occur in the oxide from stress imposed by changes in temperature. The oxide may crack with a slight shear. In addition, even if the pellet may not fracture, it may sustain enough compressive pressure for a fault site in the dielectric not submitted to the applied voltages to grow or extend further into the dielectric and develop into a breakdown site at lower voltages.

Field crystallization is one possible failure mechanism under these (high temperature/added voltage) conditions. High temperature can cause field crystallization. If we consider the electric field in addition to the high temperature, the combination of voltage and temperature creates a higher total energy and a higher crystal growth acceleration factor [12]. However, field crystallization may

Table 4
Calculated mean voltages to failure, shape parameters, and scale parameters.

90% Confidence	No test	Test 1a	Test 1b	Test 1c	Test 2a	Test 2b	Test 2c	Test 2d
Upper	×	140	118	96	×	221	144	169
Mean	×	110	95	88	×	135	112	115
Lower	×	86	76	81	×	83	87	79
β	×	4.8	2.6	6.5	×	3.2	3.9	1.9
η	×	120	107	94	×	151	124	130

have only a limited impact in the whole temperature cycling test and its effects on maximum voltages.

Added voltage may only have accelerated the effects of radical changes in temperature (cracking in the tantalum pentoxide dielectric) and thus the same failure mechanism could be expected in tests 1 and 2. However, based on this experimental data (since optical analysis of the cross-sections brought no further information) we can not rule out the possible new failure mechanisms that the added voltage brings to picture.

Mean voltages to failure with 90% confidence were calculated by Maximum Likelihood Estimation (MLE), that is, to determine the parameters that maximize the probability of the sample data. MLE is versatile and applicable to most models and different types of data. Weibull was used for lifetime distribution (because of its flexibility, the Weibull distribution can be fitted to many kinds of data) [11] (calculated results, shape parameters (β), and scale parameters (η) shown in Table 4).

Weibull distributions with $\beta > 1$ have a failure rate that increases with time, which was the case in all tests. Maximum voltages could not be calculated for capacitors without testing or for capacitors in test 2a, since no failures occurred. Calculated maximum voltages in tests 1a, 1b, and 1c were 110, 95, and 88, respectively. This means that adding voltage lowers the maximum voltage, and that a higher voltage lowers it even more.

Calculated maximum voltages in tests 2b, 2c, and 2d were 135, 112, and 115, respectively. They were very close to the value in the standard test (1a), which means that the results were similar but achieved in a considerably shorter time by increasing the upper temperature. The mean voltage to failure in test 2d is higher than that in test 2c, because the failure data in test 2d seems to be very spread and capacitors that did not fail at voltages under 90 V can last long after 90 V, whereas in test 2c, all failures occurred near 90 V, thus failures near 90 V are expected. However, there are a lot of suspensions, so there is a lot of uncertainty that should be taken into account. Tests with a larger amount of components should be done.

In order to find a relation from an accelerated combination of temperature cycling and added voltage to operation conditions, we need a stress-life relation. When a test involves multiple accelerating stresses, a general multivariable relationship is needed. Such a relationship is the general log–linear relationship. It should be used in this type of test. Both stresses (voltage and temperature) should have logarithmic transformation, because thermal cycling is a fatigue like stress.

In case we just want to analyze thermal cycling under two voltage levels, we can only analyze it as there was only one stress (voltage) and keep use conditions as they are (temperature changes). In this case, inverse power law relationship could be chosen to model life–voltage relationship. Again, uncertainty of results should be taken into account and tests with larger amount of components should be done in order to do reliable statistical analysis of the results.

5. Conclusions

Temperature changes occur commonly in the field whether the device is on or off. A standard temperature cycling test affects tantalum capacitors in that it weakens their characteristics and lowers their maximum voltages. However, the test takes a long time to run and overlooks the fact that temperature changes often happen while the voltage is on. The test could be replaced with a less time-consuming one, and cycling tests could be further accelerated by adding voltage, as shown in this paper. However, more research should be done on appropriate testing times and temperatures, as well as tests with and without voltage.

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