Step Stress Testing of Solid Tantalum Capacitors

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Abstract –Solid tantalum capacitors were introduced to the market more than five decades ago and continue to be widely used. Reliability issues arise when tantalum capacitors are exposed to excessive thermo-mechanical or electrical stresses. While the failure modes and mechanisms due to each of the stresses, thermo-mechanical or electrical, are well researched, the failure mechanics of tantalum capacitors being subjected to simultaneous voltage stressing at elevated temperature have not been thoroughly examined yet.

This paper investigates the degradation of tantalum capacitors under simultaneous thermo-mechanical and electrical stresses. Tantalum capacitors with MnO_2 electrodes from two different vendors were examined at an elevated temperature and voltage step stress conditions. Electrical characterization prior to and after the tests was performed to identify degradation and indicators of reliability of the parts. Additionally, destructive and non-destructive failure analysis was performed on virgin and stressed samples.

The results revealed degradation and breakdown of the dielectric as the relevant failure mechanism due to thermo-mechanical and electrical stresses. This knowledge provides a better understanding of the possible reliability risks experienced in the field and may help in the development of screening or qualification tests to address these risks.

1. Introduction

1.1. Motivation

Due to their high volumetric efficiency, low equivalent series resistance (ESR), parametric stability over a wide temperature and voltage range, and high reliability, solid tantalum capacitors are still widely used in electronic assemblies after being initiated into the market more than half a century ago [1]. Figure 1 depicts the schematic of a solid tantalum capacitor. Industrial and military grade tantalum capacitors with manganese dioxide cathodes are typically rated for temperatures from -55°C to +125°C. The qualification tests of industrial grade tantalum capacitors include accelerated life testing for 2000 hours at the rated voltage and elevated temperature of 125°C [2] [3]. In addition, surge voltage tests at temperatures of 85°C and 125°C, and voltages of 1.32 and 1.2 times the rated voltages are performed for 1000 cycles [3]. Accelerated tests are designed to precipitate failure mechanisms occurring under the normal operating conditions of the component. Due to the long operating life of tantalum capacitors, even at maximum rated stress conditions, accelerated testing is necessary to perform life testing within a reasonable timeframe so that the relevant failure modes and mechanisms can be identified.

Knowledge of the relevant failure modes and mechanisms helps in the development of screening or qualification tests that address the reliability risks experienced in the field. However, accelerated testing of components beyond their ratings might activate different failure mechanisms, which are usually not seen during qualification testing [4]. Typical accelerated life testing of capacitors is limited to 1.5276 times the rated voltage, as per MIL-STD-55365, [5]. While tantalum capacitors can potentially see voltage overstress conditions much larger than the rated voltage at elevated temperatures for extended periods, the failure modes and mechanisms resulting from these conditions have not been studied thoroughly yet. Paulson [6] examined the effect of accelerated voltage stress up to 3 x V_R (rated voltage) and under elevated temperatures above the rated temperature (up to 165°C). Analysis of the failure distributions suggests that even long exposure to voltage and temperature stresses that are significantly higher than the rated specifications does not introduce new failure mechanisms. This is based on the observation that the greatly accelerated stress conditions did not result in notable shape distortions of the time-to-failure distributions, compared to distributions of parts stressed at lower accelerated conditions [6]. However, detailed failure analysis to confirm this hypothesis was not performed as part of the study.

In the present study, industrial grade 35 V tantalum capacitors from two different vendors with a MnO_2 cathode were step stress tested at their rated temperature of 125°C to achieve failure within a reasonable amount of time. Afterward, failure analysis was performed to identify the dominant failure modes and mechanisms.

1.2. Failure Modes and Mechanisms of Solid Tantalum Capacitors

Failure of the tantalum capacitors is usually associated with degradation of the dielectric layer Ta_2O_5 (Tantalum pentoxide) followed by dielectric breakdown. The failure mechanism of dielectric breakdown is a localized voltage overstress at points with the weakest dielectric strength, while the observed failure mode is an increase in leakage current. During the event of dielectric breakdown, the tantalum pentoxide layer ruptures due to voltage overstress, and a localized path of low resistance is formed. This path of lower resistance leads to a current concentration that can be observed as increased leakage current, which also results in a localized temperature rise.

1.3. Degradation of the Tantalum Pentoxide Dielectric

The dielectric strength degrades as a result of temperature and voltage stressing of the parts, due to the thermodynamically unstable state of Ta_2O_5. The first reason for the unstable dielectric is the amorphous structure of the Ta_2O_5 layer, which tends to reduce its internal energy through crystallization [1] [5] [8] [9] [10] [11]. The crystallized structures within the amorphous matrix cause mechanical stresses due to the different densities, which can rupture the dielectric film. The second reason is that Ta_2O_5 and Ta form a non-equilibrium pair at their interface, which tends towards an equilibrium by oxygen migration from the Ta_2O_5 to the Ta close to the interface [1]. As a result of oxygen migration from the dielectric layer, oxygen vacancies amass and degrade the dielectric layer. It is assumed that the leakage current in the dielectric layer increases with the number of oxygen vacancies [12]. Temperature and voltage are both critical driving factors toward dielectric failure, since crystallization and oxygen migration are both exponentially accelerated by a temperature increase [1]. Activation energy for the initiation of crystalline growth can additionally be provided by an electric field [9].

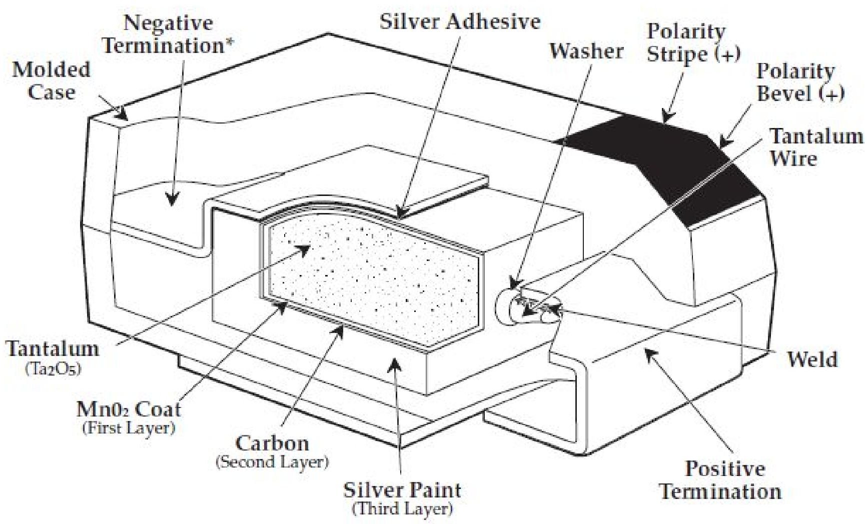

Figure 1: Schematic of a solid tantalum capacitor depicting internal structure [3].

2. Experimental Design

In this study, accelerated testing was used to test solid tantalum capacitors with MnO_2 cathodes. Industrial grade tantalum capacitors of EIA size code 2917 from two different vendors were tested. The parts were rated to 35 V, 6.8 μF, and temperatures from -55°C to +125°C. A summary of the characteristics of the parts are shown in Table 1.

Table 1: Electrical characteristics, design characteristics, and failure thresholds of tested tantalum capacitors.

Vendor	A/B
Rated voltage [Vdc]	35
Capacitance [µF]	6.8
Tolerance [%]	10
Temperature range [°C]	-55 to +125
Max. leakage current [µA]	2.4
Dissipation factor [-]	0.06
Max. ESR @ 100 kHz [Ω]	1.3
Length [mm]	7.3±0.3
Width [mm]	4.3±0.3
Height [mm]	2.8±0.3

Before exposure to the thermal and electrical stresses, the test specimens were baked at +125°C for 24 hours, per JEDEC JESD22-A113D standard, to remove moisture from the package. Ten parts from each vendor were electrically characterized with capacitance (C), dissipation factor (DF), equivalent series resistance (ESR), and leakage current (LC) measurements. According to the performance specification of MIL-PRF-39003J, capacitance and dissipation factor were measured at a voltage of 0.5 V_{rms} and a frequency of 120 Hz. Equivalent series resistance was measured at 0.5 V_{rms} and a frequency of 100 kHz. DC leakage current was obtained after 60 sec of electrification at the rated voltage. All measurements were obtained at 25°C. In order to eliminate the resistance of the circuitry, the equivalent series resistance was manually measured with a tweezers fixture. After the initial electrical characterization, the parts were reflow soldered and re-characterized. The accelerated parameters to stress the parts to failure were temperature and voltage. The parts were thermally stressed at a temperature of 125°C, while applying a voltage step stress. The voltage was stepped from the rated voltage of 1 x V_R up to an accelerated voltage stress of 3.66 x V_R. At each voltage stress step level, the test specimens were exposed to the stresses for 72 hrs. To avoid surge currents, the current was limited by 1 MΩ resistors in series. After exposure, the parts were cooled down to 25°C, discharged over a 2 kΩ power resistor, and electrically characterized. As degradation progressed due to increasing stress levels, samples with various degrees of degradation were extracted for failure analysis. The remaining capacitors were then exposed to the next step stress level. A summarizing table of the test plan is shown in Table 2.

Table 2: Test conditions for 10 parts from each vendor at +125°C and increasing voltages.

Applied voltage/rated voltage	1.00	1.33	1.66	2.00	2.33	2.66	3.00	3.33	3.66
Test started with 10 samples from each vendor	20	20	18	16	16	15	12	10	4
Temperature conditions	+125°C								

3. Results

3.1. Measurements of Capacitance, Dissipation Factor, ESR and Leakage Current

Exposure of the parts to thermal and electrical stresses resulted in the failure of 6 out of 10 parts from each vendor. The test was stopped at a voltage level of 3.66 x V_R before the remaining samples from each vendor reached the failure threshold. The results showed that out of the monitored parameters of capacitance, dissipation factor, equivalent series resistance, and leakage current, leakage current was the most sensitive parameter of degradation of the parts.

Leakage current increased significantly (Figure 2, figure 3), while the other parameters were not affected by degradation, which indicates that simultaneous electrical and thermal stress predominantly affected the dielectric layer. This is expected based on the discussion of the accelerating factors of degradation in solid tantalum capacitors in section 3. The initial leakage current of parts from vendor B was about twice as high as parts from vendor A. It should be noted that most of the parts from vendor A showed only little degradation of leakage current after the initial voltage stress step at the rated voltage 35 V. One anomaly was noticeable with a sample from vendor A, showing a significant decrease compared to the rest of the samples from vendor A. The effect of the same stress level on parts from vendor B was more significant and resulted in a consistent increase of leakage current of the sample set. The trend of degradation was observed to be consistent across the population of vendor A, whereas two samples from vendor B failed early after exposure to the stress step at 70 V. These early failures were probably caused by quality variations within the lot, resulting in a reduced dielectric strength of these particular components compared to the rest. The slope of the leakage current trends for both populations indicates that the applied voltages did not exceed the strength of the dielectric, but rather resulted in degradation of the dielectric layer.

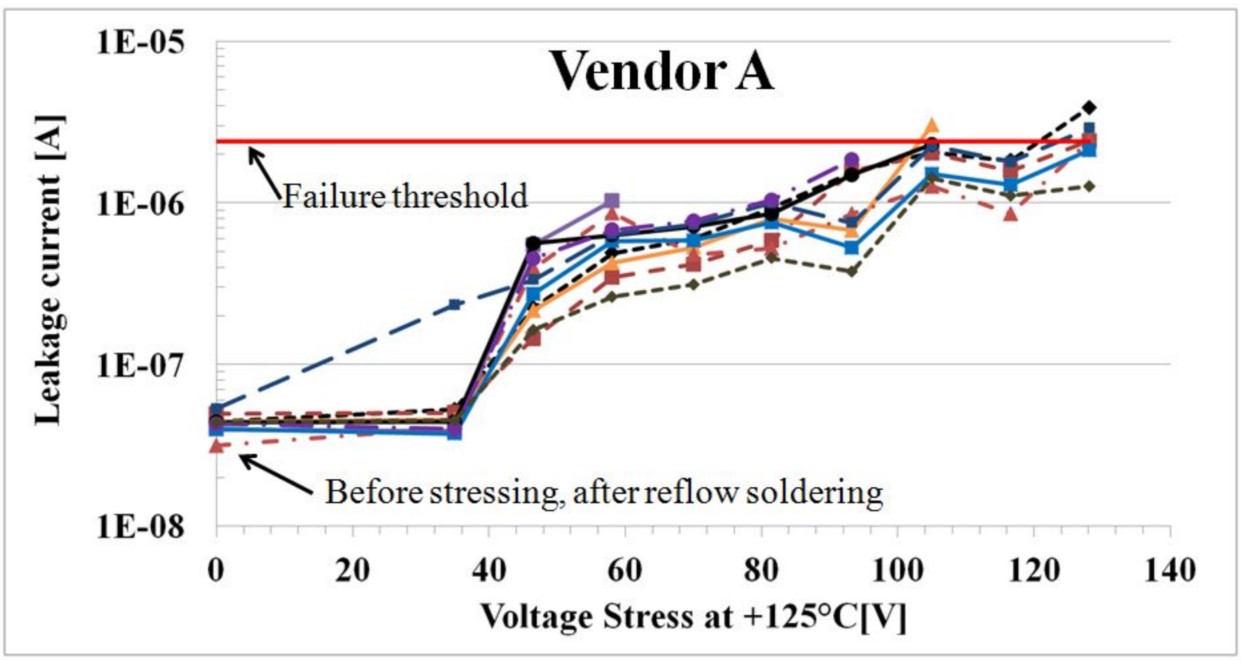

Figure 2: Degradation of leakage current in 10 samples from vendor A during voltage step stress testing at +125°C.

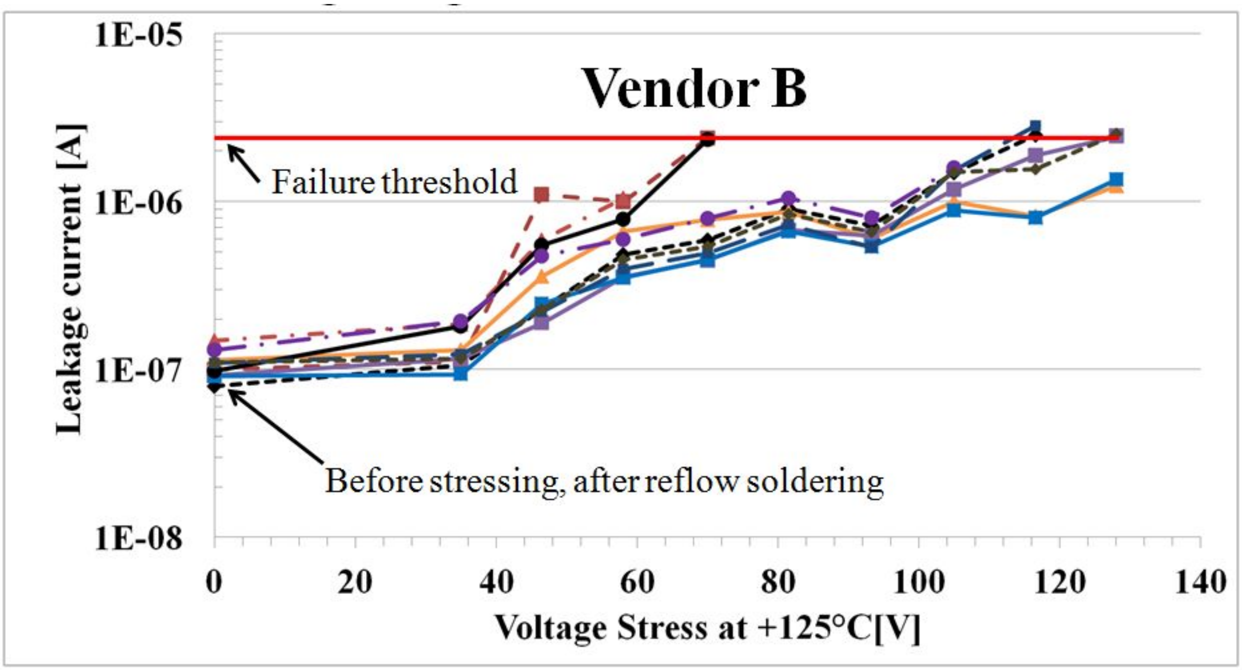

Figure 3: Degradation of leakage current in 10 samples from vendor B during voltage step stress testing at +125°C.

The response of capacitance of both tantalum capacitor designs to voltage and temperature stresses showed that degradation of capacitance is not at all or only slightly observable. Both sets of samples showed a stabilized capacitance over the entire voltage stress range. However, one exception could be observed for vendor B, which showed a decrease in capacitance after the initial voltage stress step at 35 V and +125°C. In the subsequent voltage stress steps, the capacitance stabilized.

Analysis of dissipation factor during the voltage step stress test showed no trend of degradation for parts from either vendor. A small variation in the dissipation factor among the part population of vendor A was noticeable, compared to parts from vendor B. One part from vendor B showed a higher dissipation factor initially, but returned to a stable value after stressing of the samples. Two other samples showed a higher DF at the voltage stress step of 116 V, but also returned to the same level of DF as the rest of the population. This suggests a measurement error caused by the manual probing with the tweezers.

Equivalent series resistance (ESR) showed a similar pattern to what was observed in capacitance and dissipation factor. The measurements of ESR before stressing of the parts were well below the failure threshold, which was not crossed during the experiment. Variations of ESR due to manual probing with the tweezers were noted, which could be observed as an unstable trend.

3.2. Failure Analysis

The results show that degradation was exclusively observable in leakage current. Observation of an increased leakage current suggests dielectric breakdown as the failure mechanism. Identification of failure sites due to dielectric breakdown can be difficult, since breakdown of the dielectric can occur anywhere in the tantalum pellet and is restricted to small areas. A useful method for inspection of the dielectric layer of tantalum capacitors is decapsulation, since it allows optical examination of a large area of the dielectric, as opposed to cross-sectioning. In order to expose the dielectric layer, the mold compound, lead frame, and contacting layers (C, Ag, MnO_2) have to be removed. After decapsulation, the outer surfaces of the tantalum pellet are exposed, but one should note that the pellet is a porous structure and breakdown of the dielectric can also occur within the bulk of the pellet. Figure 4 and figure 5 show decapsulated virgin capacitors from both vendors. The color differences of the pellet surfaces are noticeable. The pellet surfaces of parts from vendor A have a purple color, while parts from vendor B are green colored. This is due to the interference of light reflecting from the front and back surface of the dielectric layer. Depending on the thickness of the dielectric, a different color is constructively created by the reflected light. This allows a qualitative comparison of the dielectric thicknesses of samples, which are related to the applied forming voltage. Comparing the colors of the examined samples, the purple colored samples from vendor A have a lower dielectric thickness than the green colored samples from vendor B [7].

Figure 4: Decapsulated virgin capacitor from vendor A after tin plating under reverse voltage.

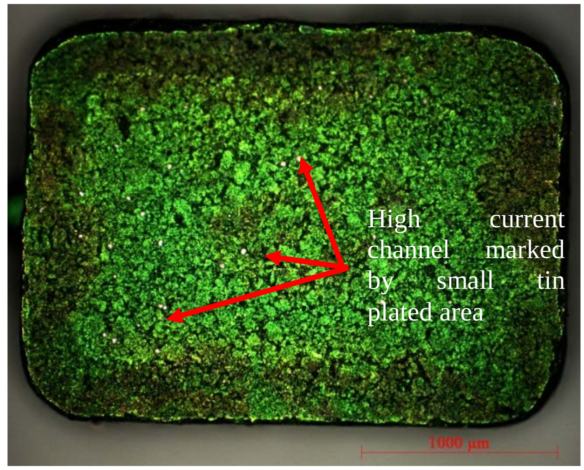

Figure 5: Decapsulated virgin capacitor from vendor B after tin-plating under reverse voltage.

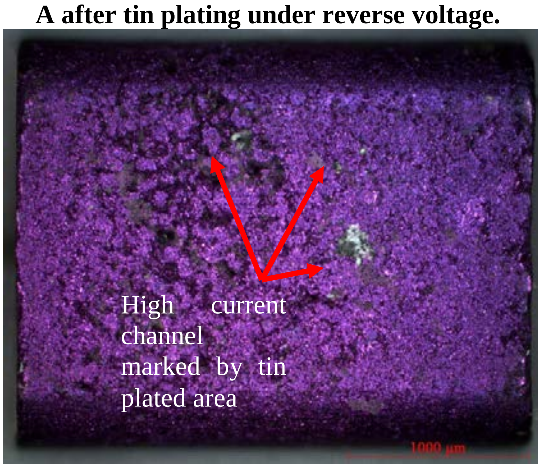

Figure 6: Decapsulated step stress tested capacitor from vendor A after tin plating under reverse voltage.

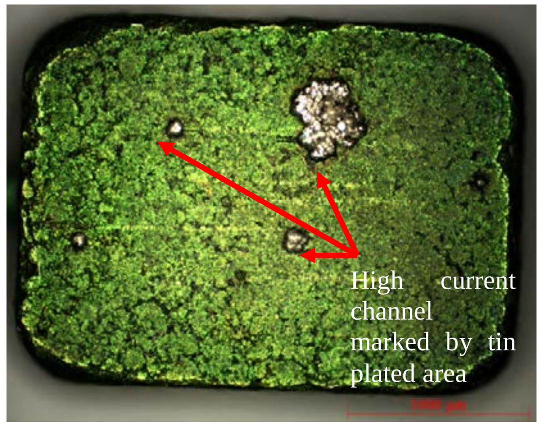

Figure 7: Decapsulated step stress tested capacitor from vendor B after tin plating under reverse voltage.

Identification of the dielectric breakdown site, if there is one on the exposed surface, can be difficult due to the small size of the breakdown site. To visualize the sites, the samples were electroplated in reverse voltage mode. Since dielectric breakdown is associated with high current channels, this non-uniform current distribution across the pellet surface can be exploited with tin-plating to highlight the failure sites. In this method, the decapsulated tantalum pellet is used as the cathode and the tin foil serves as the anode. Since the capacitor is used in reverse voltage mode, the plating voltage must be carefully chosen in order to avoid degradation of the dielectric. In our experiment, we used a constant plating voltage of 0.3 V, which was well below the vendor's maximum specification for the reverse voltage mode operation of 1 V. The sample was cleaned in sulfuric acid and fully immersed in a tin plating solution for 10 minutes, while the plating voltage was applied. The images show high current channels marked by silver colored tin. While virgin parts showed only a few small areas covered by tin (Figure 4, figure 5), stressed samples from both vendors showed substantially increased areas of tin plating (Figure 6, figure 7).

In addition to decapsulation and tin-plating, cross-sectioning was performed to identify possible differences in the composition of the materials. However, the bulk of the tantalum pellet showed only minor differences in the designs of the vendors in weight and atomic percentage of oxygen, tantalum, and manganese. Cross-sectional analysis did not reveal changes in contacting layers, which is in agreement with the insignificant changes in ESR. However, we observed that the pressed tantalum particles forming the pellet from vendor A had an elongated shape, whereas the particles from vendor B had a spherical form. The increased surface area, due to the spherical particles, might be the reason for the slightly higher measured average capacitance of 6.74 µF of components from vendor B, as compared to 6.53 µF of parts from vendor A.

4. Summary and Conclusions

Solid tantalum capacitors are often exposed to simultaneous thermal and electrical stresses higher than their rated specifications. Temperature and voltage are both driving factors toward the failure of tantalum capacitors; however, the effect of exposure to both stress conditions and the relevant failure modes and mechanisms had not yet been thoroughly investigated. To identify the effect of both types of stresses on the robustness of tantalum capacitors, step stress testing at +125°C and voltages up to 3.66 x V_R was performed on 10 samples from each of two vendors. Failure was observed in 6 out of 10 samples from each vendor. The slope of the leakage current increase supports the hypothesis that degradation of the dielectric layer was responsible for failure of the parts rather than a voltage overstress higher than the forming voltage. The concern that step stress testing might result in abrupt increases of leakage current was not observed. This suggests that for life testing, step stress testing might be a valuable tool to assess the life of solid tantalum capacitors with high reliability.

Degradation of the leakage current showed an adverse effect of the applied stresses on the dielectric layer. In order to identify the relevant degradation mechanism, failure analysis was performed. Decapsulation and tin-plating in reverse voltage mode were used to confirm degradation of the dielectric layer, which resulted in high current channels due to dielectric breakdown. A substantial increase in the number and size of high current areas was observed, providing further proof that the tantalum pentoxide layer was predominantly affected by voltage and thermal stresses.

The reliability of solid tantalum capacitors is critically affected by high electrical and thermal stresses that result in degradation of the thermodynamically unstable dielectric. While both stress conditions may often be unavoidable, a good understanding of their effects on reliability and degradation will help to assess the reliability and risks associated with the use of tantalum capacitors in these stress conditions.

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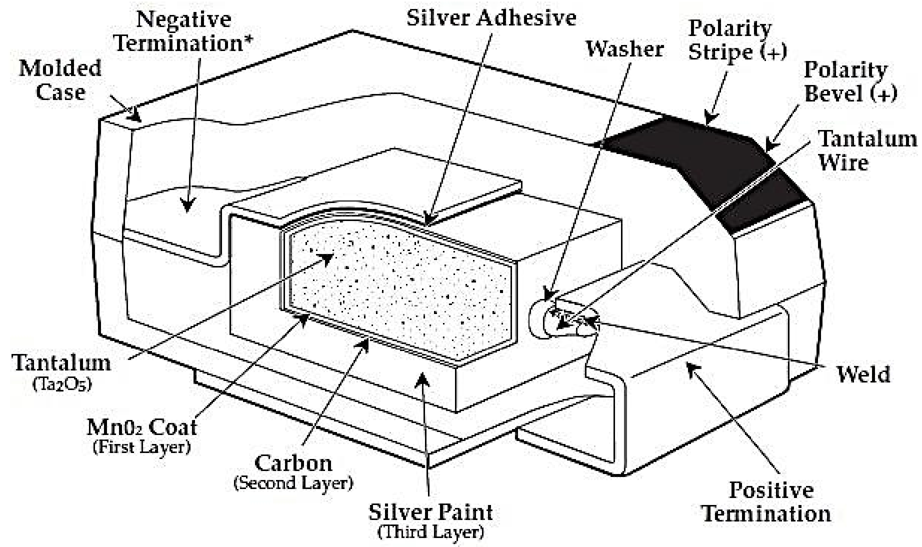
Introduction

- Tantalum (Ta) capacitors offer a high volumetric efficiency, parametric stability, along with high reliability.
- In their actual usage conditions, tantalum capacitors are usually thermally and electrically stressed. Temperature and voltage stresses are driving factors towards the degradation of tantalum capacitors.
- While failure modes and mechanisms at steady-state conditions of temperature and voltage are known, the effect of simultaneous temperature and voltage stress has not been thoroughly investigated previously.
- Knowledge of relevant failure modes and mechanisms helps in the development of screening and qualification tests that address reliability risks experienced in the field.

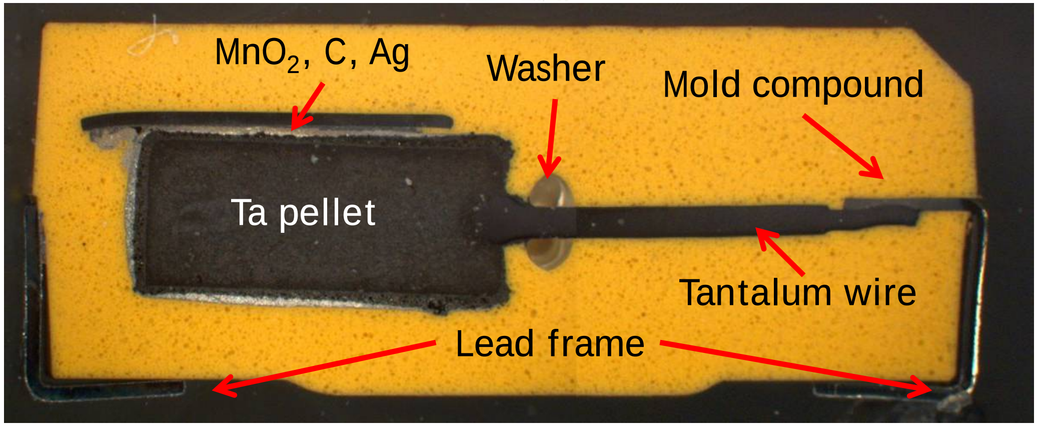
Properties and Construction of Ta Capacitors

- Tantalum capacitors have a high volumetric efficiency (Capacitance/Volume) due to their large effective surface (porous Ta “slug”).
- They offer parameter stability over a wide temperature range of -55 to +125° C.
- Available for voltages of up to 50 V and capacitance ranges from 0.1 μF to 2200μF.



[1]

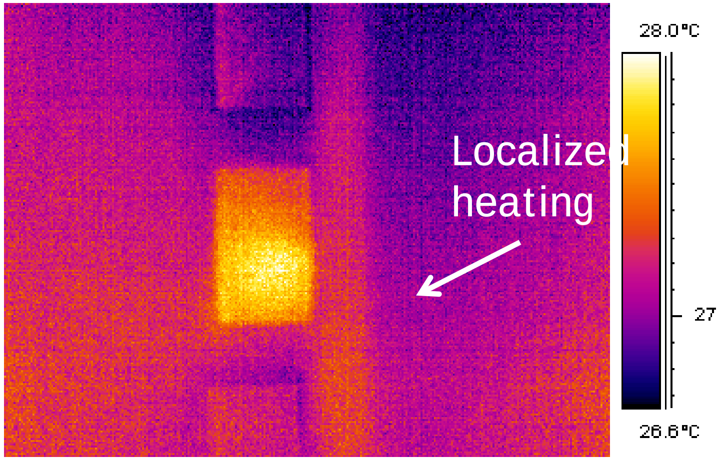
Cross-section of capacitor



Degradation of the Dielectric

- Dielectric breakdown due to voltage overstress is the primary failure mechanism of tantalum capacitors.
- The failure site of dielectric breakdown is the point with the lowest dielectric strength, while the observed failure mode is typically an increased leakage current.
- Temperature and voltage are both critical driving factors towards dielectric failure [2]-[8]:
  - Temperature accelerates crystallization and oxygen migration.
  - In addition to temperature, the activation energy for crystallization can also be provided by an electric field.

Breakdown process observed in IR camera

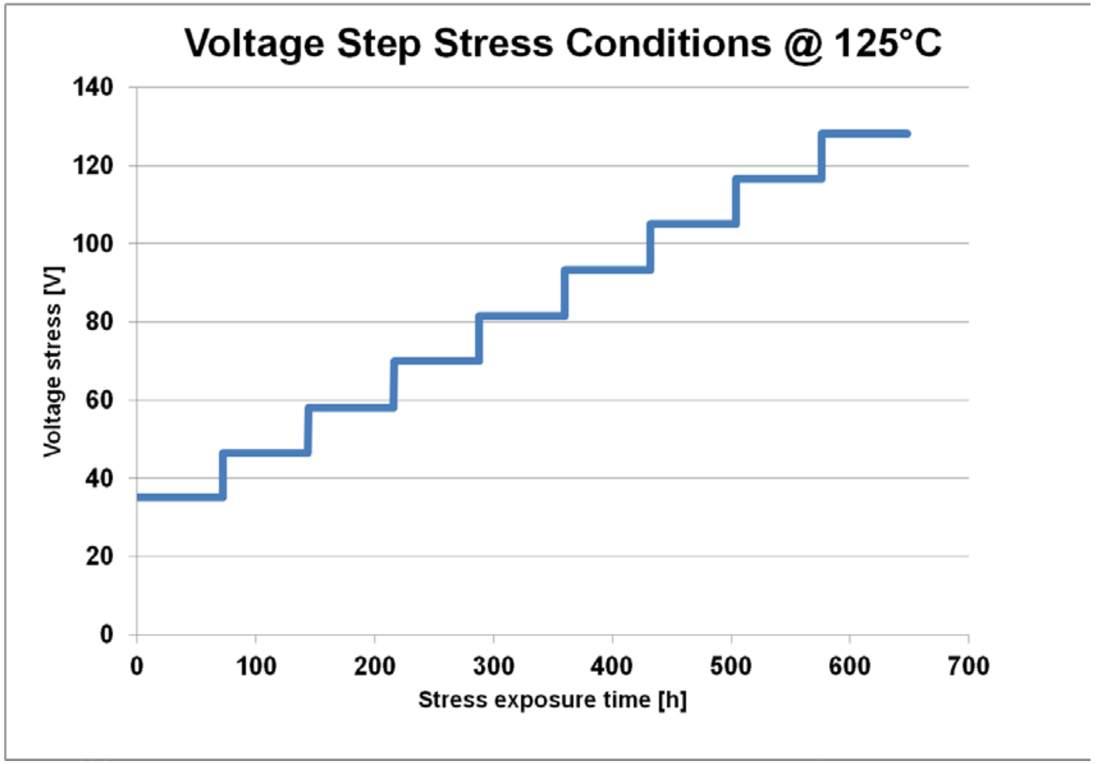


Objectives

- Highly accelerated stimulation of failure using electrical and thermal stresses including a failure criterion based on leakage current.
- Identification of the dominant failure mechanism due to electrical step stressing of capacitors under temperature stress conditions.
- Identification of reliability indicators for qualification testing and stress screening.

Approach

- Step stress testing using temperature and voltage stresses. Step stress testing was chosen since it induces failures in a relatively short time.
  - Voltage step stress testing at constant elevated temperature of +125° C.
- Electrical characterization to identify failure mode, and potential indicators of quality and degradation.
- Failure analysis to identify failure sites and mechanisms.



Test Specimens

- Test samples with the same design parameters from two manufacturers were chosen for the tests.
- Both capacitor types are industrial standard, EIA size 2917 tantalum capacitors with MnO_2 cathodes.

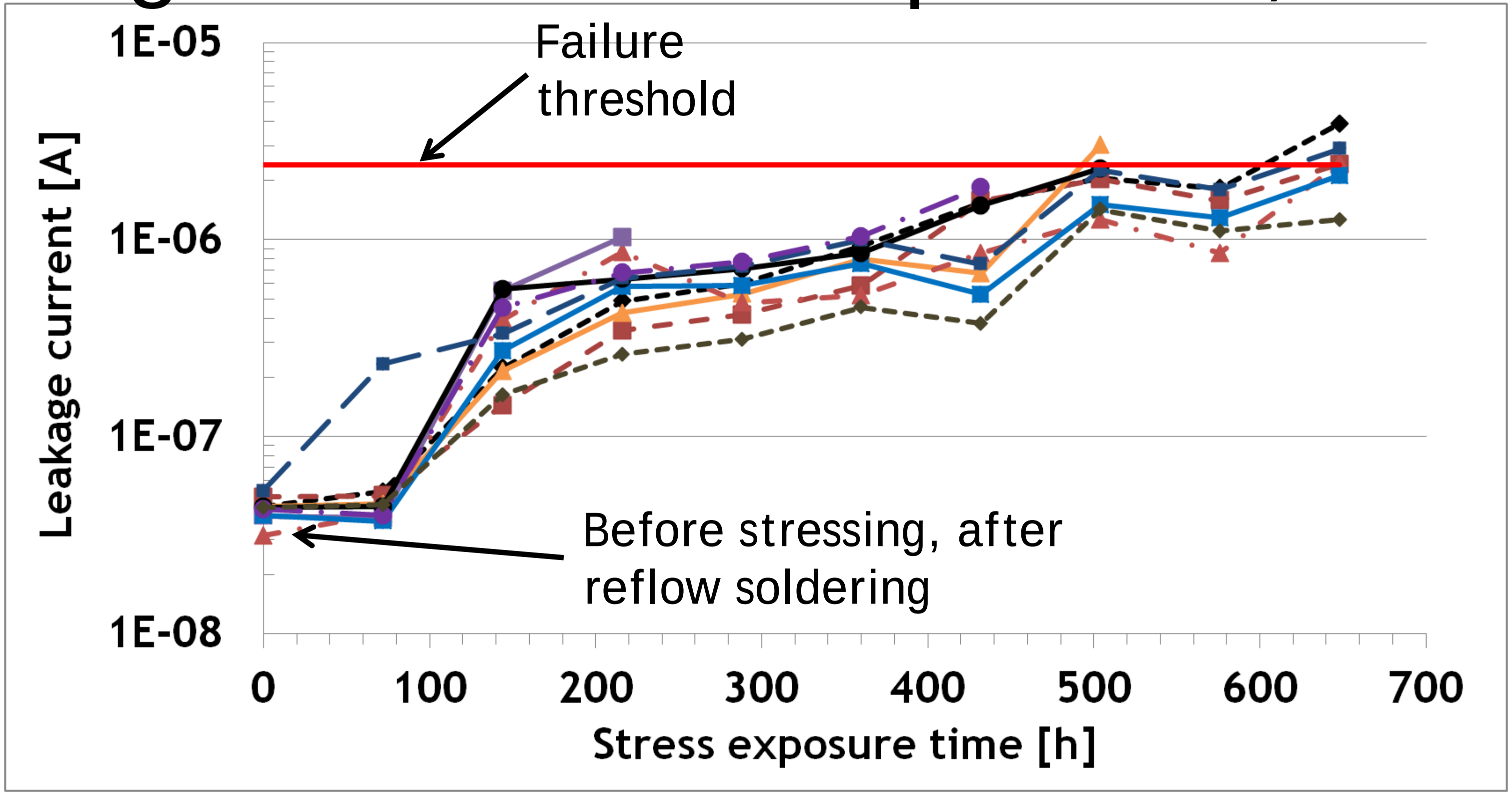
Manufacturer	A/B
Rated Voltage [Vdc]	35
Capacitance [μF]	6.8
Tolerance [%]	10
Temperature range [° C]	-55 to +125
Max. leakage current [A]	2.4E-6
Length [mm]	7.3±0.3
Width [mm]	4.3 ±0.3

Test Plan for Step Stress Tests at Constant Elevated Temperature

Applied voltage/rated voltage		1.00	1.33	1.66	2.00	2.33	2.66	3.00	3.33	3.66
Test started with 10 samples from each vendor	Vendor A	10	10	9	9	9	8	6	6	2
	Vendor B	10	10	9	7	7	7	6	4	2
Temperature conditions		+125°C								

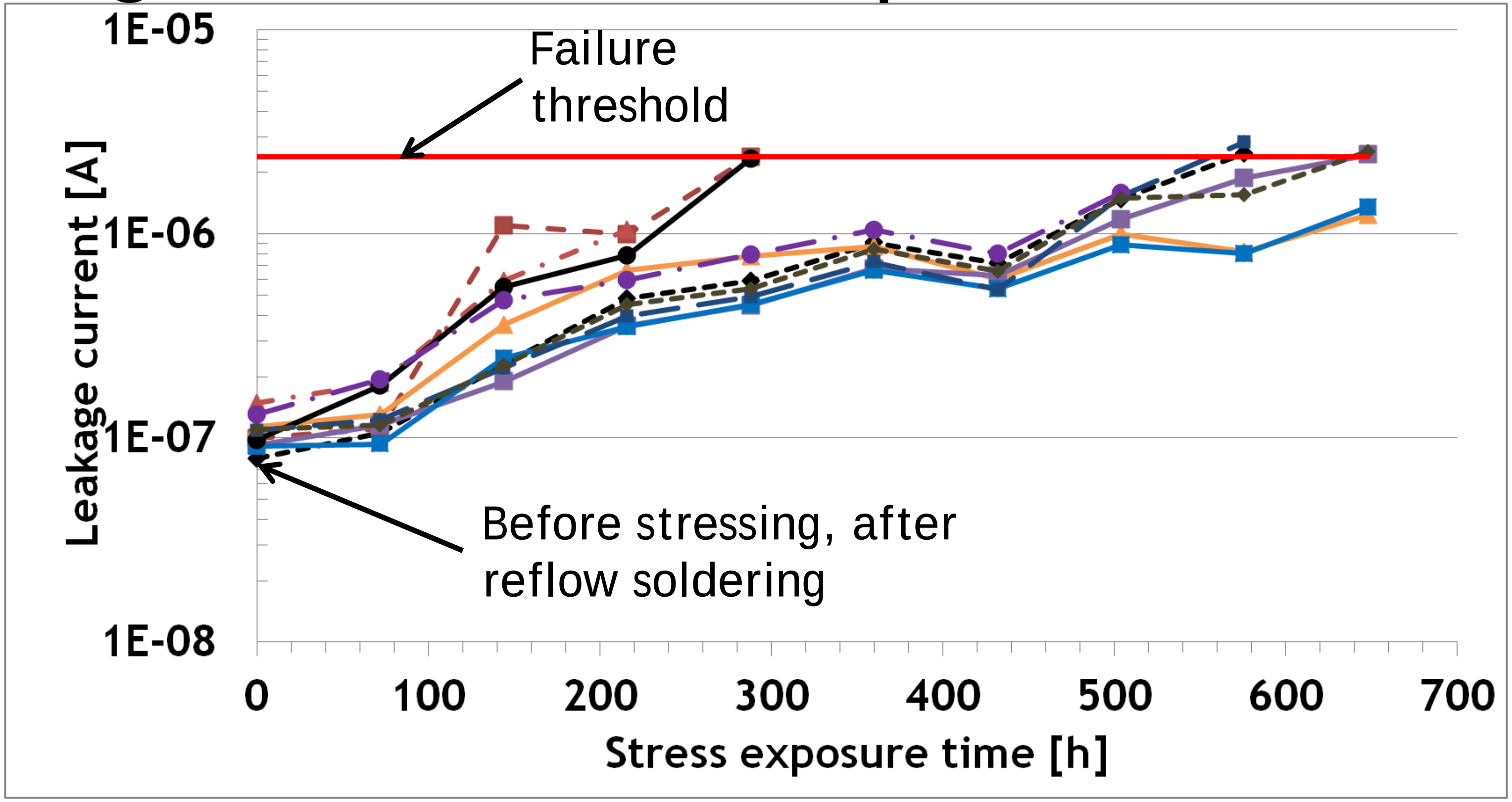
- The samples were exposed to a constant temperature of +125° C during voltage step stressing. The voltage stresses were increased every 72 h.
- After each 72h exposure step, electrical characterization (C, DF, ESR, LC) was performed.
- As degradation progressed due to increasing stress levels, failed samples were extracted for failure analysis. The remaining capacitors were then exposed to the next step stress level.

Leakage Current Results of Step Stress Testing at Constant Temperature, Vendor A



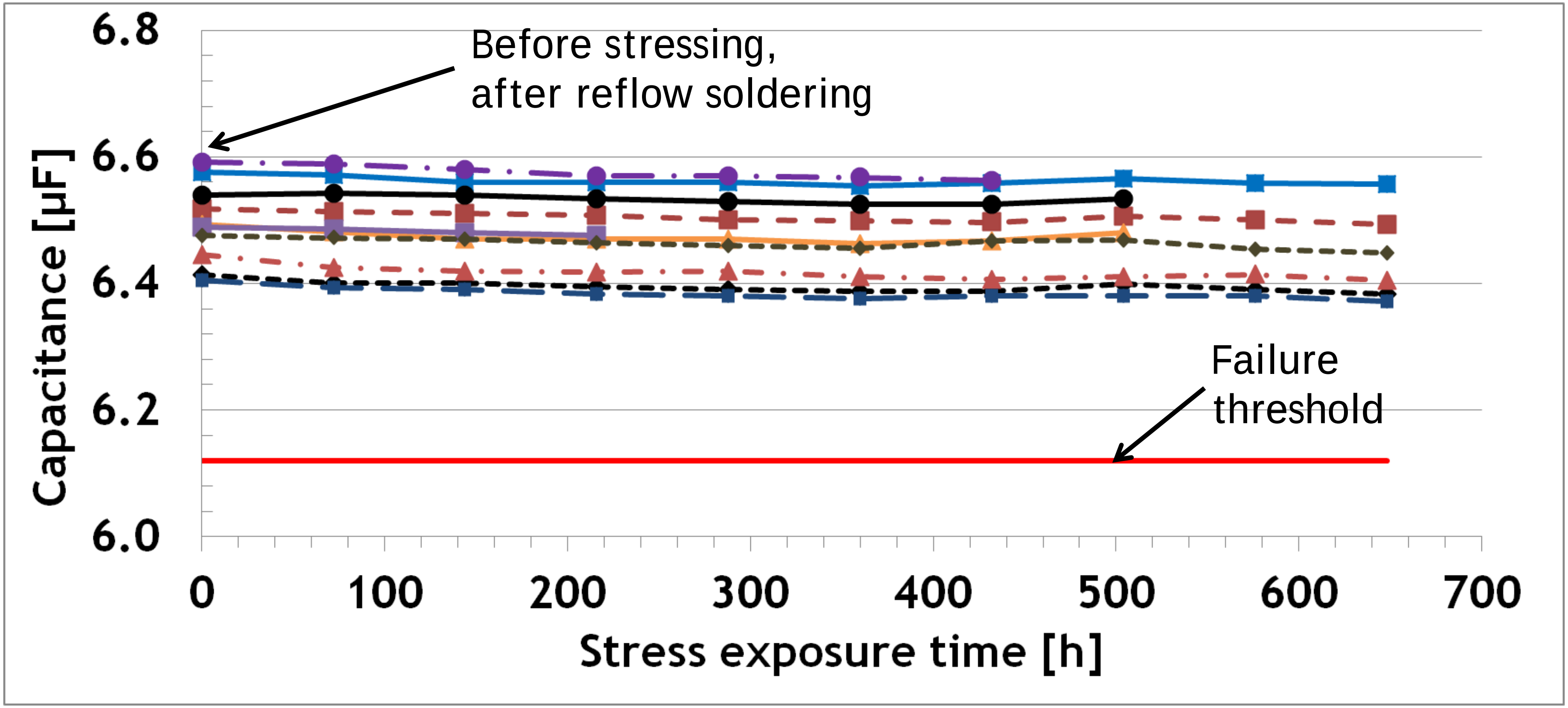
- Leakage current measured at 25° C.
- Parts were exposed to one reflow cycle prior to step-stress testing.
- Increase of leakage current observable.

Leakage Current Results of Step Stress Testing at Constant Temperature, Vendor B



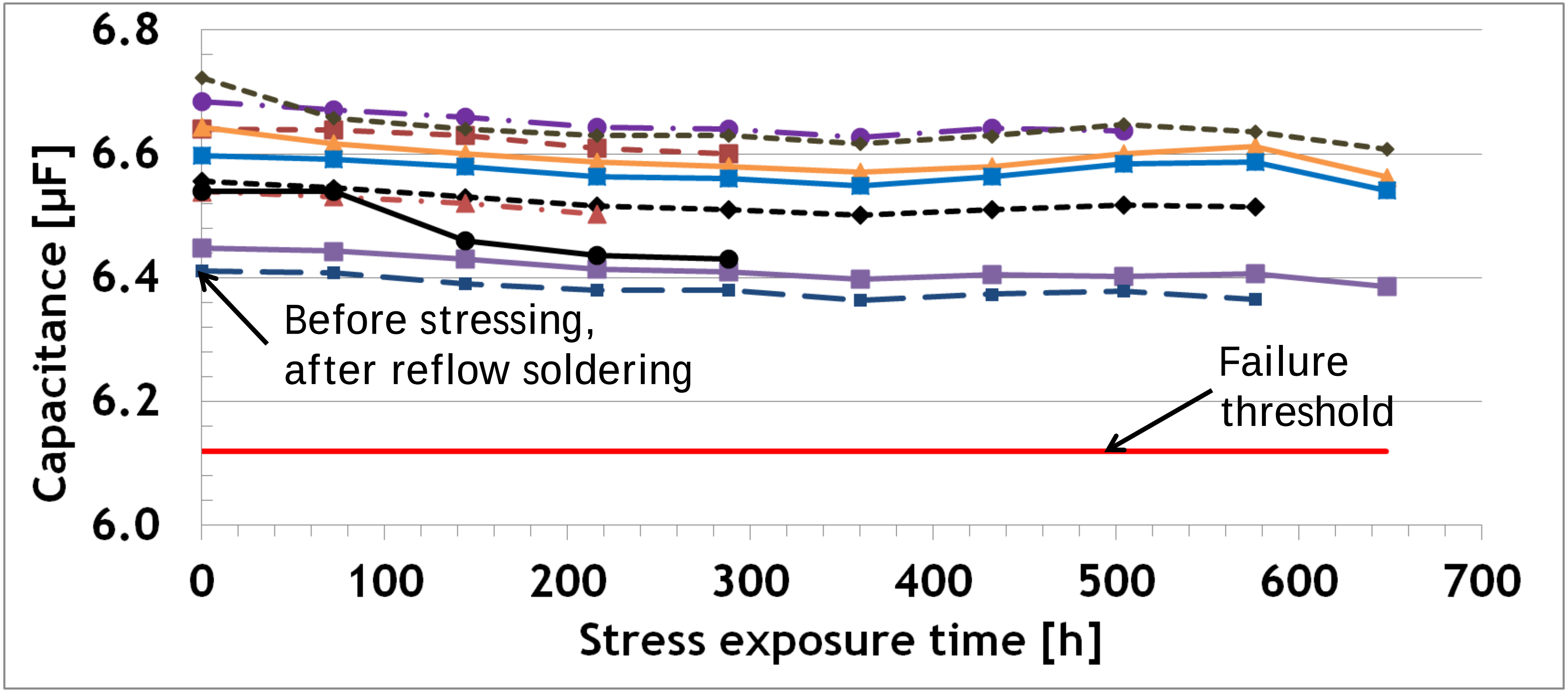
- Two early failures were observed.
- Increase of leakage current observable.

Capacitance Results of Step Stress Testing at Constant Temperature, Vendor A



- Stabilized capacitance over the entire voltage stress range observable.

Capacitance Results of Step Stress Testing at Constant Temperature, Vendor B



- Slight decrease of capacitance with increasing stress steps observable.
- One early failure part shows a drop of capacitance before failure.

Observations from Step Stress Testing

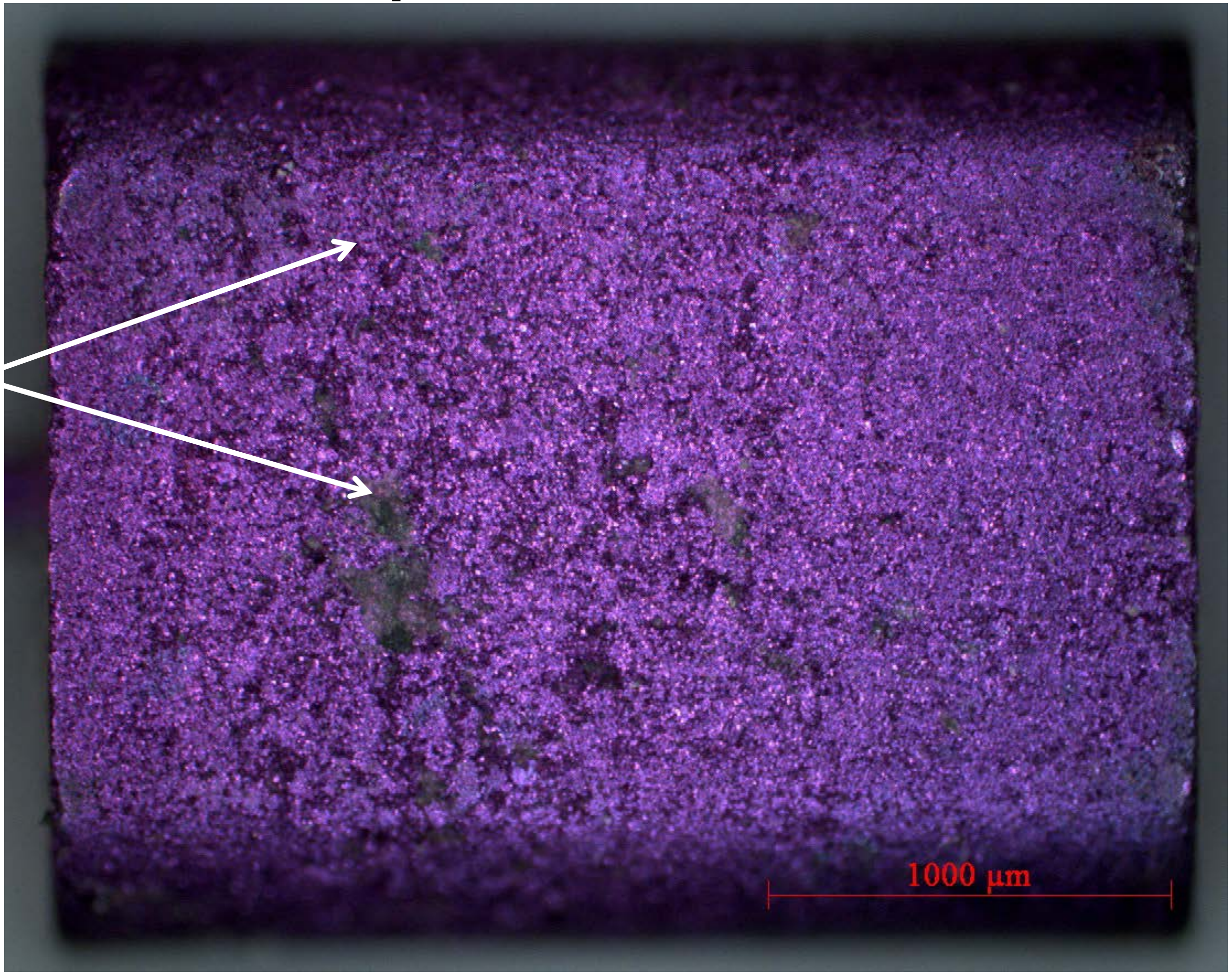
- Leakage current was the most sensitive parameter towards degradation. Two early failures were observed for parts from vendor B.
- Degradation of leakage current suggests that the dielectric layer is predominantly affected by thermal and electrical stresses. The slopes of the leakage current trends indicate that the applied voltages did not exceed the dielectric strength.
- Capacitance showed an insignificant decrease over the range of stress steps.
- ESR measurements did not show degradation, indicating that detachment of the cathode lead frame is not a reliability concern.

Failure Analysis of Tantalum Capacitors

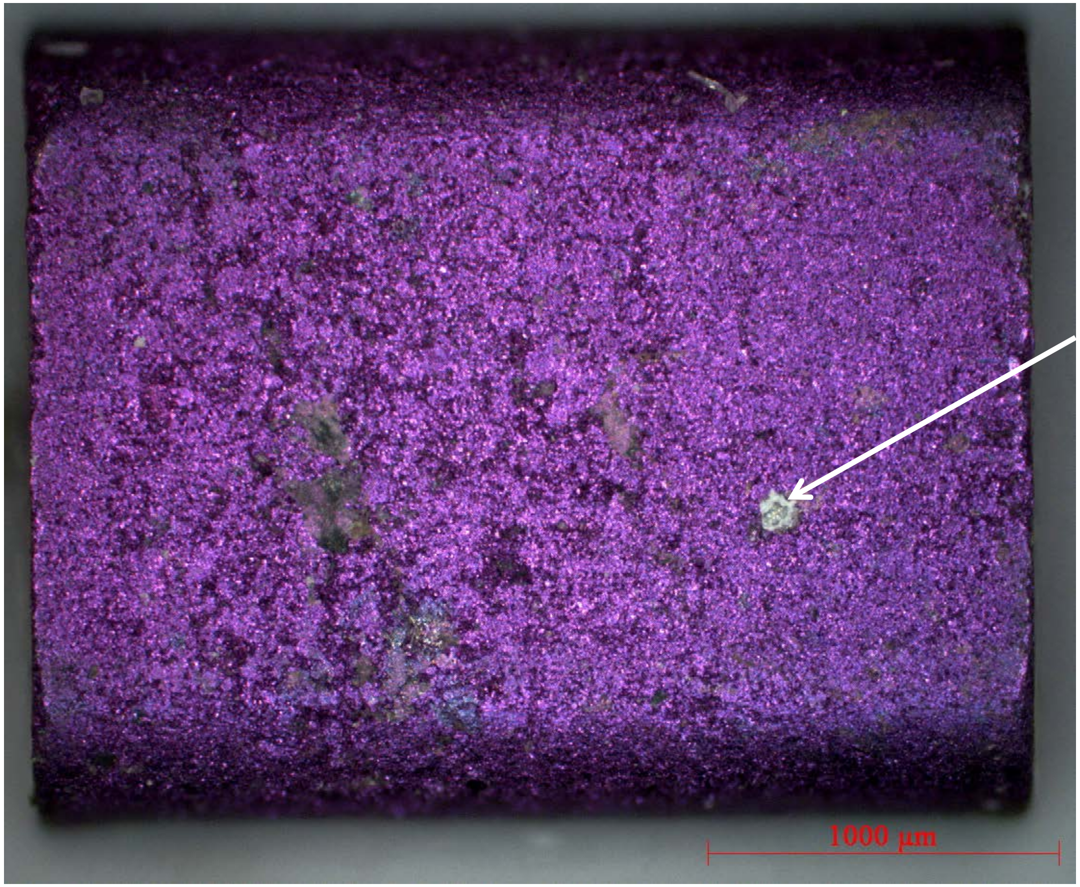
- Experimental results suggest that the dielectric layers were significantly degraded.
- Identification of dielectric breakdown sites can be difficult due to their small size and their appearance similar to healthy dielectric surfaces.
- Dielectric breakdown results in high current channels, which allowed the use of tin-plating to deposit tin on high current sites.
- Decapsulation and tin-plating allow visualization of a larger surface area of the dielectric than cross-sectional analysis.

Before Tin Plating of Decapsulated, Stressed Sample From Vendor A

Possible residues from MnO_2 or Ag adhesive



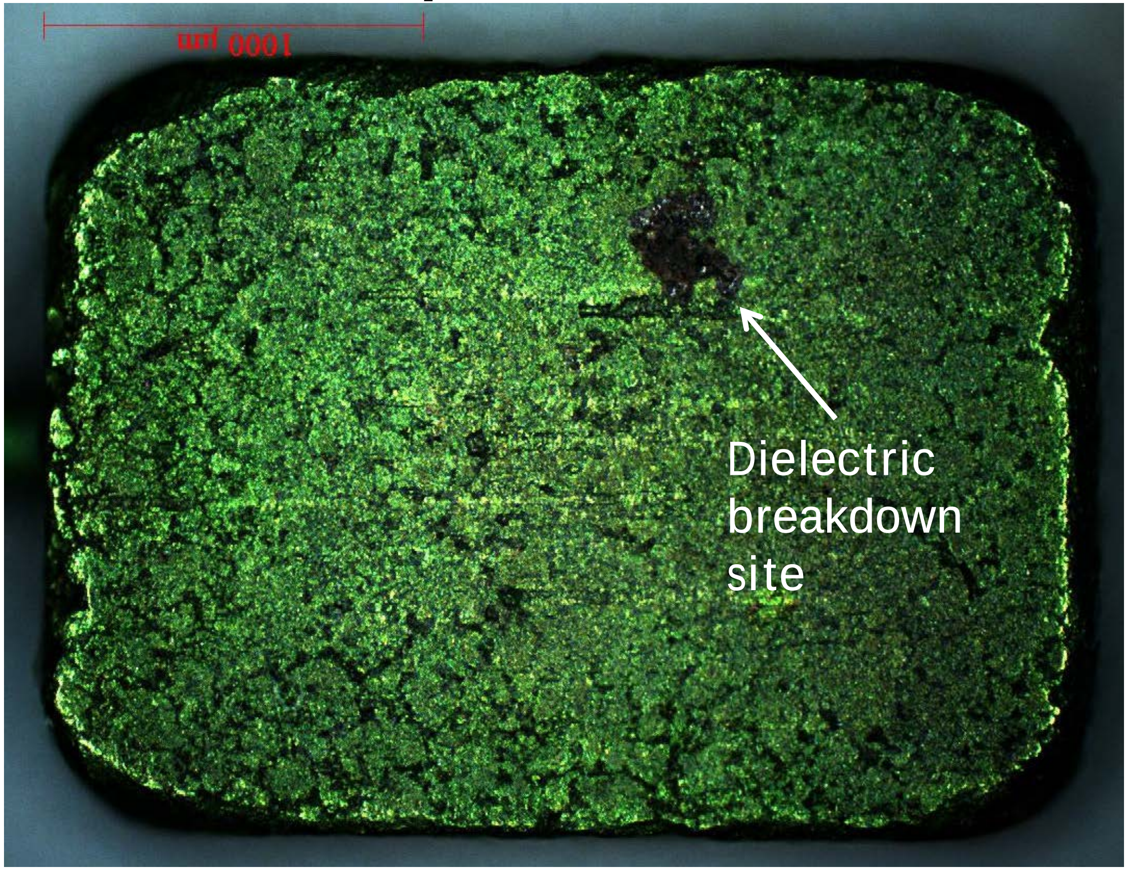
After Tin Plating of Decapsulated, Stressed Sample From Vendor A



High current channel marked by tin grain growth.

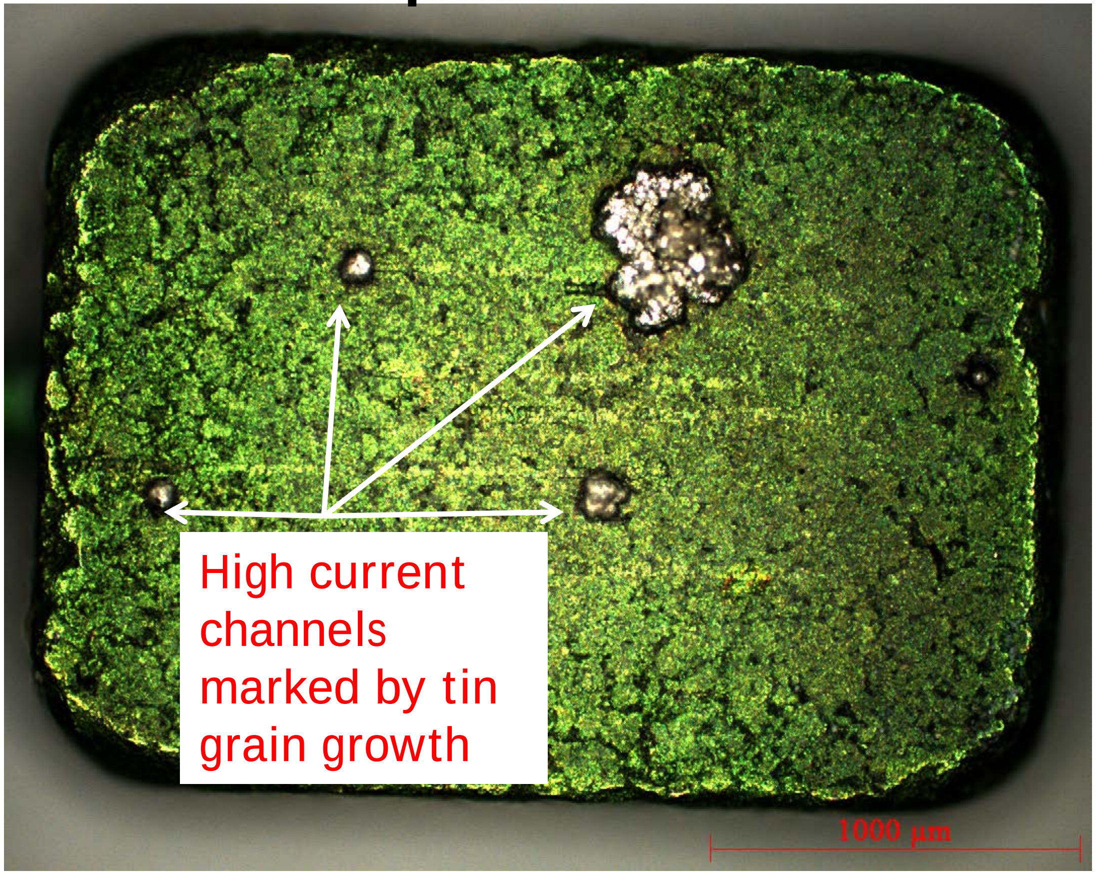
- Failed samples show larger tin-plated breakdown sites as compared to virgin parts.

Before Tin Plating of Decapsulated, Stressed Sample From Vendor B



- Color differences of the pellet surfaces were noticeable due to interference of light, indicating a higher dielectric thickness in parts from vendor B.

After Tin Plating of Decapsulated, Stressed Sample From Vendor B



- Stressed parts show numerous large breakdown locations with severe leakage current compared to virgin parts.

Conclusions

- The times of failure for parts from both vendors were similar, despite different thicknesses of the dielectric layer.
- Voltage step stress testing above the rated voltage at constant elevated temperatures did not introduce unknown failure mechanisms. Dielectric breakdown was identified as the dominant failure mechanism.
- Leakage current is the most sensitive indicator of degradation of tantalum capacitors for step stress testing at constant temperatures. Thus a failure criterion based on leakage current should be used in life testing of tantalum capacitors.
- Failure due to dielectric breakdown resulted in numerous breakdown sites, which were likely accumulated during the stress exposure until the failure threshold for leakage current was reached.
- Since no new failure mechanisms were introduced even when stressing the parts up to 3.66x V_R, step stress testing can be valuable tool for part selection or lot acceptance.

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