# An Original Methodology to Assess Fatigue Behavior in RF MEMS Devices

O. Millet[1)], P. Bertrand[2)], B. Legrand[2)], D. Collard[2,3)], L. Buchaillot[2)]

[1)] DELFMEMS
IEMN, Avenue Poincaré, Cité Scientifique, 59652, Villeneuve d'Ascq, France
[2)] IEMN, Silicon Microsystems Group
Institute of Electronic, Microelectronic and Nanotechnologies, UMR CNRS 8520
Dept. ISEN, Avenue Poincaré, Cité Scientifique, 59652, Villeneuve d'Ascq, France
[3)] CIRMM / IIS-CNRS
Institute of Industrial Sciences. The University of Tokyo.

olivier.millet@delfmems.com lionel.buchaillot@isen.iemn.univ-lille1.fr

**Abstract __ The analysis of fatigue behavior for polycrystalline gold microbridges is the aim of this paper. A description of the fatigue phenomenon for these elementary structures is presented. It is obtained by combining elementary *in situ* test benches of varying dimensions and cyclic actuation; in the same way, the debugging-time is determined according to the design. Test benches have been developed allowing performing bending fatigue tests of polycrystalline gold structural layers, describing the fatigue phenomenon and obtaining a constant debugging-time, whatever the excitation frequency and the beams length.**

## I. INTRODUCTION

RF MEMS aim at being commercialized. Reliability aspects for this type of device concern stiction problem, mechanical stability, power, non-linear phenomenon, radiation, etc. Concerning mechanical fatigue, one of the final goals is to get a predictive modeling, indicating the evolution of the dynamic system behavior when subjected to high-cyclic actuation in order to determine the debugging-time, the stability phase and the lifetime of devices. It is important to note that cyclic stresses induce material degradation via the generation and motion of dislocations. The fatigue phenomenon has been studied for single-crystal material: the first work on the cyclic fatigue of Si MEMS structures was done by Connally and Brown, showing that cyclic damage processes can appear in this type of structures [1]. Van Arsdell and Brown *et al.* have established that polycrystalline layer undergoes fatigue damage under ambient environment [2]. DeWolf *et al.* have studied stiction/lifetime of RF MEMS switches due to accumulation of charges [3]. Sandia Lab. has worked on the lifetime of multi-levels polysilicon microengines and on the influence of the environment (vibration, humidity, etc.) on the failure probability [4]. Millet *et al.* has studied the fatigue phenomenon for polycrystalline materials [5].

This work aims at showing the debugging-time existence and determining it for polycrystalline gold layers by observing the fatigue phenomenon for elementary actuated microbridges. Most of RF MEMS capacitive switches have actually a clamped-clamped beam topology. So, based on M-Test [6], test benches have been actuated allowing performing bending fatigue tests of polycrystalline gold structural layers, showing the existence of a debugging-time and obtaining a predictive modeling for the debugging-time determination.

This paper presents recent experimental evidence of debugging-time for gold structural layer devices. First, the used *in situ* benches are described. Secondly, FEM analysis of the structures will be presented in order to determine the stress induced during actuation, followed by the fabrication process presentation. After the characterization methods and the experimental results of the fatigue tests are presented. Afterwards, the determination of the predictive modeling is explained. Finally, the built predictive modeling is experimentally validated.

## II. PRINCIPLE

In the case of RF MEMS capacitive switches, bending solicitation is preponderant. So, to quantify the fatigue phenomenon in dynamic mode, it appears interesting to analyze the evolution of properties (stiffness, etc.) of microbridges, which are submitted to a bending stress due to upward and downward movements, *vs.* the number of operations. M-Test benches are suitable as *in situ* test benches for fatigue test for several reasons [6] : bending tests induce large displacements but require small force as M-Test structures already studied and the test procedures of this type of devices have already been setup, like pull-in voltage measurement.

The specific structure which is studied here consists in clamped-clamped beams with a buried electrode placed underneath the mechanical layer. The principle of the designed benches is that under electrostatic forces action, the free plate achieves out-of-plane displacements. During fatigue tests, the structure is then submitted to a cyclic actuation and is characterized every *n* cycle. The gap movable plate/fixed electrode is 2 µm. The structure is 50 µm in width (*w*), its length (*L*) ranges from 200 µm to 500 µm by step of 50 µm and its thickness (*t*) is 0.6 µm.

## III. FABRICATION

The fabrication process of the used test benches is based on surface micromachining and requires two levels (buried electrode, structural layer). The structural materials of the devices are gold.

A 0.35 µm Plasma Enhanced Chemical Vapor Deposition (PECVD) oxide is deposited followed by the evaporation of Titanium (0,1 µm) and Gold (0,25 µm). After electrode patterning, the metallic bilayer is covered by a PECVD $Si_3N_4$ layer at 200°C. A 2 µm PMGI photoresist was deposited followed by the etching of bushing and contact. Aluminum mask (0,1 µm) was used during contact etching. A 0,6 µm gold was sputtered. The structural pattern was defined by chemical etching (KI wet etching). Finally, the structure has been released using $O_2$ RIE and EBRPG etching.

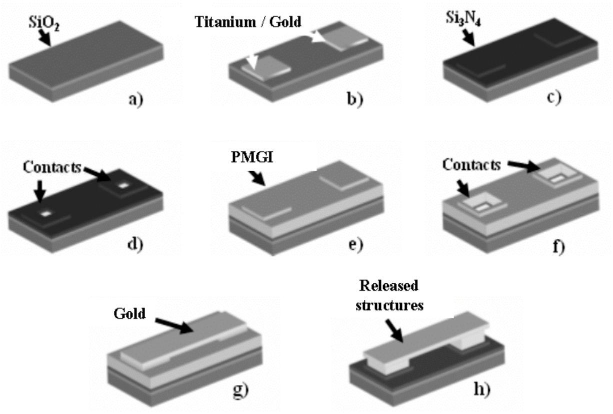

Fig. 1: Thin film surface micromachining of gold structures with one structural layer.

## IV. TESTING

### A. Modeling

CoventorWare™ has been used to analyze the systems; via Finite Element Method (FEM), the natural frequencies of the structures have been found. Moreover, simulations have allowed the determination of the actuation voltages and the level of applied stress during actuation of the structure (Figure 2).

### B. Measurements

Scanning Electron Microscopy (SEM) picture of gold microbridges is shown in Figure (3). It has been determined by interferometer measurements resonant frequencies and the fact that the movable structural parts have a negligible stress gradient (that is, no buckling or bending of the microbridges). Finally, a SEM picture reveals nano-scale structure with an average grain size of about 0.1-0.2 µm (see Fig. 3)

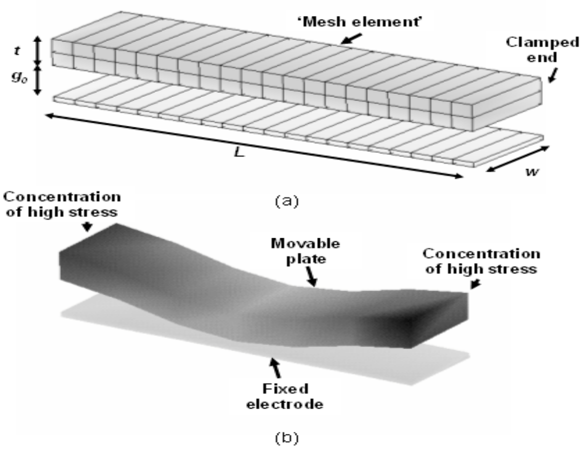

Fig. 2: a) Meshed structure consisted in (10 µm, 30 µm, 0.3 µm) brick elements on Coventorware™. (b) Picture of the simulated structure in pull-in configuration, with the concentration of high stresses in the vicinity of the clamped ends.

Next, cyclic electrostatic actuation has been performed in air environment (RH 65%, 27°C); electromechanical determination -pull-in voltage measurement- has been used to characterize the stiffness of the tested beams (Figure 4), verifications have been performed with mechanical stiffness measurements (Atomic Force Microscope) and resonant frequency measurements. A buried electrode is underneath the microbridge and a direct visual observation via optical microscopy techniques allows the detection of the pull-in, aided by the buried electrode/microbeam capacitance observation. A slowly voltage ramp is applied between the two electrodes until the pull-in detection. Moreover, electrical resistance variations of the tested structures have been measured during cyclic actuation phase.

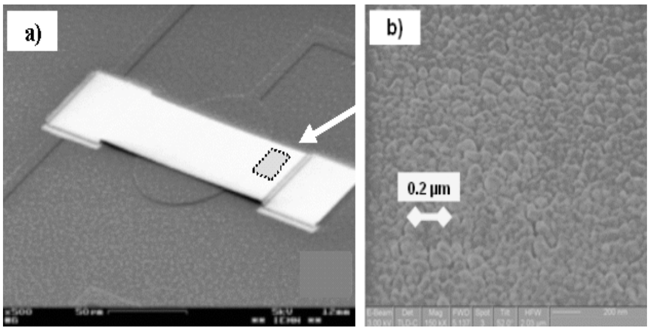

Fig. 3: (a) SEM observation of gold clamped-clamped beams observed with interferometer. (b) SEM picture of the nanoscale Au grains

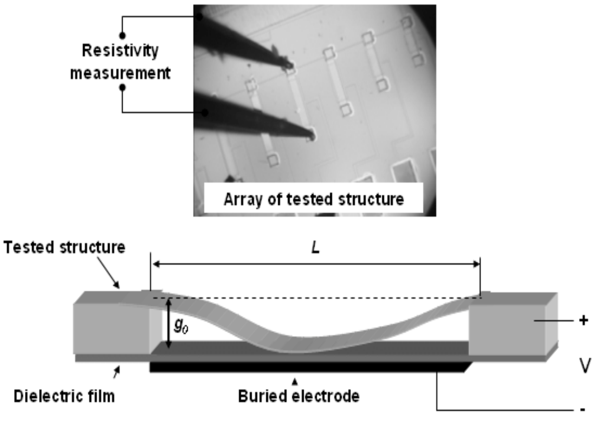

Fig. 4: Pull-in voltage measurement combined to electrical resistance determination

The test procedure for the analysis of the evolution of the stiffness *vs.* the number of operations is: the test benches are initially characterized and are next actuated in the air using an alternative current signal. The actuation voltage corresponds to the last measured pull-in voltage and the excitation frequency is synchronized to the first natural frequency estimated via FEM analysis / resonant frequency measurement. Afterwards, every *n* cycles, the *in situ* benches are characterized, allowing the observation of the evolution of the stiffness *vs.* the number of functioning cycles (Figure 5). Concerning electrical resistance measurements, a low current is applied to result in a very low Joule heating in order to avoid deformation/destruction of the gold layer.

## V. RESULTS

From the experimental results, it can be shown that the fatigue phenomenon can be divided in five different phases (Figure 5, 6) due to several successive failure mechanisms: dislocations in the grain joints (increase of stiffness), microcracks apparition (decrease of stiffness), second increase of the stiffness, second decrease of the stiffness and a stability phase (Figure 6) [7].

At that point, a change from operations number scale to time scale has been realized by normalizing to the resonant frequency of the beams (Figure 5); the time scale is then the time of actuation at the resonance frequency. This modification has allowed observing that stiffness evolutions of all tested beams were stable after a constant time that we define as the debugging-time (Figure 5).

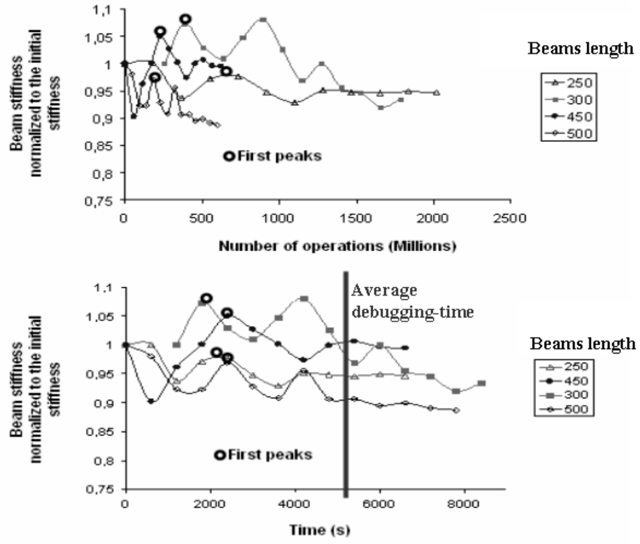

Fig. 5: Conversion from operations number scale to time scale in the case of the evolution of the stiffness of clamped-clamped beams

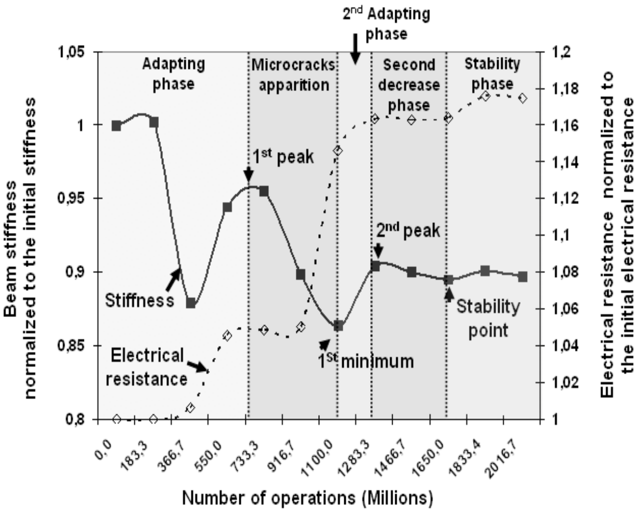

Fig. 6: Evolution of the stiffness and of the electrical resistance vs. the number of operations, in the case of a beam submitted to cyclic actuation and characterized with an electro-mechanical technique (pull-in measurement).

An average of all points' x-coordinates (representing the beginning of the stability phase) has been performed to get an estimate of the debugging-time, based on experimental results obtained with (200, 250, 350, 400, 450) µm length beams (Figure 6). The estimated debugging-time of the tested structural layer is then 5400 seconds for gold structures.

Based on the division of the 'stability point' x-coordinates (Figure 3) by the resonant frequency of a clamped-clamped beam, the debugging-time of a specific polycrystalline structural material determining the beginning of the stiffness stability phase can be established. This prediction has been validated with experimental results (*i.e.* obtained with (300, 500) µm length beams) not included in the first estimation of the debugging-time (Figure 7), the error is 17% (Figure 7). These results show that the debugging-time can be predictable, the total error being less than 12 %. Finally, the built modeling allows predicting when the stability of the beam stiffness occurs; concerning the stiffness value, the modeling only gives qualitative data (decrease during stability is 5-10%).

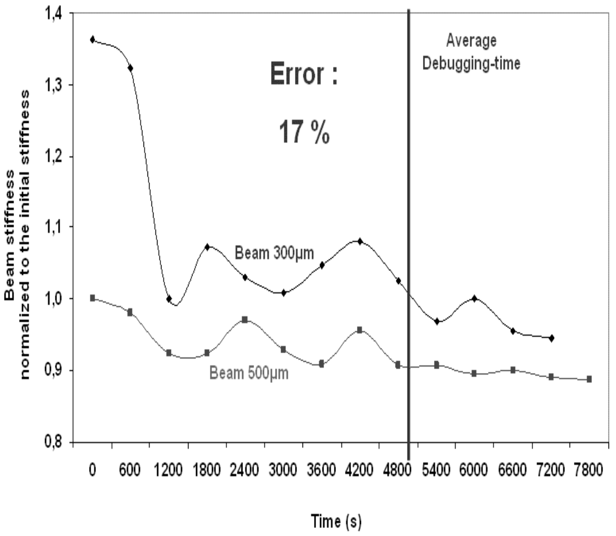

Fig. 7: Comparison between the predictive debugging-time and the experimental results concerning the evolution of the stiffness vs. the number of operations.

Finally, the modeling has been validated with structures that were not excited at the resonant frequency, allowing confirming that the fatigue phenomenon does not depend on the time and on excitation frequency. Thus, no tracking of the resonance frequency was required during cyclic actuation of the structures.

## VI. CONCLUSION

This study presents behavior of gold elementary microbridges, which are submitted to elementary movements (bending), in order to determine fatigue phenomenon for RF MEMS capacitive switches. Test benches have been used to analyze the fatigue phenomenon. It appears that this phenomenon can be divided in four different phases and a stability phase. It has been shown that the debugging-time of the structures can be predicted and is linked to the structural material. This modeling allows predicting the debugging- time of microbridges; it will have to be taken into account to improve the design and reliability of RF switches or electromechanical radiofrequency resonators.

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