MEMS behavioral simulation: a potential use for Physics of Failure (PoF) modeling

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Abstract — **The reliability of MEMS based systems might be increased by the use of a Physics of Failure (PoF) methodology. This methodology necessitates the development of corresponding models that can be used for reliability evaluation. The model development is based on a good knowledge of effects of environmental influences on the MEMS. For the reliability evaluation of MEMS based systems the used models should be behavioral models. In system simulation behavioral models have a good ratio between simulation time and accuracy. This paper addresses in a first part the PoF methodology and in a second part a case study. The RF switch case study combines the use of environmental tests (temperature variations and irradiation) and modeling tools.**

I. INTRODUCTION

Compared to conventional systems MEMS are more lightweight, smaller and less power consuming. All these qualities make MEMS very promising devices for space applications. However, to be space compatible, they need a robust behavior towards harsh environmental conditions, such as vacuum, temperature cycles, irradiation…. In order to meet with success they have to be reliable under these conditions.

The high integration of MEMS and high unit prizes make it difficult to apply classical test methods to MEMS testing, such as the test of a large number of samples. The evaluation of MEMS reliability might be done by the use of a Physics of Failure (PoF) approach. This approach has been applied to electronic devices and is based on physical laws. Hence it should possible to use it also in MEMS reliability assessment.

In order to be able to evaluate the reliability of a system including MEMS by means of a Physics of Failure approach, it is necessary to dispose of information about the reliability attributes of the MEMS. This knowledge has to be presented in a way that makes it usable for system simulation. This presentation can be done by the creation of behavioral models including environmental aspects of MEMS components.[1]

In the first paragraph of this paper we address the Physics of Failure methodology. The second paragraph consists of a case study: a RF microswitch that has been exposed to temperature changes and irradiation.

II. PHYSICS OF FAILURE METHODOLOGY

In the future the reliability assessment of a MEMS device might be done by the Physics of Failure approach as presented in the following paragraphs:

The MEMS itself (packaging, assembly,…) and the terms of usage are described in the specifications. These data serve as information for the simulation of the development of the MEMS performances in the course of time. A database composed of reliability models and material data provides the basic data that are necessary for the simulation. In order to improve the simulation results, the user adds his own knowledge and experience as well as all other data that might be interesting. The simulation result will be the MEMS reliability phrased in terms of a number of cycles to failure. In this way it is possible to obtain a lifetime assessment for a given mission profile.[2] [3]

By the use of this approach the designer introduces reliability early into the design process. The product design can already be ameliorated at this stage of its development process and thus can be made hardy to environmental stresses. So the final device's reliability can be enhanced, the number of tests can be restricted and the understanding and modeling of failure mechanisms can be facilitated.

In a MEMS the variety of involved physical domains, the high amount of integration, the complexity and the specific packaging create new failure mechanisms that are different from microelectronics ones. Nowadays these MEMS failure mechanisms are not well understood and in a first time it is thus necessary to identify MEMS failure modes, sites and mechanisms and to start the design of corresponding models. These models must describe the environmental influences on the MEMS device and the stresses that are induced by the environment.

The corresponding model development is based on three pillars: material parameters, environmental tests and the chosen modeling approaches.

Material parameters, such as layer thicknesses or Young's modulus might vary in function of the used technological processes. At the same time a precise knowledge of them is necessary to make possible realistic simulation results. Their acquisition is made by conventional technological analysis tools, as for example FIB and SEM, test structures or microcharacterization tools and methods, such as optical profilo/vibrometers.

CNES and MEMSCAP are developing an environmental MEMS Analyzer EMA 3D that is an assembly of an optical profilo/vibrometer and environmental chambers. This tool makes it possible to study MEMS behavior in a variety of different environments (various temperatures, different gazes, various humidity levels, various pressure levels) and has been used to perform our environmental tests.[4]

The modeling can be done by two different approaches: the finite element analysis (FEA) and behavioral models. The finite element analysis approach is very accurate and enables the coupling of different physical domains (thermal, mechanical, fluidic…). On the other hand it is very time and processor consuming. This limits its use to the analysis of MEMS components (e. g. the membrane of a pressure sensor). Behavioral models can be built based on analytical models, FEA interpolations and/or empirical models. These models are less accurate than FEA simulations but they also consume less resources. These properties make them particularly interesting for system level simulations.[5]

In the following paragraph a case study of a RF microswitch is presented. In space applications, temperature changes as well as irradiation are environmental influences that might induce failure. The switch has thus been exposed to two different types of environmental stresses. A behavioral model for the gap variation as a function of the temperature is developed, as well as a first description of the pull-in voltage changes induced by irradiation.

III. RF SWITCH

RF switches are interesting devices for a lot communication applications. During their life cycle they must operate under various environmental conditions. In the following, we will investigate the influence of temperature changes and irradiation on the performances of a RF switch.

A. Technology Description

The used RF switch is a parallel capacitive switch that has been developed by the LAAS-CNRS.[6]

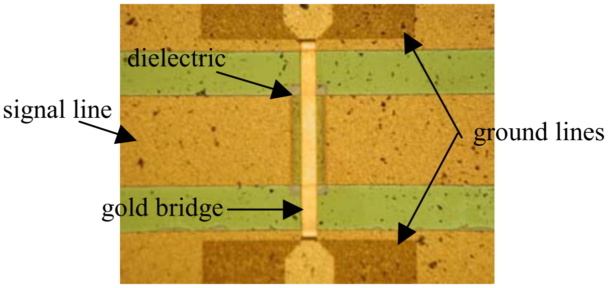

Fig. 1: Photo of the RF switch

In order to fabricate the switch, a silicon substrate is covered with two layers: SiO_2 and Si_xN_y. These two layers will form a membrane after silicon backside etching. The golden signal and ground lines are deposited on the top of the two layers and a small part of the signal line is covered by a dielectric. The gold bridge is deposited by electroplating and released by plasma etch.

B. The Gap Behavior

For various temperatures between 20 and 120 °C the behavior of the gold bridge was observed with an optical profilometer and the gap between bridge and signal line was determined. As it can be seen in Fig. 2 the metallic gold bridge dilates and the gap increases with increasing temperature.

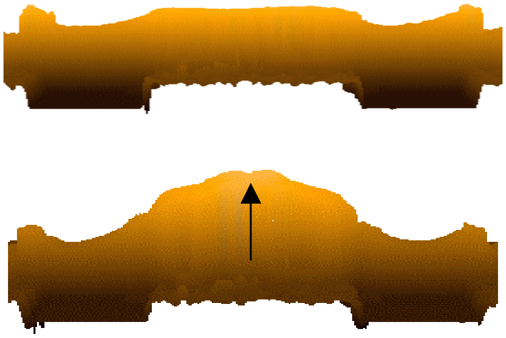

Fig. 2: Static profile of the RF switch (20 & 100°C)

The gap was measured for switches with various geometric properties (different bridge lengths, widths and signal line widths). For all types of switches a linear increase of the gap with temperature was obtained (cf. Fig. 3).

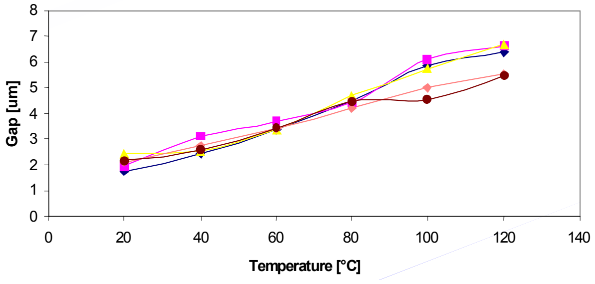

Fig. 3: Influence of gap versus temperature

The temperature-dependent gap increase can be described by an behavioral model based on analytical equations.

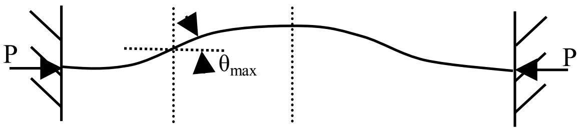

Fig. 4: Buckling fixed-fixed beam

The switch profile is quite complex and thus difficult to model by an analytical approach. Its complexity can be reduced if we consider only the central part of the beam. The behavior of this part with increasing temperature can be modeled by a buckling fixed-fixed beam under thermal stress. The thermal stress is represented by two lateral forces that are applied to the two ends of the beam. The gap is obtained by solving the classical problem of elastica:[7]

$$\frac{d^2\theta}{ds^2} + \frac{P}{EI}\sin\theta = 0 \qquad (1)$$

where s is the coordinate along the deflected beam, E Young's Modulus, I the moment of inertia, P the loading of the beam and θ the deflection angle with respect to the original horizontal axis as represented in Fig. 4. The thermal stress can be related to the temperature changes by a one-dimensional Duhamel-Neumann law:

$$\frac{P}{A} = E\varepsilon - \alpha E(T - T_{ref}) \qquad (2)$$

where ε is the thermal strain, A the cross-sectional area of the beam, α the thermal expansion coefficient of the beam material, T the temperature of the beam and T_{ref} a reference temperature that has been adjusted in function of the residual stresses.

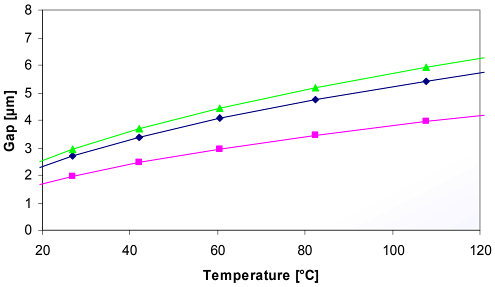

Fig. 5: Gap in function of temperature

As it can be seen in Fig. 5, this quite simplified model already gives us a good agreement with the experimental results. The buckling hypothesis is important to get such large beam deflections.

C. The Pull-in Voltage Behavior

a) Influence of temperature

In the following we consider the influence of temperature on the pull-in voltage. Theoretically, there are two opposite effects acting on the pull-in voltage of the switch. On one hand, the bridge dilates with increasing temperature, the gap increases and thus also the pull-in voltage. On the other hand, the Young's modulus decreases with increasing temperature, therefore the bridge's stiffness and consequently the pull-in voltage decrease. Experimentally we observe a linear increase of the the pull-in and pull-out voltage with increasing temperature (cf. Fig. 6).

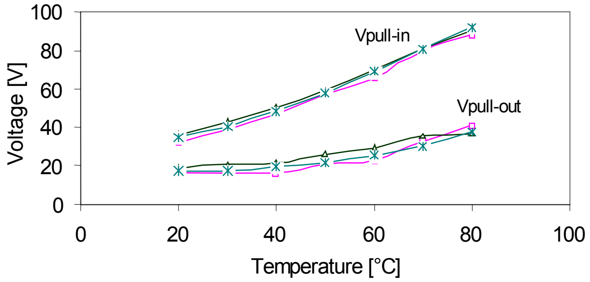

Fig. 6: Actuation voltage drift due to temperature

Beyond 80°C, we observe another phenomenon: the switches now have two actuation voltages. The first one, relatively constant, pulls the switch to signal line border while the bridge center remains buckled (cf. Fig. 7). The bridge only touches the signal line border and the RF signal is disturbed but not interrupted. The second actuation voltage attracts the buckled center to the signal line and interrupts the RF signal.

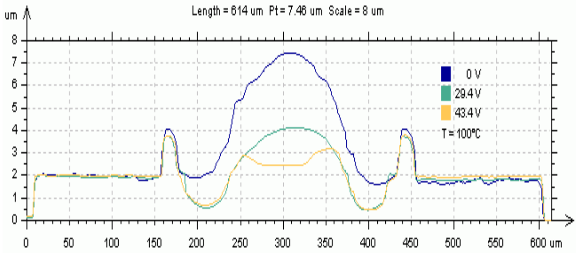

Fig. 7: Double actuation

b) Influence of irradiation

During a space mission a MEMS might be exposed to various types of irradiation. It is therefore important to evaluate the components behavior in such an environment. In the following paragraphs we present some results investigating the influence of irradiation on the performances of the switch. The reported results are preliminary results that will have to be investigated further.

The un-biased switches were exposed to the irradiation of a Co-60 source (dose rate 50 rad/h) and the pull-in voltage was determined at different dose levels.

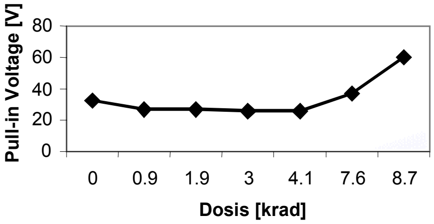

Fig. 8: Actuation voltage drift due to irradiation

As presented in Fig. 8 the pull-in voltage slightly decreases after the first irradiation and increases very sharply at doses above 4 krad. The switch exploded at a dose level of 8.7 krad and a voltage of 60 V.

The increase of the pull-in voltage can be explained by the accumulation of charges in the dielectric. They create a parasitic electric field that superposes the electric field created by the applied actuation voltage.[8] The pull-in voltage shift can be calculated as

$$V_1 = V_0 + \frac{Q_r d^2}{2\varepsilon_{dielectric}} \tag{3}$$

where Q_r is the charge induced in the dielectric, d the thickness of the dielectric and $\varepsilon_{dielectric}$ the dielectric constant.

The increase of the pull-in voltage calculated with this simple model is much smaller than the measured one. This might be due to a charging not only of the dielectric but also of the golden structures of the switch. It is necessary to investigate the Au/Si_3N_4 charge trapping and the influence of the neighbor structures in further studies.

IV. CONCLUSION

The reliability of MEMS becomes more and more important due to their increasing use and maturity. The utilization of a Physics of Failure approach is one possibility to increase the reliability of MEMS based systems. This methodology has been presented in this paper and its application to MEMS has been discussed.

In order to enable the use of this methodology the present day priority must be the identification and understanding of MEMS failure mechanisms. Based on the obtained results, corresponding models have to be evolved. The development of these models is based on three principal pillars: technological characterization, environmental tests and appropriated modeling tools. For the simulation of MEMS based systems behavioral modeling is particularly interesting.

The presented methodology has been used to investigate and model the sensitivity of MEMS to environmental stresses. It also has been applied to a case study: the sensitivity of a RF switch to temperature changes and irradiation.

As the experimental results show, the RF switch gap (between signal line and bridge) increases with temperature. Due to this elevation the pull-in voltage also increases significantly in function of temperature. The gap increase has been described by a simplified model that can be incorporated into system simulations. Irradiation also seems to increase the pull-in voltage but further studies are necessary to confirm these first results.

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