Failure mechanisms and qualification testing of passive components

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Abstract

New electronic architectures and mechatronic integration in automotive and oil-field applications lead to increasing requirements concerning operating temperatures and vibration levels. At the same time, reliability and lifetime have to fulfil strong demands.
In the European funded project PROCURE (Program for the development of passive devices used in rough environments) a generic spectrum of passive components needed for electronic control units has been developed. The failure mechanisms, the technological challenges, and the test requirements are highlighted below.

1. Introduction

Microelectronics is the key to innovation in many industrial and automotive electronic systems. Potential applications for high-temperature mechatronic systems in the car are transmission control, next generation motor control, and hybrid vehicles.

Mounting electronics directly on the engine block or, as another example, near the brake disk leads to a very harsh environment for all the built-in components.

Similar requirements come from aerospace industry, where temperatures of approximately 200°C can occur in the vicinity of gas turbines. Also for oil exploration, the availability of a viable, reliable and cost-effective high-temperature electronics system compatible with the deep oil logging environment below the earth’s surface (up to 225°C) is a real need.

2. Environmental requirements in automotive and oil exploration

Components for the applications above have to bear high ambient temperatures exceeding 150°C, high temperature changes from -40°C up to the named maximum temperature and heavy mechanical vibrations and shocks.

For automotive applications, the conditions of table 1 have been defined in the project PROCURE (Program for the development of passive components used in rough environments) [1].

The characteristic service life of electronic and electrical components in a vehicle is based on 17 years or 300,000 km driving distance, comprised of 6,000 operating hours and 145,000 hours of dormant time.

For oil exploration, two possible applications with two different maximum temperature ranges (175°C and 225°C) were identified. The corresponding mission profiles have a cumulated time at maximum temperature of 1000 hours.

3. Technology development

The primary technical goal of the project was the development of technologies and prototypes of generic passive components, which are necessary for the realization of the next generation of automotive electronic control units for harsh environments. These are devices suited for lead-free surface mount technology. The first step was to identify the dominant failure modes in order to optimize the device construction.

3.1 MLCC

Multilayer ceramic capacitors are very stable in their electrical properties. Electrical lifetime testing is performed usually with a much higher voltage than rated. But they are brittle, and cracking due to mechanical stresses is a very common failure mode, leading to capacitance loss and to increased leakage currents.

Table 1
Automotive high temperature mission profile

Automotive Mission profile	
Storage	-55°C to +125°C
Max Operating Temperature	175°C
Min Operating Temperature	-40°C
Temperature profile	-40°C to –20°C 300 h -20°C to 20°C: 600 h 20°C to 140°C 3840 h 140°C to 160°C: 1200 h 175°C: 60 h
Temp. gradient	3 to 5°C/min
Vibration	Sinus 10 – 1000 Hz 20 to 40 g
Mechanical shocks	Half sine-wave Acceleration: 50g Time: 11 ms

3.1.1 Technology Development for MLCC

In order to meet the temperature requirements, improvement of the dielectric, the fabrication process and the termination system was necessary. The developed type II ceramic dielectric is based on BaTiO3 with a dielectric constant of 2000. With optimized firing the temperature characteristic meets the X8R requirement (175°C).

For application up to 175°C termination construction is based on classical tinned Nickel on Silver and for application up to 225 °C the termination material is an AgPdPt alloy. Development includes lead free tinning. These choices are motivated by leaching tests that show Ni barrier is the only termination compatible with lead free soldering. AgPdPt termination is compatible with high lead content solder for 225 °C application and is preferred due to less thermal shock sensitivity during soldering.

3.1.2 Results for 175 °C applications

We carried out thermal shocks, substrate bending and endurance tests.

100 thermal shocks -40 / +175°C were done according to IEC 68-2-14. Parts were soldered on polyimide substrate by reflow using lead free solder. The capacitance was measured before and after test to detect capacitance drop caused by crack formation. We did not observe any failure.

Endurance tests were performed at 175 °C under 75 V. Capacitance, dissipation factor, and insulation resistance were measured.

Last generation of type II parts did not exhibit any defect before 500 h. Afterward some insulation resistance drop has been measured. It has been established that this type of failure is linked to nickel barrier processing.

3.1.3 Electrical Impedance Analysis for MLCC

In order to evaluate the potential reliability at high operation temperature, an aging at 200°C was performed, and to follow the evolution of capacitors, we have used a specific measurement based on electrical impedance analysis around piezoelectric resonance under DC bias. We have shown in previous papers [4-6], that using the residual piezoelectricity properties existing in $BaTiO_3$ based capacitors, allows to point out structural defects inside the device, and to derive both quality estimation and a monitoring of degradation under stress.

It was shown in particular that cracks or delaminations induce an attenuation of the impedance peak at anti-resonance. Possible detection of defects down to $100\mu m^3$ has been shown [6]. It is assumed in this work that such defects could generate failures during thermal, mechanical or thermo-mechanical stresses when the component is mounted on board and used in automotive conditions. As indicator, we have used the ratio Fa/Za, defined as the anti resonance peak frequency divided by the impedance at anti resonance, measured on the peak following the width side of the capacitor. In a precedent paper [5] it was assessed that when the value of Za decreases of about 25% the component could be considered as failed. Such a decrease is generally related to the presence of a crack or delamination of significative dimensions (around 150µm width). Measuring the corresponding effect of Fa, it appears that 35% of increase of Fa/Za values could give a good indicator of component failure

After testing 5000 hours at 200°C, no failure is observed following the above the defined criterion. On the figure 1, we have reported the Fa/Za variations, observed during aging. The increase of the "degradation" parameter does not exceed 5% and it is noticeable that its mean value is following a nearly linear evolution. Assuming this evolution up to the failure limit, this gives a rough estimation of the median time in accelerated (200°C) conditions at about 14000h, which seems to be an encouraging behaviour for this type of components.

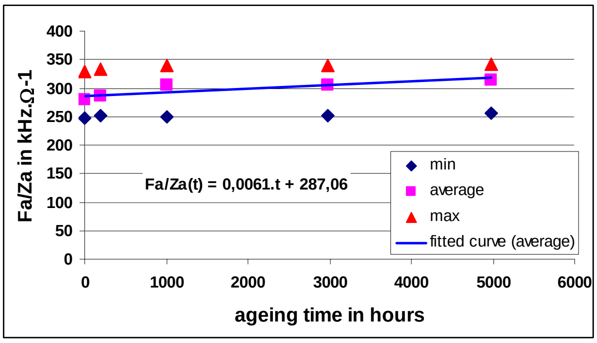

Fig. 1. Variation of the distribution of Fa/Za during an ageing at 200C vs. the time of ageing

3.2 Metallized Plastic Film Capacitors

The motivation to develop metallized plastic film capacitors to be used in high temperatures is twofold:

- There are new films available, which makes it possible to offer products above the traditional 125 ºC, namely Polyphenylene Sulphide (PPS) and Polyethylene Naphtalate (PEN)
- In the capacitance range from 10 nF to 10 µF there are very little if any alternatives available, if a great capacitance stability over large temperature range is needed. PPS and PEN films can fill this gap at least up to 150 ºC, and most probably to 175 ºC. At top of the inherent capacitance stability over temperature, the capacitance value is not voltage dependent, and shows no aging and minimal permanent capacitance change in high temperature storage.

Metallized film capacitors are very reliable parts. They are less susceptible to board bending because of their elasticity. High voltage and high temperature may lead to breakdown of the insulating film, in most cases breakdown is self-healing, i.e. the short is isolated by thermal decomposition of the surrounding material.
Metallized PPS and PEN capacitors have been produced with winding technology, and encapsulated against acute environmental stresses. Film thicknesses from 1.5 µm to 9 µm have been used, which for 125 ºC use correspond with DC voltages 50 V to 400V. The electrodes are made of Sn coated solid bronze plates for good solderability. The mechanical sizes range from 2220 to 6560, capacitance values from 1nF to 3,3 µF.
Both PEN and PPS show good results in 150 °C tests, and PPS very promising in 175 °C.
The typical Capacitance Drift in 2000 h life test with voltage is shown in table 2 below.

Table 2
Typical capacitance drift measured

PPS 50 VDC	PPS 250 VDC
- 0,2 % @ 150 °C	- 0,5 % @ 150 °C
+ 0,2 % @ 175 °C	- 0,5 % @ 175 °C
PEN 50 VDC	PEN 250 VDC
- 1,0 % @ 150 °C	- 2,5 % @ 150 °C
+ 0,4 % @ 175 °C	- 2,0 % @ 175 °C

3.3 *Tantalum Chip Capacitors*

3.3.1 Construction

In principle a tantalum chip capacitor consists of three main elements: anode and cathode, separated by a dielectric layer, the tantalum pentoxide.

The anode is made by pressing small cubes of tantalum powder with a tantalum wire inside. These pressed anodes are sintered in a high vacuum chamber at temperatures up to 2000°C to get a mechanically stable but porous anode (sponge structure). All parameters like sintering temperature, press density, anode dimension and the powder class are optimized to the designated application of the capacitor.

The dielectric layer (tantalum pentoxide) is formed by anodic oxidation of the tantalum in an electrolytic bath. During this process a voltage is applied (pre-forming voltage) to get the growth of the dielectric layer, one volt results in ~2nm thickness of tantalum pentoxide. This step is performed two times with a vacuum tempering process in between to improve and stabilize the dielectric layer.

The cathode is build up by manganese dioxide, a semi conductive material. For this the anodes are dipped in a manganese nitrate $Mn(NO_3)_2$ solution, followed by a thermal decomposition (pyrolysis). The manganese nitrate decomposes to nitrogen gases NO_x and manganese dioxide MnO_2 that remains on the anode's dielectric. The chemical reaction is expressed by the following equation:

$$Mn(NO_3)_2 \xrightarrow{\text{Pyrolysis}} MnO_2 + NO_x$$

Above mentioned ambient temperature requirements are not covered by common series which actually have an upper application temperature limit of 150°C. Using standard capacitors at this temperature will lead to increased failure rates and decreased lifetime in terms of leakage current and impedance. The reason for this thermal breakdown is leakage current overload and an override of degradation temperatures of the contact layers.

3.3.2 Technological approach

Anode Design:

In general, to build capacitors for automotive applications the first step to do is to select special powder types and to increase the ratio between preforming voltage and rated voltage, which is a direct indicator for the stability, reliability and the security reserves for the capacitor under rough environmental conditions.

Second, the pressing parameters are changed to higher press densities resulting in a good contact between the tantalum powder grains and the wire. This leads to a good mechanical stability after sintering and lowers the capacitors sensitivity to low ohm surge current loads.

Furthermore to impede silver migration additionally a humidity protection is applied, to get a hydrophobic behavior.

To avoid mechanical stress caused by welding the anode to the positive terminal laser technique is used. This improves the long term stability concerning leakage current and low ohm surge current loads.

3.3.3 Results

All capacitors are tested by a so called inrush test. This is a low ohm (Rser<0.5Ω) fast (5ms) charging and discharging cycle test (5 times) with rated voltage.

Life test results prove a high temperature stable technology at ambient temperatures up to 175°C.

From actual point of view a collective of 500h @ 175°C and 150°C for 2000h is possible. Furthermore an adequate derating to 33% Urated was found to be necessary to keep the dielectric stress on an acceptable level.

3.4 *Aluminium electrolytic capacitors*

Main failure cause for electrolytic capacitors is dry-out of the electrolyte. The isolating Al-oxide may deteriorate under high voltage and high temperature load. Since aluminium electrolytic capacitors are wound foils with a paper spacer, vibration may cause relative movements in the devices. Special constructions are necessary to improve the vibration robustness of such devices.

To accommodate for the above mentioned 'mission profiles' Aluminum Capacitors need to have a life time of 500 - 1.000 h at 175 °C and 4.000 – 5.000 h at 150 °C. Until now no Non-Solid Aluminum Capacitors are reported for 175°C application temperature. The work presented here is focused on the high temperature requirements and is described in more detail in [2].

To enable application at the required high temperature of 175 °C as main issues the temperature stability of these key technology materials and their low rate of (electro-) chemical interactions at 175°C has to be solved. Furthermore the electrolyte solvent must have a boiling point sufficiently well above 175°C.

For the sealing element and sealing method, stability at 175 °C specially chosen rubber qualities were needed and have been identified and tested. For the SMD component these are necessary to prevent adverse effects like bulging of the capacitor housing.

With the new technology described above the required performance on Life Test at 175 °C / 63V for 500 – 1.000 h and at 150 °C / 63V for 4.000 - 5.000h is achieved for the different existing versions of Aluminum Capacitors, see table 4.

3.5 SMD inductors

Failure mechanisms of SMT inductors are shorts due to local overheating and destruction of the wire insulation, cracks in the brittle ferrite cores, internal delaminations and opening of the wire to terminal contacts.

Project goal was the development of SMT inductors for application at ambient temperature of 175 resp. 200°C (225°C), size 1812 or 2220, inductance range of 1µH to 470µH, rated current 0.09 A to 1.85A and reliability prediction for 1000 hours.

The needed alternative materials, processes and tests to be performed were:

Core material with high Curie temperature Tc > 200°C (250°C). A suitable core material was found with Tc > 300°C, high magnetic flux density and sufficient high permeability.

Dispensable adhesive to connect core and terminals with high thermal strength. An adhesive was found for application up to 175°C operating temperature.

Suitable magnet wires are P180 (mod. polyurethane with temperature index of 190°C), A200 (mod. polyesterimide with temperature index of 210°) and ML220 (mod. polyesteramide with temperature index of 245°C)

Encapsulation materials withstanding high temperature requirements (lead-free solder profiles) have been tested. Glass fibre filled thermoplastic materials (PPS and LCP) have been applied.

Test results:

Load tests at 175°C ambient temperature with rated current, storage tests at 200°C for 1000 hours and 1000 temperature cycles -55°C/+175°C were done without failure (totally 520 samples in size 1812 and 2220 inductance range of 1µH to 470µH, wound with P180 and A200 magnet wires, welded by laser resp. by ultrasonic).

Additional load tests at 200°C ambient temperature with rated current, storage tests at 225°C for 1000h and temperature cycles -55°C/+200°C were done in addition. The inductors manufactured with A200 magnet wire and laser welded after laser stripping met the requirements without failure (totally 120 samples in size 1812 and 2220 inductance range of 1µH to 470µH).

3.6 *Quartz resonators*

Quartz resonators consist of a metallized quartz disk having two contact terminals. Ageing is critical, since the devices are meant to have an extreme stability. Ageing can be caused by diffusion processes in the metallization, mechanical stresses in the package or contaminations.

There are many failure modes on resonator but the main modes are: aging (frequency variation with time), dips (jumps of frequency at a precise temperature due to spurious mode), bad frequency drift with temperature, broken crystal or change of frequency due to shocks or vibrations. Concerning lifetime, our products are generally guaranteed for 10 years to 20 years.

In the project, quartz crystal resonators in HC45 gull wing package within the range –40°C to 175°C according the following specification have been achieved:

ESR <100 ohms, Frequency 20MHz ±50ppm, C0=1.5pF ± 0.3pF and C1=5.08fF ±1.08fF.

Of course, it is easy to modify the value of C0 and C1 according the customer requirements.

Typical tests used for qualification are precision measurements on a goniometer concerning frequency drift with temperature. Concerning dips, it is possible to make a simulation of this phenomenon on a computer.

Table 3
Vibration test results at quartz resonators

Vibration Tests	40g 96h / axis 25°C	40g 22h / axis 175°C
Number of failed components	**0**	**0**
Frequency drift (ppm)	**-3.4**	**-0.4**

Concerning ageing under vibration, temperature shock or storage our last tests showed that we are able to be under 10ppm after thermal shocks on this low cost product (see table 3).

These values could be improved to less than 1ppm for space and military products.

3.7 Thin film resistors

Thin film resistors are very reliable components, reaching sub- ppb levels of failures. Failures can be caused by overcurrent pulses or corrosion of the resistive layer if the protection coating fails. Resistance drift is caused by aging of the thin film at high current or high temperature levels.

During the first project period the main emphasis was on initial stability investigations of thin film resistors at higher temperatures. According to current automotive mission profiles and corresponding operating temperatures of the thin film layer temperatures of 150°C and 210°C respectively were chosen.

Endurance tests up to 1000 h, thermo cycling, humidity tests as well as sequential tests were carried out.

No open circuits were found even after 1000 h endurance at temperatures up to 210°C. The drift behaviour is in accordance with the established stability behaviour of thin metal films.

In some cases resistor changes after subsequent humidity exposure were observed, caused by degradation in the laquer protection layer. At high temperatures irreversible changes of the lacquer coating can take place which will cause exposure to climatic and atmospheric stress.

For this test prototype thin film resistors were developed using an optimized process technology regarding the deposition of the thin film contact and the curing of lacquer coating.

Test results of these samples showed the suitability of optimized thin film resistors at surface temperatures of up to 175°C for up to 1000h or even 200°C for 100h even with subsequent climatic and thermo-mechanical stress tests after high temperature exposure.

4. Qualification testing

Harsh test conditions have been defined intended to resemble 17 years of operation in a car. 4 different test sequences were applied ranging up to 175°C.

After each test step, a number of devices were taken out of the sequences and characterized in order to investigate the individual contributions to eventual parametric changes. All developed devices were still functional after these test conditions.

5. Outlook

The authors believe, that an extension of the maximum temperature range to 175°C is feasible for a wide spectrum of passive devices. Based on the positive results obtained so far, further improvements of lifetime are expected in the coming future.

Using specific technologies, even 200°C or 225°C operation may be achieved. This is still a challenging target.

6. Acknowledgements

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