Capacitors and Resistors with Extended Operating Temperature Range for GaN Applications– Development and Space Evaluation

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During the last decade, a growing number of applications demanding higher power electrical consumption have emerged in some industrial sectors such as in the military, automotive or space ones. Consequently, electrical components with higher temperature range and rating voltage operation are needed. In addition, the good thermal characteristics of Silicon Carbide (SiC) and Gallium Nitride (GaN) allow the fabrication of devices suitable for working in extreme conditions. In order to satisfy these demands, an evaluation of selected capacitors and resistors for future space SiC & GaN applications is presented. They have extended temperatures ranges to the ones specified by manufacturers for current today's applications. Under the framework of ESA Contract awarded by ALTER TECHNOLOGY, different families of tantalum and ceramic capacitors and thin, thick film and wraparound chip resistors were chosen from a compendium of market competitors according to their possible good performance for these applications. For their evaluation, different tests were performed with the aim of constructing a derating curve with extended temperature conditions: firstly, a preliminary characterization including an initial destructive physical analysis, after destructive tests such as thermal shocks, voltage temperature (V-T) step stress processes, an accelerated life test of 2000 hours long and to conclude, a surge test determined by the ESCC Generic Specification No. 3012 were performed.
Relevant results as well as conclusions and recommendations will be then presented within this paper.

Keywords
Space, destructive tests, ceramic, tantalum, thin, thick, wraparound resistors, derating curve

INTRODUCTION

One of the most relevant characteristics that passive electronic components used in Space [1] applications during different missions must accomplish is their high resistance to extreme conditions such as low and high temperature, high voltage and fast high electrical current discharges. Furthermore, they have to be reliable enough to operate efficiently during all their lifetime long.

In addition, space applications such as satellite communications systems are nowadays demanding an increase in the power amplifiers efficiency the same as a reduction in manufacture launch costs. Regarding communications, GaN has recently begun to be used in C-band high power amplifiers (HPA) in the frequency range of 3.7 GHz to 4.2 GHz in order to satisfy these needs [2]. Other advantages of using HPA designs with GaN technology is the low electrical power usage (OPEX), the reduction in size and fabrication costs due to the lower amount of heated dissipated and the high operating voltage: they often operate with a power supply voltage up to 50 V, similar to the power feeder voltage of 47 V used in communication equipment. Furthermore, these amplifiers are benefitted from GaN characteristics such as higher performance and wider frequency coverage.

For these reasons, passive electrical components integrated in space applications systems are desired to operate according to GaN technology characteristics such as functioning in an extended operating range, having low energy consumption, being integrated in miniaturized circuits, etc.

In this work, we present the results obtained from the evaluation and testing of different passive components such as ceramic and tantalum capacitors the same as thin, thick film and wraparound chip resistors carried out in the international project under the framework of ESA contract 4000109461/13/NL/PA named *Capacitor and Resistors with extended operating temperature range for GaN applications – Development and Space Evaluation* or the 4000110740/14/NL/SFe named *Silicon Capacitors – Development and Space Pre Evaluation* which has economically supported this work.

Capacitors and resistors that better adapted to previous characteristics were chosen between the different today's market passive electrical components manufacturers. Following family capacitors and resistors were decided the best ones for GaN technology based space applications: regarding ceramic capacitors, Syfer X8R and AVX X8R. Regarding tantalum capacitors: AVX-TCH, AVX-THH and AVX-THJ. Regarding resistors: Vishay CRCW, Vishay FRSH, Vishay Beyschlag MC, Vishay Sfernice PHT and Vishay VPG HTH-A.

In order to perform a qualification of the components, an evaluation and testing plan was followed: firstly, an initial characterization of the parts at room and at different temperatures. Then thermal shocks, V-T step stress, life endurance and surge tests. After and once V-T step stress and life endurance tests results were analyzed, different derating curve rules were defined. Previously to these tests, DPA (Destructive Physical Analysis) was performed in order to analyze their physical structure.

To summarize, this paper reports on passive capacitors and resistors for aerospace applications, where miniaturization, weight saving with enhanced reliability, low energy consumption and extended temperature range is targeted. Experimental results of these tests are presented and some conclusions such as their good response to high V and T and to fast electrical high current pulses are reported. Furthermore, derating rules were defined towards a possible component qualification. It is concluded that these capacitors could be used in space applications.

SELECTION OF THE PASSIVE ELECTRICAL COMPONENTS AND EVALUATION AND TEST PLAN

Capacitors were chosen in base of their high operating range and in base of the similar voltages to the ones required by GaN technology space applications. Ceramic and tantalum capacitors were considered as the most suitable for these characteristics and in the case of resistors, thin, thick film and wraparound chip resistors. It is shown in the following table the different components selected, the kind of tests supported by each components and the number of units used for each test.

Table 1. Capacitors with an extended operating range to be evaluated and tested for possible space applications.

Kind of component	**Kind of test supported**	**Number of units**
Syfer X8R 12 nF, 100 nF, 18 nF Ceramic Capacitor	Thermal shock (12 nF)	3
	Step stress/life endurance (100 nF)	6/9
	CA/Derating (18nF/100 nF)	3/6&9
AVX-X8R-100 nF Ceramic Capacitor	Step stress/life endurance/Derating	6/9/6&9
AVX TCH CTC-21D 330 µF, 150 µF, 220 µF, 47 µF (Tantalum Capacitor)	Thermal Shock (330 µF)	3
	Step stress/life test/CA derating 150 µF, 220 µF, 47 µF	3/3/3&3
	Surge test (150µF,220µF,330µF)	1 each
AVX-THH 6.8µF/47 µF /100 µF/22 µF (Tantalum Capacitor)	Thermal Shock (6.8 µF)	3
	Step stress/life endurance 47 µF/100 µF/22 µF	3/3
	CA/Derating (6.8 µF,47 µF)	2/2/3&3

	Surge test (10 µF, 100 µF)	1 each
AVX-THJ 100 µF, 10 µF (Tantalum Capacitor)	Thermal Shock (100 µF)	3
	Step stress/life endurance (10 µF)	6/9
	CA/Derating (1 µF /10 µF)	3/6&9
	Surge test (10 µF, 100 µF)	1 each

The same criterion was used for resistors. In the following table the different resistors selected, the kind of tests supported by each components, the number of units used for each test and the operating T range and V_{Rate} used is presented.

Table 2. Resistors with an extended operating range to be evaluated and tested for possible space applications.

Kind of component	Kind of test supported	Number of units
Vishay CRCW 4.7 kΩ, 250 Ω, 26 kΩ	Thermal shock (250 Ω)	3
	Step stress / life endurance (4.7 kΩ)	6/9
	CA/Derating (26 kΩ /4.7 kΩ)	3/6&9
Vishay VPG FRSH 125 kΩ, 1kΩ	Thermal shock (125 kΩ)	3
	Step stress / life endurance (1kΩ)	6/9
	CA	3
Vishay Beyschlag MC 100 kΩ, 10kΩ	Thermal shock (100 kΩ)	3
	Step stress /life endurance (10 kΩ)	6/9
	CA	3
Vishay Sfernice PHT 10 kΩ, 1 kΩ	Thermal shock (10 kΩ),	3
	Step stress / life endurance (1 kΩ),	6/9
	CA/Derating (1 kΩ)	3/6&9
Vishay VPG HTH-A 1 kΩ	Step stress/life endurance/Derating	6/9/3

For the surge test following tantalum capacitors were used:

Table 3. Tantalum capacitors with an extended operating range used in the surge test

Kind of capacitor	AVX THJ	AVX THJ	AVX THH	AVX THH	AVX TCH	AVX TCH	AVX TCH
Capacitance	100 µF	10 µF	6.7 µF	47 µF	330 µF	150 µF	220 µF

INITIAL CHARACTERIZATION OF THE COMPONENTS

All the resistors, ceramic and tantalum capacitors presented in tables 1 and 3 were soldered in different boards in order to supply them different voltage values in base of the tests supported. They were initially characterized by measuring their capacitance, equivalent series resistance (ESR), equivalent series inductance (ESL), impedance (Z), tangent of losses (tgd), voltage proof values and leakage currents, at different frequencies up to 1 GHz and at room temperature. However, the current operating frequency range was the most interesting for our studies. In case of capacitors of C≤100 nF, the interesting frequency range was between 1 – 10 kHz and 100 kHz - 1 MHz. For capacitors of C ≥ 1 µF, the relevant operating frequency range was between 100 Hz and 1 kHz. Results show that all these measurements were inside the operating range determined by the manufacturer. Furthermore, a preliminary characterization in temperature was carried out: the components were monitored at increasing temperature from the minimum temperature operating range to the maximum temperature defined in the datasheet with the aim of a preliminary check of their behavior at extreme temperatures. Figure 1 shows an example of this characterization in which AVX TCH 330µF capacitance values is presented for different temperatures and in the frequency range of 100Hz- 1kHz.

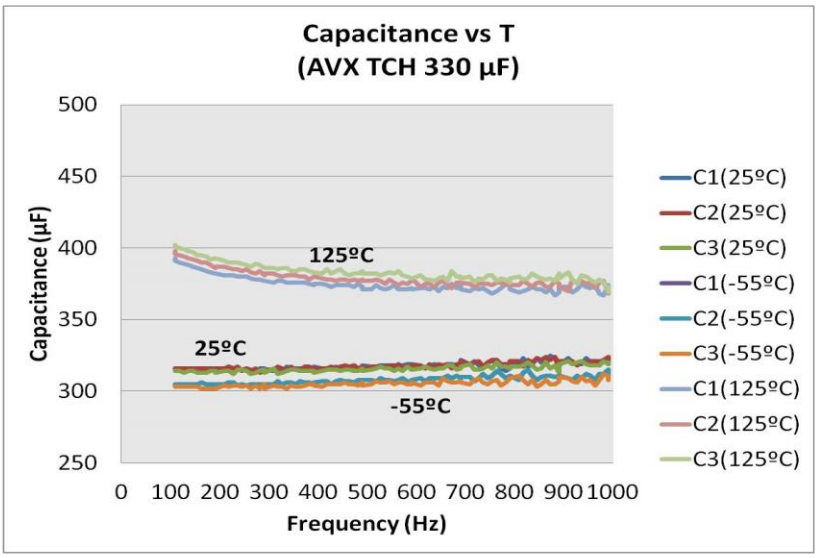

Figure 1. Example of preliminary characterization: groups of three 330 µF AVX TCH capacitance values for frequencies up to 1 kHz at temperature values of T=-55ºC, 25ºC and 150ºC

THERMAL SHOCK

Thermal shocks experimental conditions supported by capacitors are presented in the following tables.
Regarding caapcitors, 25 cycles running from T_1 to T_2 determined by the operating T limits specified by the manufacturer. After, components were characterised at room temperature.

Table 4. Thermal shock conditions applied to silicon capacitors

Test conditions				
Kind of Capacitor	**Step**	**Temperature (ºC)**	**Exposure Time (min)**	**Rate**
Syfer X8R 12 nF	1	-55	5	5 ºC/min
	2	150	5	5 ºC/min
AVX TCH CTC-21D330 µF	1	-55	5	5 ºC/min
	2	125	5	5 ºC/min
AVX-THH 6.8 µF	1	-55	5	5 ºC/min
	2	240	5	5 ºC/min
AVX-THJ 100 µF	1	-55	5	5 ºC/min
	2	175	5	5 ºC/min

Resistors supported 25 cycles running from T_1 to T_2 determined by the operating T limits specified by the manufacturer. After, components were characterised at room temperature.

Table 5. Thermal shock conditions applied to resistors

Test conditions				
Kind of resistor	**Step**	**Temperature (ºC)**	**Exposure Time (min)**	**Rate**
Vishay CRCW 250 Ω	1	-55	5	5 ºC/min
Vishay CRCW 250 Ω	2	155	5	5 ºC/min
Vishay VPG FRSH 125 kΩ	1	-55	5	5 ºC/min
Vishay VPG FRSH 125 kΩ	2	225	5	5 ºC/min
VSH. B. MC 0603 10K Ω	1	-55	5	5 ºC/min
VSH. B. MC 0603 10K Ω	2	125	5	5 ºC/min
Vishay SF PHT 10 kΩ	1	-55	5	5 ºC/min
Vishay SF PHT 10 kΩ	2	225	5	5 ºC/min

Results show that either capacitors or resistors electrical properties measured at room T after thermal cycles are inside the range defined by the manufacturer.

TEMPERATURE AND VOLTAGE STEP-STRESS

In order to determine the resistance of capacitors and resistors to extreme conditions such as high temperatures and voltages higher than their rated values specified by the manufacturer and with the aim of carrying out a qualification for a possible commercial use in the space field, capacitors and resistors were stressed to the different V and T conditions presented in tables 6-13. Step-stress tests were divided in 5 steps. For capacitors, each step lasted 168 h long and for resistors, 1.5 h.

Table 6. V Step-Stress conditions applied to ceramic and tantalum capacitors

Kind of capacitor	Step 1 V (V)/T (ºC)	Step 2 V (V)/T (ºC)	Step 3 V (V)/T (ºC)	Step 4 V (V)/T (ºC)	Step 5 V (V)/T (ºC)
Syfer X8R 1206 100 nF	50/ 85	60/85	72/85	86.4/85	103.7/85
AVX X8R 1206 100 nF	50/ 85	60/85	72/85	86.4/85	103.7/85
AVX TCH CTC-21D (150 µF,220 µF, 47µF)	25, 16, 50/85	30, 19.2, 60/85	36, 23.04, 72/85	43.2, 27.6, 86.4/85	51.8, 33.2, 103.7/85
AVX THH CTC-21D (47µF,100µF, 22µF)	60,30, 15/200	72,36,18/200	86.4,43.2, 21.6/200	103.68,51.8, 25.9/200	124.4,62.2, 31.1/200
AVX THJ 2917 10µF	30/85	36/85	43.2/85	51.8/85	62.21/85

Table 7. V Step-Stress conditions applied to resistors (power stress)

Kind of Resistor	Step 1 V (V)/T (ºC)	Step 2 V (V)/T (ºC)	Step 3 V (V)/T (ºC)	Step 4 V (V)/T (ºC)	Step 5 V (V)/T (ºC)
VSH.D.CRCW 0603 4.7 kΩ	60/ 70	72/70	86.5/70	103.7/70	124.4/70
VPG FSRH 0603 1kΩ	8.5/ 70	10.2/70	12.25/70	14.7/70	17.65/70
VSH.SF.PHT 0603 1kΩ	8.5/ 70	10.2/70	12.25/70	14.7/70	17.65/70
VSH. B. MC 0603 10K	60/ 70	72/70	86.5/70	103.7/70	124.4/70
VPG.HTHA.0603 1K	8.5/ 70	10.2/70	12.25/70	14.7/70	17.65/70

Table 8. T Step-Stress conditions applied to ceramic and tantalum capacitors

Kind of capacitor	**Step 1 V (V)/T (ºC)**	**Step 2 V (V)/T (ºC)**	**Step 3 V (V)/T (ºC)**	**Step 4 V (V)/T (ºC)**	**Step 5 V (V)/T (ºC)**
Syfer X8R 1206 100 nF	50/ 85	50/ 110	50/ 135	50/ 160	50/ 185
AVX X8R 1206 100 nF	50/ 85	50/ 110	50/ 135	50/ 160	50/ 185
AVX TCH CTC-21D (150 µF, 220 µF, 47µF)	25, 16, 50 / 85	25, 16, 50 / 110	25, 16, 50 /135	25, 16, 50 /160	25, 16, 50 /185
AVX THH CTC-21D (47µF, 100µF, 22µF)	63,35, 16/ 200	63,35, 16/ 210	63,35, 16/ 220	63,35, 16/ 230	63,35, 16/240
AVX THJ 2917 10 µF	30/ 85	30/110	30/135	30/160	30/185

Table 9. T Step-Stress conditions applied to resistors (power stress)

Kind of Resistor	**Step 1 V (V)/T (ºC)**	**Step 2 V (V)/T (ºC)**	**Step 3 V (V)/T (ºC)**	**Step 4 V (V)/T (ºC)**	**Step 5 V (V)/T (ºC)**
VSH. D. CRCW 0603 4.7 k	60/ 70	60/95	60/120	60/145	60/170
VPG FSRH 0603 1kΩ	10/ 70	10/95	10/120	10/145	10/170
VSH.SF.PHT 0603 1kΩ	10/ 70	10/95	10/120	10/145	10/170
VSH. B. MC 0603 10K	60/ 70	60/95	60/120	60/145	60/170
VPG.HTHA. 0603 1KΩ	10/ 70	10/95	10/120	10/145	10/170

Experimental results are presented in the following tables. Following nomenclature was used: X/Y means Failed Parts in the Characteristic Step/Number of Parts Used at the Beginning of the Step.

Table 10. V Step-Stress results obtained with capacitors

Kind of Capacitor	**Step 1 V (V)/T (ºC)**	**Step 2 V (V)/T (ºC)**	**Step 3 V (V)/T (ºC)**	**Step 4 V (V)/T (ºC)**	**Step 5 V (V)/T (ºC)**
Syfer X8R 1206 100 nF	0/3	0/3	0/3	0/3	0/3
AVX X8R 1206 100 nF	0/3	0/3	0/3	0/3	0/3
AVX TCH CTC-21D(150 µF, 220 µF, 47µF)	0/3	0/3	0/3	0/3	1/3
AVX THH CTC-21D (47µF,100µF,22µF)	0/3	0/3	1/3	0/2	1/2
AVX THJ 2917 10 µF	0/3	0/3	0/3	0/3	0/3

Table 11. V Step-Stress results obtained with resistors (power stress)

Kind of Resistor	**Step 1 V (V)/T (ºC)**	**Step 2 V (V)/T (ºC)**	**Step 3 V (V)/T (ºC)**	**Step 4 V (V)/T (ºC)**	**Step 5 V (V)/T (ºC)**
VSH. D. CRCW 0603 4.7 kΩ	0/3	0/3	0/3	0/3	0/3
VPG FSRH 0603 1kΩ	0/3	0/3	0/3	0/3	0/3
VSH.SF.PHT 0603 1kΩ	0/3	0/3	0/3	0/3	0/3
VSH. B. MC 0603 10KΩ	0/3	0/3	0/3	0/3	3/3
VPG.HTHA.0603 1KΩ	0/3	0/3	0/3	0/3	3/3

Table 12. T Step-Stress results obtained with capacitors

Kind of Capacitor	Step 1 V (V)/T (ºC)	Step 2 V (V)/T (ºC)	Step 3 V (V)/T (ºC)	Step 4 V (V)/T (ºC)	Step 5 V (V)/T (ºC)
Syfer X8R1206 100 nF	0/3	0/3	0/3	0/3	0/3
AVX X8R1206 100 nF	0/3	0/3	0/3	0/3	0/3
AVX TCH CTC-21D (150 µF,220 µF,47µF)	0/3	0/3	0/3	0/3	1/3
AVX THHCTC-21D (47µF,100µF,22µF)	0/3	0/3	1/3	2/3	1/1
AVX THJ 2917 10 µF	0/3	0/3	0/3	0/3	0/3

Table 13. T Step-Stress results obtained with resistors (power stress)

Kind of Resistor	Step 1 V(V)/T(ºC)	Step 2 V(V)/T(ºC)	Step 3 V(V)/T(ºC)	Step 4 V(V)/T(ºC)	Step 5 V (V)/T(ºC)
VSH. D. CRCW 0603 4.7kΩ	0/3	0/3	0/3	0/3	0/3
VPG FSRH 0603 1kΩ	0/3	0/3	0/3	0/3	0/3
VSH.SF.PHT 0603 1kΩ	0/3	0/3	0/3	0/3	0/3
VSH. B. MC 0603 10K	0/3	0/3	0/3	0/3	0/3
VPG.HTHA.0603 1KΩ	0/3	0/3	0/3	0/3	0/3

Experimental results described in previous tables show that AVX TCH and AVX THH capacitors are more sensitive to temperature and voltage step stress conditions than ceramic and AVX THJ tantalum capacitors. Life endurance test described in the next section was highly conditioned by these step stress results.

LIFE ENDURANCE TESTS

With the purpose of evaluating the resistance of each family capacitors to different long lifetime voltage and temperature conditions, three tests were carried out with three units of each of the capacitors presented in Table 1. These tests had four characteristic steps lengths: the first one lasted 200 h, the next one other 200h, the 3rd one 300 h and the following one, 300 h. To finish the endurance test, the last step was planned to be 1000 h long so that at the end, the components supported 2000 h long under different life endurance tests conditions. Towards a possible qualification, life endurance test is very important to determine capacitors reliability and allows constructing a derating curve for each capacitors family that had supported the tests.

Tests conditions were proposed in base of datasheet life endurance specifications determined by the manufacturer and step stress results presented in previous section. In case of tantalum capacitors, voltage and temperature values were slightly higher (1.1 or 1.2 times) than their V and T rated magnitudes. Furthermore, V and T conditions supported by ceramic capacitors are much higher than their rated values specified in the datasheet (4 and 5 times their V_{rate}). Regarding resistors, most conditions were established according to their maximum power specified in the datasheet, although there were some cases that conditions were more aggressive.

Table 14. Life endurance tests conditions proposed for tantalum and ceramic capacitors

Kind of Capacitor	Test 1 V (V)/T (ºC)	Test 2 V (V)/T (ºC)	Test 3 V (V)/T (ºC)
Syfer X8R 1206 100 nF	200V/150ºC	250V/150ºC	200V/170ºC
AVX X8R 1206 100 nF	200V/150ºC	250V/150ºC	200V/170ºC
AVX TCH CTC-21D (150 µF,220 µF, 47µF)	25V/150ºC 16V/150ºC 50V/150ºC	30V/150ºC 19.2V/150ºC 60V/150ºC	30V/170ºC 19.2V/170ºC 60V/170ºC
AVX THH CTC-21D (47µF,100µF,22µF)	63V/150ºC 35V/150ºC 16V/150ºC	75.6V/150ºC 42V/150ºC 19.2V/150ºC	75.6V/170ºC 42V/170ºC 19.2V/170ºC
AVX THJ 2917 10 µF	35V/150ºC	42V/150ºC	42V/170ºC

Table 15. Life endurance tests conditions proposed for resistors and operating power conditions specified by the manufacturer

Resistors 0603 (PHT, FRSH, HTH-A) (1 kΩ)				
Test	Temperature °C	Power	Test voltage	Power Datasheet
1	T_0= 150ºC Target chip temperature 160C	P_0= 160mW	V=12.5V	90 mW (FRSH) 56.25 mW (PHT) 202.5 mW(HTH)
2	T_0= 150ºC Target chip temperature 170C	P_0= 320mW	V=18V	90 mW (FRSH) 75 mW (PHT) 202.5 mW(HTH)
3	T_0+ 20 = 170ºC Target chip temperature 180C	P_0= 160mW	V=12.5V	0 mW (FRSH) 48.75 mW(PHT) 180 mW (HTH)

Resistors MC0603 (10 kΩ)				
Test	Temperature °C	Power	Test voltage	Power Datasheet
1	T_0= 150 Target chip temperature 160C	P_0= 160mW	V=40V	0 mw
2	T_0= 150 Target chip temperature 170C	P_0= 320mW	V=55V	0 mw
3	T_0+ 20 = 170 Target chip temperature 180C	P_0= 160mW	V=40 V	0 mw

Resistors CRCW 2512 (4.7 kΩ),				
Test	Temperature °C	Power	Test voltage	Power Datasheet
1	T_0= 150 Target chip temperature 160C	P_0= 625mW	V=54V	5%P_{Rate}=50mW
2	T_0= 150 Target chip temperature 170C	P_0= 1250mW	V=75V	5%P_{Rate}=50mW
3	T_0+ 20 = 170 Target chip temperature 180C	P_0= 650mW	V=54V	0

Experimental results obtained are presented in the following figures. Regarding resistors, only samples that failed less than 67% in tests 1 and 2 are presented in the figures.

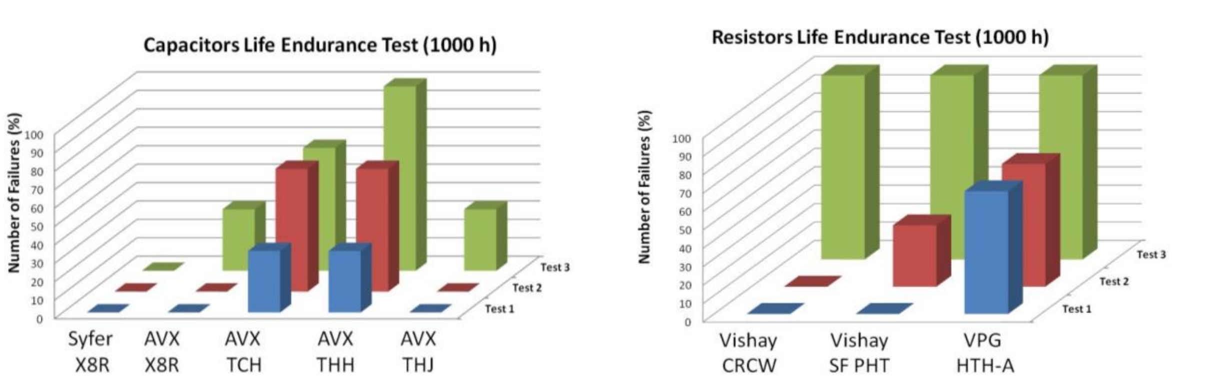

Figure 2. Life endurance tests results for capacitors and resistors

1000 h Life endurance tests show that Syfer X8R, AVX X8R and AVX THJ capacitors are the most robust to these tests conditions. Conversely, AVX TCH and THH tantalum capacitors are more sensitive to such conditions. Regarding resistors, Vishay CRCW resistors only failed in the test 3 and only 33 % of the Vishay SF PHT resistors only failed in the test 2. In the case of VPG HTH-A resistors, 33% of them passed tests 1 and 2. These results allowed establishing derating rules for these passive components.

SURGE TESTS

This test was performed only for tantalum capacitors at room and their maximum rating temperature. This test is based on ESCC Generic Specification No. 3012. It consists of supplying 5 current pulses of 3A with a frequency of ½ Hz. The test circuit used has the schematic presented in the next Figure 3: a power supply, a $1x10^6$ µF capacitor that allows charging and discharging the small capacitors to be tested with pulses of frequency ½ Hz and current values of 3A, fuses to protect the circuit and releys that allow these short capacitors charges and discharges.

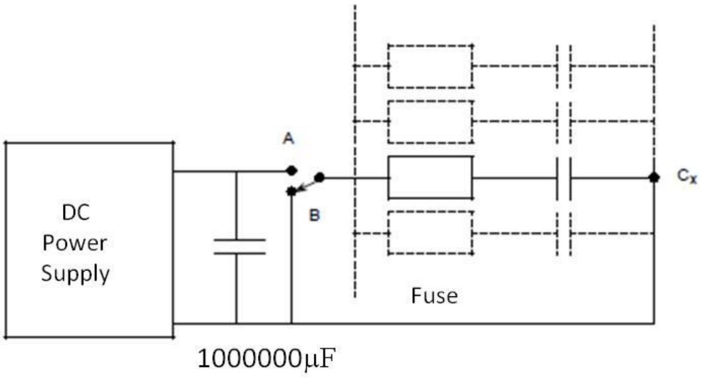

Figure 3: Test circuit for the surge current test

All the tantalum capacitors passed the surge test. This means that capacitors are prepared to support electrical discharges that can occur during their operation time in applications such as space. This malfunctioning can be due to a wrong operation of the electronic devices in which they are integrated, such as a shortcut that can result in a sudden increase of the operating electrical current.

CONSTRUCTIONAL ANALYSIS

DPA (destructive physical analysis) including external visual inspection, solderability test and cross section was performed to ceramic and tantalum capacitors the same as thin film and foil wraparound resistors. This analysis was performed by ALTER TECHNOLOGY in Sevilla facilities.

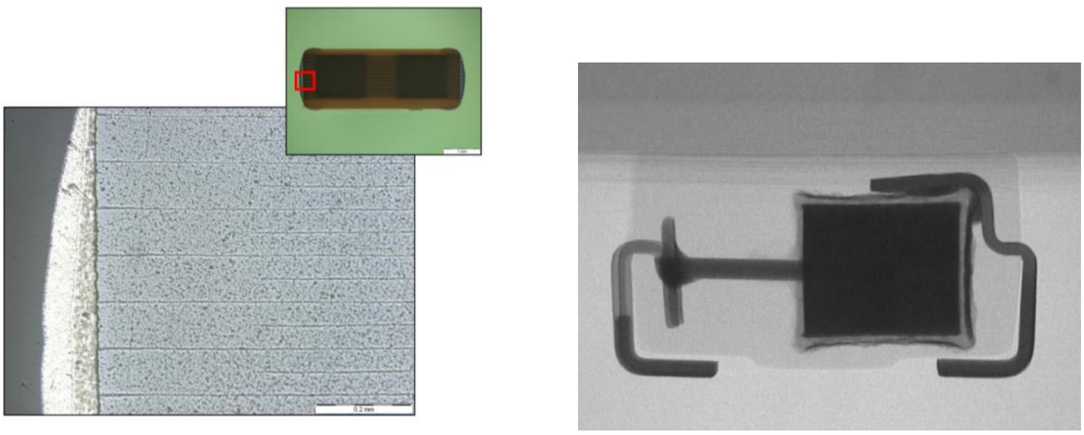

Figure 8: (Left) AVX X8R cross sectioning detailed overlap onto the electrodes and contacts. (Right) X-ray general review of a AVX THJ capacitor.

CONCLUSIONS

In this paper we present the evaluation and testing analysis of ceramic and tantalum capacitors the same as thin, thick film and wraparound chip resistors. For this purpose, thermal shocks, V-T step stress, life endurance and surge tests were performed with these components. Furthermore, a destructive physical analysis was carried out in order to determine the physical internal structure.

Results show that these capacitors are robust to high voltage and temperature long lifetime conditions, especially ceramic and AVX THJ capacitors the same as Vishay CRCW and Vishay SF PHT resistors. We can conclude that these capacitors and resistors with the novel derating curve defined can be used in space applications such as the ones that operate with GaN technology because of their good response to the extreme V and T conditions described above.

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