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Abstract

This paper presents the work realized on a new RF MEMS design for micro-switch application. This design relies on the separation between the commutation and actuation electrodes for improving the switch lifetime. The design can reduce electrical charging effects during the actuation by preventing a direct contact with the actuation electrode. The proposed structure is optimized by addressing key design points. In our simulation the residual stresses into the bi-layer gold beam is taken into account in order to describe the experimental behaviour of the device. The optimized switch could be an excellent alternative in the search for reliable RF MEMS switches.

Keyword : MEMS, RF switch, actuation, capacitance, dielectric insulation, residual stress.

I- Introduction

In the last decade, tremendous efforts have been invested in the R&D of RF MEMS. Through the world, universities, laboratories and companies have developed RF MEMS based switches, phase shifters, antennas and filters. RF MEMS performances are superior compared to solid states electronic devices from DC to 100 Ghz in terms of power consumption, losses, linearity and Q factor [1]. Today those efforts have permitted the realisation of RF MEMS switches with outstanding performances in some specific conditions: in the literature, more than 100 billion cycles is claimed [2]. The most promessing switch technology seems to be the capacitive switch involving a metallic actuation electrode carrying a dielectric that can, by electrostatic forces attract a close by metallic structure, inducing thus a capacitance variation. Yet reliability issues are still keeping that technology from achieving is full commercial potential [3]. One of the most critical problems is the charging of the integrated dielectric. Ultimately, the accumulated charges can induce erratic device behaviour or permanent adhesion of the moving part on the actuation electrode. So, lot of work including modelling and experimental approaches, is being carried out in order to understand the physics of this dielectric charging mechanism [4,5, 6].

To tackle that issue, our approach relies in the physical separation of the actuation and the commutation electrode carrying the capacitor dielectric. In this way, as oppose to the classical capacitive switch, the dielectric layer won't have to withstand electric field that could reach 1 or 3 MV/cm inducing charging that could lead to device failure during the actuation cycles. It has been shown that there is an exponential relationship between lifetime and decreasing actuation voltage [7]. But with that approach one challenging problem have to be overcome: one has to ensure a good contact between the dielectric and the moving metallic part in such a way to obtain the maximum capacitance in the switch down state. So, the studying and the modelling of the commutation mechanics become mandatory for designing an optimized structure.

This article presents the study carried out on this new design with separate actuation and commutation electrodes. It first defines the modelling strategy. Then it deals with the initial deflection due to the residual stresses of the beam. The impact of the MEMS geometry on the beam rigidity and the needed electrical forces is finally discussed

II- Design description

The device is design according to the following key points: The theoretical capacitance is set to 3.6pF imposing a 250*100 µm^2 commutation electrode surface with a 0.4µm thick dielectric (SiNx). The other geometrical parameters are defined in order to obtain an initial commutation around 25V and a maximum stable capacitance around 40V. The relevant parameters are:

- the length of the beam **L**,
- the thickness of the beam **h**,
- the initial air gap between dielectric and beam **d**,
- the width of the beam **b**, which is imposed to 300µm (the commutation electrode width is 100µm).
- The beam built in stress

These parameters are shown in the figure 1.

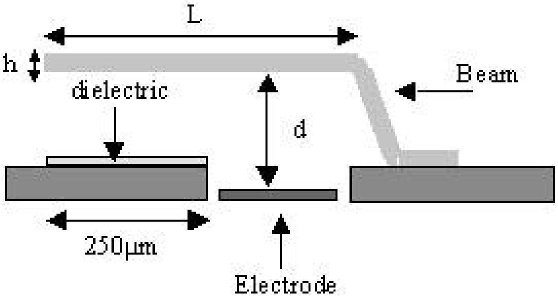

Figure 1: Design geometry

The realized beam structure is a bi-layer cantilever comprising a thin evaporated "seed layer" and a thick electro-deposited layer. The cantilever beam has been chosen as oppose to bridge because it less prone to buckling due to dilation. To ensure that the free end of the cantilever will contact the commutation electrode in a planar way, the actuation electrode is prolonged on both side of the commutation electrode. Thus the quality of the contact is improved as well as capacitance value. This improvement is shown in the figure 3.

For the simulation of device actuation and commutation Ansys software [8] has been used. This software provides implementation of APDL encoded law. To represent the actuation of the MEMS, EPSILON has developed a specific encoding of the electrostatic law defined by the formulae:

$$F_{elec} = \frac{S e_0 e_{r1}^2}{2} \frac{V^2}{(d_{r1} + e_{r1} d_0)^2}$$

F_{elec}: electrical force (N) S: electrode area (m²) V: voltage (V) e_0 : vacuum permittivity (F/m)	e_{r1} : dielectric constant d_0 : air gap between dielectric and beam (m) d_{r1} : dielectric thickness (m)

The encoded law allows a very good convergence of the displacement during actuation, which is the major difficulty in actuation simulation.
The FEM model is reduced to a half model due to the axial symmetry. Top and bottom views of the design obtained with a symmetrical expansion are shown in figure 2 and 3.

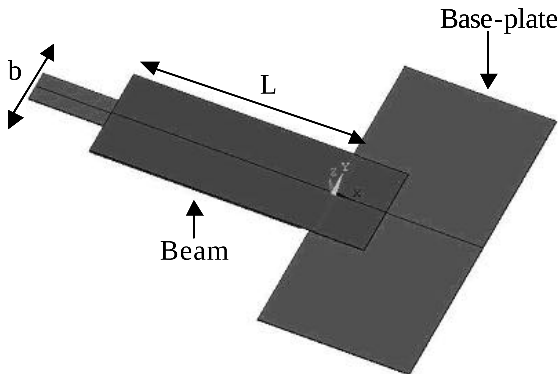

Figure 2: Design top view

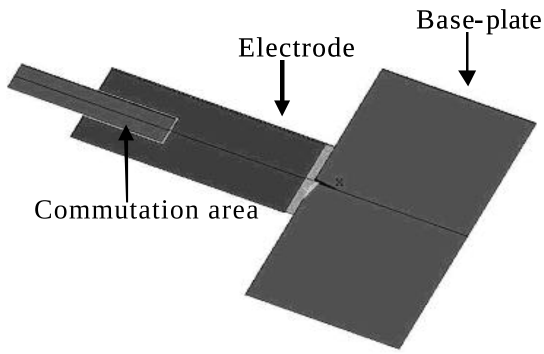

Figure 3: Design bottom view

The design takes into account the separation of the actuation and commutation areas. The gap between the two electrodes is set to 10µm for avoid edge effect with ESD.

III- Initial deflection

The initial deflection is a very important parameter because it defines the initial average gap between the actuation electrode and the cantilever. It defines the electrostatic force required to initiate the actuation. The initial deflection of the cantilever is due to the built in stress generated during the process between the gold layers of the structure. It can be represented as depicted in figure 4.

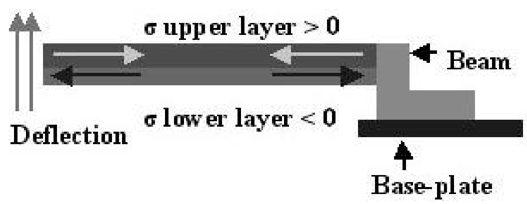

Figure 4: Deflection dues to bi-layer stresses in the beam

The simulation demonstrate~~d~~ that beams with deflection higher than 10µm are deficient because of the force required for actuation becomes too high. Indeed the actuation forces have a quadratic variation with the cantilever air gap. However a slightly initial deflection (around 7µm) allows a better actuation of the beam because this deflection balances the deformation generated during actuation. It generates a better flatness of the contact for commutation.
For the first set of fabricated samples with L=750µm, the built in stress induces an initial upward deflexion around 25 µm of the cantilever tip. To bring that initial tip deflexion below 10 um we have developed a process using low temperature annealing to release the stress in the cantilever. The annealing step is performed, at defined temperature for several hours, before the releasing of the cantilever obtained by sacrificial layer etching. This sacrificial layer uses PMGI polymer. Figure 5 shows the cantilever profile extracted from an optical profilometer scan, before and after annealing.

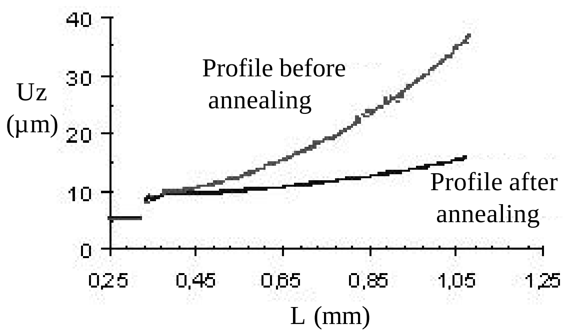

Figure 5: Stress release annealing effect

The cantilever tip deflexion is decreased from about 25 µm to about 7 µm.

IV- Design optimization

First, simulations of RF switch (with separated commutation and actuation electrodes) have been carried out for a structure with a thin and long beam (**h**=3µm; **L**>750µm) and with a 7µm beam initial deflection. The simulations were performed for several voltages, from 0V to 50V, applied between the electrode and the beam. These voltages values are typical for space equipments where MEMS are used. These simulations revealed a lot of critical problems into the device behaviour. A contact between the beam and the actuation electrode has been noticed above 30V. This contact should be avoided. The optimization of the MEMS geometry should also take into account this problem.

The design optimization has two main goals:

- to ensure robustness
- to ensure efficient commutation

The first one is achieved if the contact between the commutation electrode and the beam is avoided.
The second one is achieved if the capacitance value approaches the theoretical maximal value and if this capacitance is very stable along a large voltage range.
To avoid contact between the actuation electrode and the beam, two choices are possible:

- increasing the rigidity of the beam (length reduction or increasing thickness),
- decreasing the actuation force (decrease the electrode area or change the gap wide).

Area reduction becomes rapidly a problem because it enhances the actuation voltage and it decreases the quality of the commutation contact. In fact the area reduction will not bring efficient change to avoid the contact problem without raising another problem (no commutation or too important voltage for commutation). The gap of the cantilever could be efficiently used because of its quadratic influence on the electrostatic force with no impact on the rigidity.
Increase the rigidity is an efficient way to avoid the contact with de actuation electrode. The rigidity of the beam is controlled by:

- its length **L,** which has an impact in $\mathbf{L^3}$**,**
- its thickness **h,** which has an impact in $\mathbf{h^3}$**,**
- its width **b**.

From these parameters only the thickness **h** doesn't influence the electrostatic force (**b** and **L** influence the surface of the electrostatic force).

By increasing the thickness **h** and adjusting **L** and **d** one can increase the rigidity as desired in order to obtain a maximum capacitance value.
Adjusting the length allows the control of the capacitance evolution with the actuation voltage and provides a capacitance variation curve with an interesting profile. Sets of simulations have been performed in order to optimize these parameters. Indeed, as depicted in figure 6 the capacitance is relatively stable between 35V and 45V. This stability aspect is very important because it provides a voltage range, where the capacitance is relatively constant.

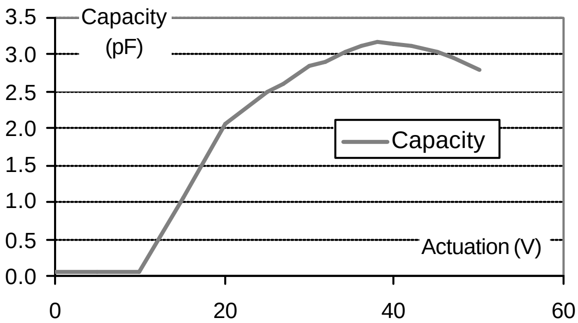

Figure 6 : Capacitance curve, for a maximal theoretical capacitance of 3.6pF

V- Conclusion

The RF switch realized with separated electrodes for the actuation and for capacitance commutation satisfies the targeted criteria of robustness and efficiency. Thanks to geometrical optimization, the MEMS capacitance is very stable for a large range of actuation voltage. The obtained capacitance at closed state is 90% of the theoretical geometric capacitance value, which would have been obtained with a perfect flat capacitance commutation contact.

VI- References

1. **Yao, JJ.** "RF MEMS from a device perspective". *Journal of Micromechanics and Micro-engineering*,. 2000, Vol. 10, pp. R9-R38.

2. **C.L. Goldsmith, D.I. Forehand, Z. Peng, J.C.M. Hwang, I.L. Ebel,.** “High-Cycle Life Testing of RF MEMS Switches”,. *IEEE/MTT-S Int. Microwave Symposium, .* 3-8 June 2007, pp.1805-1808.

3. **J. Bouchaud, H. Wicht,.** “RF MEMS: status of the industry and roadmaps”. *IEEE Radio Frequency integrated Circuits (RFIC) Symposium, Dig.,.* 14 june 2005, pp. 379- 38412.

4. **W.M. van Spengen, R. Puers, R. Mertens, I. De Wolf,.** “A comprehensive model to predict the charging and reliability of capacitive RF MEMS switches” . *Journal of Micromechanics and Microengineering, 14 (2004) pp. 514-521.* 2004, Vol. 14, pp.514-521.

5. **R.W. Herfst, P.G. Steeneken, J. Schmitz,.** “Time and voltage dependence of dielectric charging in RF MEMS capacitive switches” . *proceedings, 45th annual. IEEE int. Reliability physics symposium,.* 15-19 April 2007, pp. 417-421.

6. **X. Yuan, J.C.M. Hwang, D. Forehand, C.L. Goldsmith.** “Modeling and characterization of dielectric-charging effects in RF MEMS capacitive switches”,. *IEEE MTT-S International Microwave Symposium Dig.,.* 2005 , pp. 753-756.

7. **C. Goldsmith, J. Ehmke, A. Malczewski, B. Pillans, S. Ehmke, A. Malczewski, B. Pillans, S. Eshelman, Z. Yao, J. Brank, and M. Eberly.** “Lifetime characterization of capacitive RF MEMS switches”. *IEEE MTT S Int. Dig, 2001 Microwave Symp Dig nepp-nasa,.* 2001, pp. 222-332.

8. **ANSYS et www.ansys.com.**