This paper describes the reliability approach performs at CNES to evaluate MEMS for space application. After an introduction and a detailed state of the art on the space requirements and on the use of MEMS for space, different approaches for taking into account MEMS in the qualification phases are presented. CNES proposes improvement to these approaches in term of failure mechanisms identification. Our approach is based on a design and test phase deeply linked with a technology study. This workflow is illustrated with an example: the case of a variable capacitance processed with MUMPS process is presented.

Key words: Space, reliability, qualification, failure analysis, failure mechanisms, expertise

1. Introduction

At CNES, Quality Expertise division is in charge of support for space programs and CNES R&D activities. The covered fields are basically EEE parts, materials, mechanics and radiation effects.

Recently, MEMS showed a tremendous potential for space applications, especially for faraway expeditions and instruments with new featured functions or improved accuracy. In order to provide support in reliability and qualification issues, the Quality Expertise division developed expertise techniques and methods to analyze and qualify these new devices.

With MEMS, the quality insurance cannot be done following usual schema used for the qualification of COTS and dedicated products produced only for space applications (optical detectors, hardened memories, etc.). The main reason is because micro and nano fabricated devices use new physical phenomena and lead to a panel of new failure mechanisms that has to be addressed by the quality engineer.

We based our approach on a tight relationship between conception activities, missions needs and micro characterization of technologies and materials.

Due to the multiplicity of MEMS technologies, the main challenge is to get technological data concerning reliability in parallel of the product development. To perform the collection of these data, test vehicles are designed on different processes in order to compare reliability and to discriminate between failures coming from design and from process.

2. State of the art

2.1. Space requirements

Components and/or equipment designed for space applications i.e. HIREL applications are characterized by:

- a long design phase,
- a Hugh qualification phase,
- a short operating time (hours) at ground before launch,
- a variable operating time (up to 15 years) in orbit where no reparation is possible.

In the case of components and/or equipment used in space application but not especially designed for space, let us call them COTS, the qualification phase could be as important as for HIREL and operating time in orbit is of course the same.

In others words, and to simplify, components and/or equipment used in space system are characterized by a phase (qualification phase) during which the degree of confidence in term of quality and reliability must be proven. Of course this qualification phase does exist in other industrial area but the confidence is obtained also in the other phases: design, pre production…
The qualification phase includes (but is not limited to):
- radiation test,
- temperature cycling (at equipment and system level),
- vibration (at equipment and system level),
- shocks ….

2.2. **MEMS in space systems [1,2,3]**

Space design activities are rather conservative. Nevertheless new technologies are always welcome if they bring new performances and gain in term of mass, volume and cost. This is exactly what MEMS claim to do.

MEMS for space applications are introduced at 3 levels:
- component level: the typical example is given in figure 1: a microswitch could be used to replace a classical one. It can be demonstrated that a microswitch can easily replace PIN diodes for RF switching
- equipment level: microtechnologies are used to reduce the size of equipment. An example is given in figure 2: it is an earth sensor based on thermopile effect. The central area is made up with micromachining Si and data treatment circuits are directly mounted on the Si substrate around the micromachining cross.
- Satellite level. Some technological missions have been (or will be) launched in order to demonstrate the capability of such new technology. However today, there is no operational satellite with subsystem made up with MEMS.

In the past ten years the space business moved from an HIREL policy to a COTS policy and recently moved back to a mix policy between HIREL and COTS. In between MEMS technology and MEMS components have been emerged but their ratio risk/gain is still rather high. The use of COTS (Component and equipment) in space system is much better for this ratio. Therefore the introduction of MEMS is delayed because of the step achieved by COTS. A typical example is given by [4]. A standard TX/RX including power supply used in conventional satellite (developed before 1995) is about 4 Kg/4W @ 2GHz. The same equipment (see figure 3) with a massive use of COTS (therefore with up to date components) and also having a good confidence level regarding reliability is about 1kg/1w @ 2GHz. In this type of equipment the add of MEMS, a microswitch for example, will not increase the integration but surely decrease the reliability!
2.3. Quality approach for MEMS

Quality approach for MEMS, as it is done for the conventional element, can be applied at 3 different levels:

- **Technology level:** in this case, MEMS are considered as a set of elementary building blocks issued of a specific technology. Each building block or family of building block is studied under the reliability point of view. Then, all MEMS made with these elementary blocks can be considered as qualified. This type of philosophy is used in microelectronics for ASIC (Application Specific Integrated Circuit).

- **Component level:** the component is seen as a black box without regarding especially the basic technology. All the evaluation/qualification tests are performed without knowing the failure mechanisms physic: the assumption is made that tests are relevant and could highlight potential weakness.

- **Equipment/system level:** the philosophy used is the same described at component level but due to the heterogeneous structure of equipment or system, a component qualification must be previously done.

A new method, originally developed for electronic by CALCE Laboratories at the University of Maryland has been proposed by [5] and [6]. This approach is called deterministic: it is based on a global simulation of the component and system in order to access the reliability level. This method is very attractive but is still under development.

2.4. Improvement needed

By experiment (lesson learned) two types of improvement have been identified:

- **failure mechanisms identification.** This is the most important point. During qualification phase the assumption is made that tests performed are relevant against weakness of the technology. But without failure mechanisms knowledge it is impossible to conclude concerning the intrinsic reliability. Making "classical" qualification tests only show that the mission profile is covered but no screening is done on MEMS technology. This improvement and the methodology associated is presented in the following sections.

- **Impact of standard Qualification test.** The purpose of this on going study is to determine the validity of standard test on MEMS technologies. MEMS technologies are classified as proposed by SANDIA [7] and for each category the impact of standard test is analyzed.

3. CNES Approach

Following the state of the art presented in the previous paragraphs CNES and especially the expertise lab has developed a quality policy in order to give an operational support to space projects. Nowadays introduction of MEMS in our business is done at the component or at the subsystem level. Our approach is based on the following scheme (modified from [7]):
Generally design and test (qualification) phases are rather separated: the design engineer does the best to fit the specification and uses state of the art techniques in term of reliability. When the design is achieved the test team proceeds with all qualification tests. If a failure occurs, the technology or expertise team performs failure analysis and the design could be modified if needed.

In our approach, the first work is not performed by the designer but by the technology team: designer and analyst have to perform a technology analysis in order to identify weakness of the target technology: intrinsic weakness, non documented parameters, parameter drift, failure mechanisms, failure mode for a given design... This first test is generally performed through test vehicles.

After that the first prototype design is done and the previous obtained data are compared or completed for the target design. An analysis is also performed on the prototype to confirm all the data obtained previously.

In parallel the test team defines relevant qualification test taking into account the mission profile (if given) and the failure mechanisms (and/or identified weakness) obtained during technology and prototype analysis.

The following paragraph illustrated this approach on a real case.

4. A case study

4.1. Target object

Variable capacitance is a big challenge that has many applications: mobile RF system, tuning... [8],[9] describe devices designed and processed. The study performed at CNES lab was to design such a variable capacitance, to determine reachable performances and of course evaluate the suitability for space applications.

During the design phase the main concern was to identify a possible target technology to process the prototypes. The choice has been done on the MUMPS process form CRONOS. This MPW offers turn key library (through MEMSCAP design tools), low cost prototyping and reasonable delivery time. The flexibility of the MUMPS solution must be highlighted. Nevertheless standard MUMPS process could not be considered as a base line for a future solution.

Therefore we had to perform a deep technology study to compare the MUMPS process with the state of the art and more precisely with the foreseen technology for mass production.

4.2. Technology study

CNES has developed a set of test vehicles in order to perform technology evaluation. This set of test vehicles has been used in the frame of this technology study.

The study has been divided into different phases:
- MUMPS technology analysis (see figure 4),
- parameter extraction in order to compare the data given by CRONOS and /or to get new type of data (see figure 5),
- specific study on identified potential problems (see figure 6).
Main conclusions of the technology study are:
- MUMPS process is suitable for the intended design,
- Hugh variation could append on layer thickness,
- Residual stress is low but does exist and is difficult to control.
Therefore the design must try to turn around the potential problem induced by the analysis conclusion.

4.3. Capacitance design #1

The capacitance has been designed using Mentor CAD and MEMSCAP Design Tools.
The designed capacitance is made up with a POLY 1 membrane suspended on a POLY0 electrode by 4 arms. If an electrical potential is applied between the 2 POLY layers the gap between the 2 electrode decreases and the capacitance increases.
An optical observation of the obtained prototype is shown on figure 7. To avoid an electrical breakdown the gap between the 2 electrodes must be controlled. On the over hand, this type of design is fully transportable to another technology and is not sensitive to residual stress.
4.4. **Electrical characterization (capacitance #1)**

Results of the electrical characterization are summarized on the figure 8. Under electrostatic actuation the top electrode is attracted to the bottom but at 33% of the allowed displacement, the top electrode is suddenly stuck to the bottom one with an electrical breakdown.

![Figure 8: Electrical characterization](image)

The obtained results show that the design is functional but this type of capacitance gives poor results: the capacitance variation is around 5%. The error on the capacitance value (mean value) is also around 5%.

4.5. **New Design (capacitance #2)**

The purpose of this new design is to improve the functional behavior and to dissociate control electrode and capacitor electrode. In order to improve the conductivity a gold layer has been processed on the top electrode. The prototype obtained is showed on figure 9.

![Figure 9: Variable capacitance #2](image)

Coarse electrical characterization confirmed the better behavior in terms of electrical breakdown but the actuation voltage and the nominal value of the capacitance is slightly different from one prototype to another one. These differences could be explained with the presence of residual stress.
4.6. **Technology/failure analysis of design #2**

In order to confirm a problem of residual stress, a FIB cut has been performed to verify the layers and gap thickness. The result is shown on figure 10.

![Figure 10: FIB cut to verify layer thickness](image)

A 3D imaging (figure 11 and figure 12) has been also performed and the residual stress is highlighted.

![Figure 11: 3D imaging](image)

![Figure 12: Residual stress parameter extraction](image)

5. Conclusion
The approach is today applied at CNES by the expertise division in order to give operational support to space project using MEMS as shown in the example: a variable capacitance. Of course, to simplify, only the prototype phase and the main steps have been presented. The approach is not based on a new theory but only on know how acquired on real cases... and on a number of failure analysis.
The main corner stone is the use of test vehicle to characterize the technology and to foreseen as soon as possible the possible weakness of the target technology.
For economic reasons the evaluation of the technology must be optimized. Test vehicle set could be for example normalized, processed by the technology provider and results and/or dies delivered to users.
Reliability and characterization is the main concern for MEMS and the use of a normalized set of test vehicle is a solution to speed up the improvement of MEMS products.

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