# Evaluation of Process Reliability with Micromechanical Test Structures

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**Abstract**

The work presented in this paper concerns the evaluation of process reliability by the development of a general set of test structures, associated test and analysis methods. The MEMS test structures aim at four objectives : estimation of technological parameters as thickness of process layers, calculation of mechanical parameters as adhesion force and intrinsic stresses and measurement of relative humidity in packages. Experimental results can be used to support industry to assess the quality of their process on their production line and to enable systems engineers to incorporate MEMS into their designs with a high degree of confidence in their reliability.

## 1. Introduction

The miniaturization took an important place in space projects the last few years and gave rise to a generation of micro-satellites based on optimization of existing equipment. In fact, with the emergence of micro-technologies, integration of multi-functional systems (electronic, mechanical, magnetic, optical, chemical...) on silicon brings new perspectives of size , weight and cost reduction. Such micro-technologies make possible the realization of a new generation of few kg satellites. It will offer more frequent access to space, making missions better, faster and cheaper.

However, even if important progress has been realised these last years concerning design and fabrication of MEMS, there is a serious debate within the MEMS community about the material properties of thin films. Some MEMS devices are composed of metals or "metal composites" which can suffer from large deformations. Accurate knowledge of mechanical property data is essential for realistic predictions of performance and long-term reliability of MEMS devices. As the nature of the process limits the thickness of a film to a few microns, preparation and test of such thin specimens become more difficult. The consequence is the need of test structures for measuring thin film properties and making a reliable database.

Test structures are sensors who respond to the environment they are exposed to. They derive from a standard library of device elements including cantilever beams, membranes and other structures commonly used in MEMS technology. Some test structures have already been designed and studied for this purpose : we can note cantilever microbeams [1], microbridges[2], bent-beam strain-sensors[3], micro strain-gauges[4], pointers[5] and Guckel suspended microrings[6] for the evaluation of stresses that fall into three basic categories : stress gradient, compressive stress and tensile stress.

At CNES, we have developed a general set of test structures, associated tests and analysis methods to measure some geometrical and mechanical properties. The first part of the paper describes the test vehicles with emphasis on test structures principle and application. In the second part, experimental results from test vehicles developed by CRONOS/ MEMSCAP MPW foundry are detailed.

## 2. Test vehicles

In order to get experimental access to technological parameters (thicknesses, step, Young's modulus, ...), intrinsic stresses (stress gradient, compressive stress and tensile stress) and humidity in packages, six standard test structures have been designed and fabricated. The knowledge of these parameters is the first step to determine the possible weaknesses of a product, to understand MEMS reliability and failure mechanisms and to improve the reliability of a final object.

### *Thickness verification*

The thickness of the different layers is an important parameter for the functionality and the reliability of the final device. In consequence, a little variation of the thickness would lead for example, to modifications of stress distributions, adhesion forces or actuation voltages.

The aim of the first structure is to make a comparison between designed and fabricated layers. It will also contribute to increase the accuracy of the stress estimation by providing the actual thickness values for the other test structures. This test pattern is composed of a stack of all the process layers (see figure 1). The analysis consists in cutting a part of the stack with a FIB[7] and in measuring inside the created cavity the thickness of each layer with scanning electron microscope (SEM). Then, a comparison with theoretical values is realized for each layer.

Fig. 1. Test structure for thickness verification.

### *Adhesion Strength*

A bad adhesion between two layers can lead to reliability problems like premature fatigue or fracture. The objective of the second test structure is to evaluate the adhesion strength between two successive layers by scratch testing. The test structure is composed of six stacks (see figure 2).

Scratch test is an expedient technique using a nanoindentor, for comparatively evaluating the adhesion strength between two layers[8,9,10]. It consists in displacing a sample at constant velocity under a stylus, which applies a continuously increasing normal load to the coating surface. With increasing load, the coating/substrate generates stresses. At a given load named critical load, the stresses result in permanent damage as stripping of the coating. In order to enable this test, at least 700µm long and 150µm wide, each stack must be.

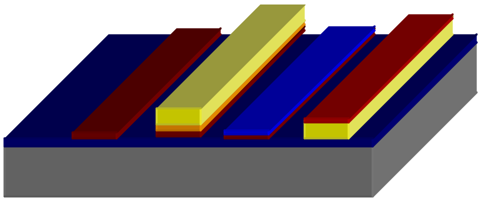


Fig. 2. Test structure for adhesion strength determinatiuon

### *Gradient Stress*

The stress gradient $\Delta\sigma$ in a cantilever is the non-uniformity of stress over thickness. A prediction of the stress gradient can be done with cantilever structure. In fact, the stress gradient causes a moment and consequently a maximum deflection of[11] :

$$\boxed{\Delta s = \frac{2zE}{L^2}}$$

with L the length of the cantilever, E the Young's modulus and z the cantilever deflection which can be measured with an optical profilometer. This test structure is composed of cantilevers of different lengths (see figure 3).

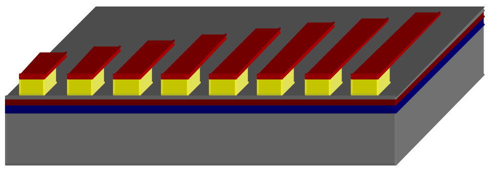


Fig. 3. Test structure for stress gradient evaluation

### *Compressive Stress*

Compressive stress can be detected with bridge networks. When the temperature changes during fabrication process, the bridges dilate or contract and they bend downward or upward. Under a critical load defined by[2] :

$$F_{crit} = \frac{p^2.E.I}{(0,5L_{crit})^2}$$

the stress reaches a critical value, named critical stress, and the bridge becomes flat. This test structure is composed of bridges of different length (see figure 4). The procedure consists in detecting the flat bridge with an optical microscope and a profilometer and to calculate then the critical load. Thus, the compressive stress is calculated by :

$$e_c = \frac{F_c}{EA}$$

with A the cross sectional area of the bridge.

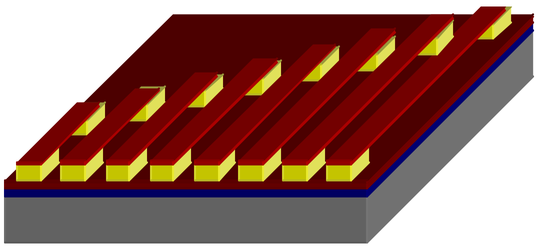


Fig. 4. Test structure for compressive stress detection

### *Tensile Stress*

The Guckel ring is a structure composed of a ring with a crossbeam inside. It is dedicated to residual tensile stress detection[12]. The principle is as follows : the release of structure with intrinsic tensile stress

causes the ring contraction and hence the crossbeam compression. The critical load is reached when the crossbeam buckling appears. The critical value of the residual strain required is then given by :

$$e_{crossbeam} = \frac{t^2 p^2}{3.(2R_{crossbeam})^2} \cdot \frac{1}{G}$$

where t, the thickness of the ring, R the length of the crossbeam and G determined by the specific geometry of the ring and the beam structure. Taking into account the process parameters, the critical stress was estimated using ANSYS software. Then a series of Guckel rings with different radii dedicated to tensile stress detection are designed and fabricated (see figure 5).

The procedure consists in detecting the first buckled crossbeam with an optical microscope and a profilometer and to calculate then the tensile stress.

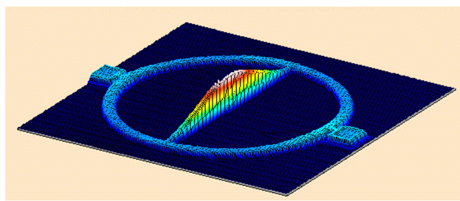


Fig. 5. ANSYS simulation for a Guckel ring

### *Humidity*

The most accurate way to determine the water vapour concentration in a gas is by measuring the dew point. This is the temperature at which water vapour condenses on a solid surface[13,14]. In most cases the method used for determining the dew point is based on the measurement of a surface conductivity sensor leakage current. The proposed test structures are dew point sensors made of interdigited stripes (see figure 6).

A voltage is applied to the terminals and the device leakage current is continuously monitored from hot (or ambient) to cold (-65°C) and back to ambient. Temperatures variation must be slow enough (below 10°C per minute) to detect the spike of current with a sufficient accuracy and in order to have a good thermalisation of the device. The relation between dew point temperature, air temperature and relative humidity can be found in charts or be calculated using few formulas[15].

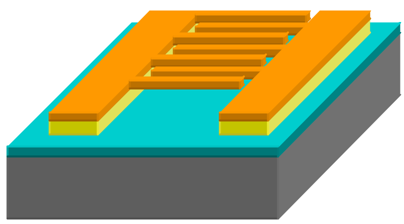


Fig. 6. Test structure for humidity evaluation in a package

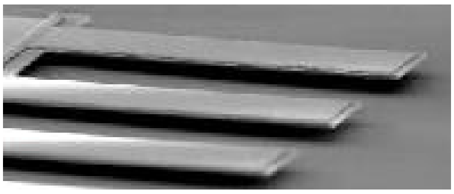
### 3. Experimental Results

In a first step, we have developed presented test vehicles using CRONOS/MEMSCAP MPW foundry. In a second step, we have implemented these vehicles on various technologies to validate them. The transfer from CRONOS/MEMSCAP foundry to a target foundry has been done by redesigning GDS2 files and making minor modifications to take into account specific design rules, available areas for test vehicles and different/specific layers.

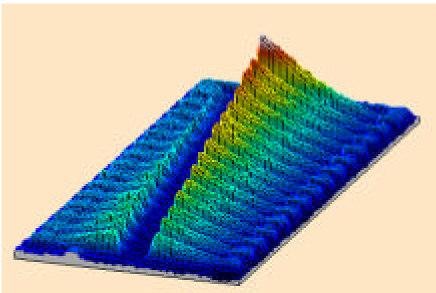
In the cantilevers network, strain relaxation generates bending when structures are released. The measurements made with the optical microscope and profilometer show very high stress gradients (see Figures 7-a and 7-b).

The very important stress gradient will have probably an impact on results of other test structures and on the mechanical behaviour of the structures.

We can note that the Young's Modulus is highly influencing the calculated value of the stress gradient. The typical value given in the literature can be very different from the value measured with nanoindentor. So the stress gradient values must be calculated with some precaution.



(a)



(b)

Fig. 7. Effect of stress gradient on cantilever structures
(a) Optical microscope picture
(b) Optical profilometer picture

For the bridges networks, the effect of the stress gradient lead to a bending of the beam's width (see Figure 8). Nevertheless, for each test structure, we have tried to determine the critical length for which bridge buckles (see Figure 9).

Results obtained for compressive stress are very dispersed. The presence of a stress gradient is probably responsible for this behaviour. As already mentioned for the cantilever network, the compressive stress must be calculated using accurate values for Young's modulus.

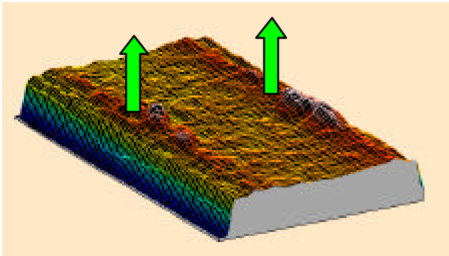


Fig. 8. Effect of stress gradient on bridges

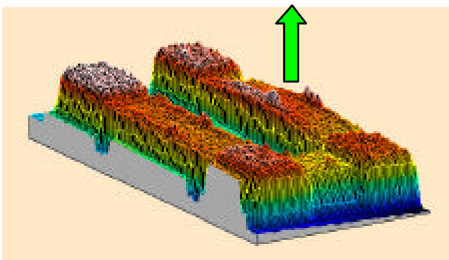


Fig. 9. Comparison between flat (on the left) and buckled bridges (on the right)

For the Guckel rings network, the stress gradient is so important that it affects the flexure of the microrings (see Figure 10). Under these conditions, the tensile stress cannot be measured properly[16].

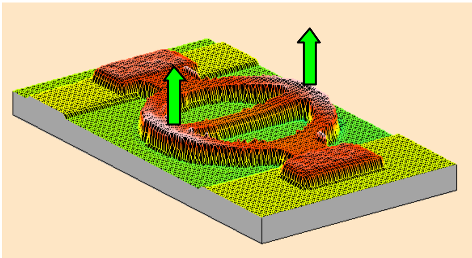


Fig. 10. Effect of a stress gradient on a Guckel ring

For other structures, we have showed that measured thicknesses are in congruence with targeted values (see figure 11). Humidity evaluation in a package and adhesion strength are still under investigation.

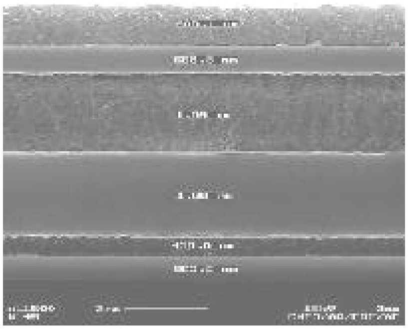


Fig. 11. Measurement of thicknesses

**4. Conclusion**

In this paper, we have presented micromechanical test structures to evaluate process reliability in order to improve the reliability of a final product. Test structures have been presented with focus on application, operating principle and test procedure.

Results concerning intrinsic stresses (stress gradient, compressive stress and tensile stress) and thickness verifications were reported. When a high stress gradient is presented in the cantilevers network, it is very difficult to extract relevant results for other test structures. Test structures developed on CRONOS/ MEMSCAP MPW foundry are easily transferable to various foundries by redesigning GDS2 files and taking into account minor modifications (design rules, areas, layers).

**Aknowledgement**

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