FEM Electromechanical Modelling of a MEMS Variable Capacitor for RF Applications

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Abstract

Accurate modelling of the electromechanical behaviour of RF-MEMS devices is critical in order to predict their characteristics, and consequently how the design has to be optimized in order to overcome the trade-offs arising when dealing with specifications both in the mechanical and electrical/electromagnetic physical domains. In this work we present a complete approach to the simulation of RF-MEMS devices based on FEM (Finite Element Method) simulations performed in ANSYS^{TM} Multiphysics.

Introduction

MEMS (MicroElectroMechanical-System) technology has recently started to be demonstrated as a valuable enabling technique for the manufacturing of low cost and high performance lumped devices like wide range and high Q-Factor variable capacitors, large isolation and low insertion loss switches and so on [1]. Availability of such basic components is also pushing forward the synthesis of complex MEMS based networks (like for instance impedance matching networks [2], phase shifters and so on) that, if employed within wireless platforms, would lead to significant benefits in terms of reconfigurability and performances [3]. Given these considerations, the accurate modelling of MEMS based structures represents a critical aspect in the design flow of devices and networks employing such a technology. It is also clear that the involvement of transversal disciplines required by the modelling of MEMS (i.e. mechanical, electrical and electromagnetic physical domains) makes impossible the use of software tools traditionally adopted when dealing with CMOS standard technology.

FBK RF-MEMS Technology

The RF MEMS technology available at the Bruno Kessler Foundation (FBK) relies on a surface micromachining process based on gold. High resistivity silicon wafers are employed as substrate and are covered by 1 µm field oxide. High resistivity PolySilicon and TiN/Ti/Al/TiN/Ti multilayer are exploited for the DC biasing of suspended membranes and RF signal lines respectively (see Figure 1) [4]. Both conductive layers are covered by silicon oxide, enabling the realization of metal insulator metal (MIM) capacitors as well as ohmic contact where vias are defined. The surface metallization consists of a 1.8 µm electroplated gold layer and the air-gaps are obtained wherever such a layer is deposited over a 3 µm sacrificial photoresist layer. In order to get stiffer gold membranes, for instance in correspondence with anchors and suspended membranes that are meant not to deform, a second gold metallization (about 3 µm thick) is electroplated over the first one mentioned above. Wherever vias to the multimetal are opened, a thin metal layer (150 nm of gold) is sputtered in order to get a gold to gold contact when the suspended membranes are actuated. Figure 1 reports a schematic cross section of the FBK technology taking as example a cantilever switch.

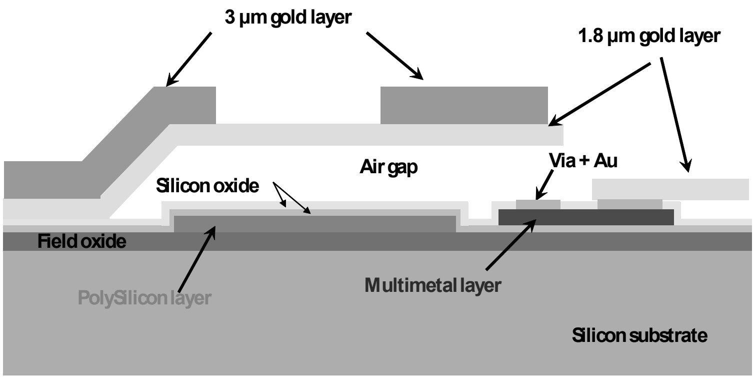

Figure 1. Schematic cross section of the FBK RF-MEMS technology. A cantilever based suspended structures realizes a ohmic micro switch. PolySilicon and multimetal layers are visible together with the two gold metallizations (1.8 µm and 3.0 µm) for the suspended structure.

FBK RF-MEMS Variable Capacitor

In this section an RF-MEMS variable capacitor, based on a central rigid plate kept suspended by four meander structures connected to its corners, is analyzed. The latter ones are based on a meander configuration of flexible beams in order to mitigate the effects of residual stress on the effective stiffness of the suspensions [5]. A schematic of the meander used in this MEMS varactor topology is reported in Figure 2. The thickness of the meander structure is about 1.8 µm while the other dimensions are reported Figure 1. Concerning the central rigid plate, its width and length are 220 µm while the thickness is around 4.8 µm. It has 20 µm side square holes, 5 along the X-axis and 5 along the Y-axis. Moreover, the distance of holes from plate edges is equal to 20 µm. The gap between the plate and the lower electrode is about 2.2 µm. The entire suspended structure is made of gold and is fabricated in FBK technology (described in previous section). A 3D view of the MEMS structure obtained by means of an optical profiling system (Veeco WYKO NT1100 DMEMS system) is shown in Figure 3.

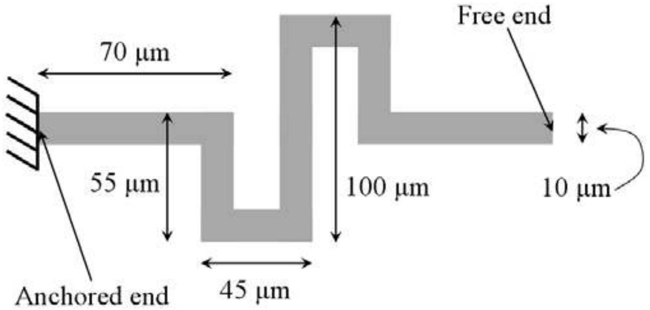

Figure 2. Schematic top-view of the meander flexible structure connected to the four plate corners.

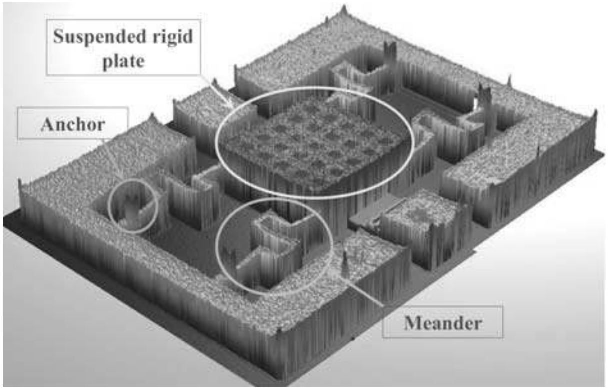

Figure 3. 3D view of the MEMS varactor obtained by means of an optical profiling system.

3D Electromechanical Modelling in ANSYS^{TM}

In this section we show the results of simulations performed in ANSYS^{TM} concerning the variable capacitor described in previous section. In order to reduce computational complexity and simulation time, only a quarter of structures has been analyzed in ANSYS^{TM} by applying suitable symmetry conditions. Such subsection of structure is shown in the variable capacitor layout of Figure 4.

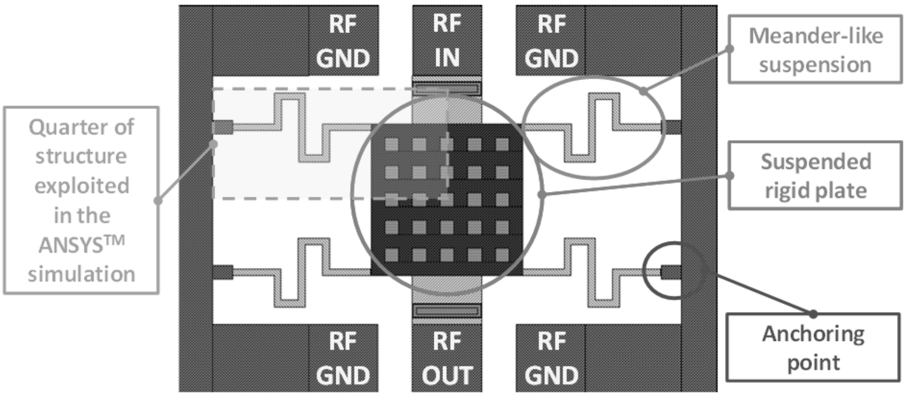

Figure 4. Variable capacitor layout. The quarter of structure exploited in the following simulation is highlighted.

Static Pull-In/Pull-Out Characteristic

The deformed structure after the pull-in is reached (i.e. collapse of the suspended plate onto the substrate) is reported in Figure 5. The static pull-in/-out simulation in ANSYS^{TM} is compared with the quasi-static experimental characteristic (obtained with the profiling system) in Figure 6. The very good agreement of the simulated trace over the experimental one is observable both for the pull in (occurring around 4.8V) and pull out (around 0.6V), validating the simulation methodology proposed in this work.

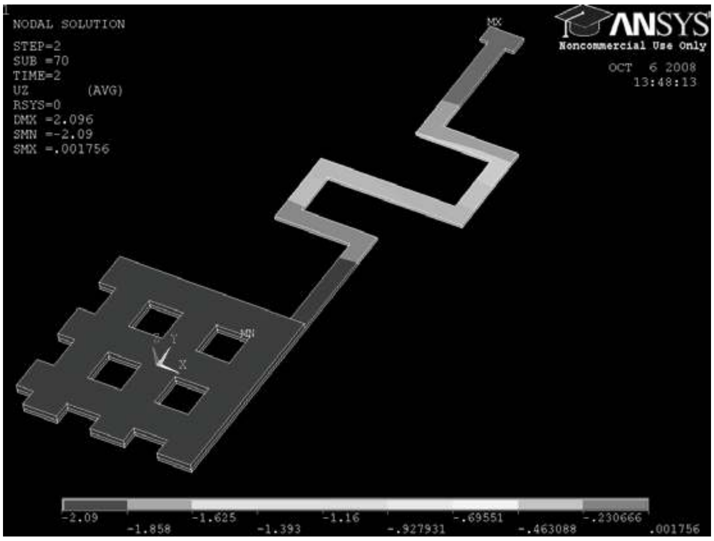

Figure 5. ANSYS^{TM} 3D schematic of the quarter of structure (shown in Figure 4) after the pull in is reached. The colour scale corresponds to the vertical displacement.

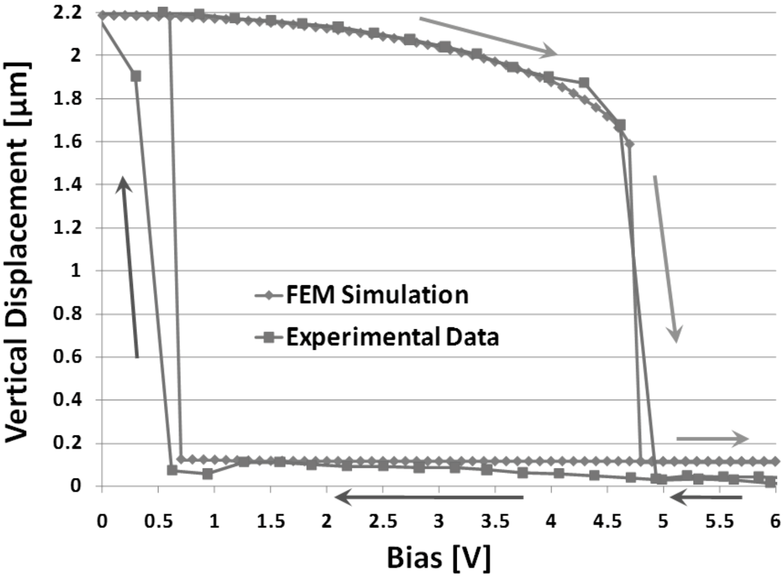

Figure 6. Comparison of the experimental and simulated pull in/pull out characteristic.

Dynamic (Transient) Characteristic

ANSYS^{TM} simulations are now extended in order to include also the dynamic behaviour of the RF-MEMS variable capacitor. The transient analysis includes also the dynamic menchanical behaviour (i.e. inertia) and the friction due to the presence of air around the device in movement (squeeze-film damping) [6]. In ANSYS^{TM} a modal (eigenfrequency) simulation has to be run, prior to the transient one, in order to extract the damping parameters, valid for the desired resonant modes to be excited, that have then to be provided in the time-domain simulation as input [7]. The experimental transient data have been collected exploiting the stroboscopic illuminator of the 3D profiling system. A square voltage with a period of 2.5 msec (400 Hz) is applied to the suspended plate. The voltage is equal to 4 V for 1.25 msec and equal to 0 V in the other half a period (50% duty-cycle). Since the varactor actuation voltage is about 4.8 V (see Figure 6) the plate does not collapse on the substrate during this analysis. The comparison of experimental and simulated data is reported in Figure 7. ANSYS^{TM} output well compares against measurements, especially concerning the activation and relaxation transitions (corresponding to the up and down edges of the square pulse) and the damped overshoots after such transitions. This result corroborates the validation of our approach to modelling of RF-MEMS presented in previous section about static behaviour of the variable capacitor.

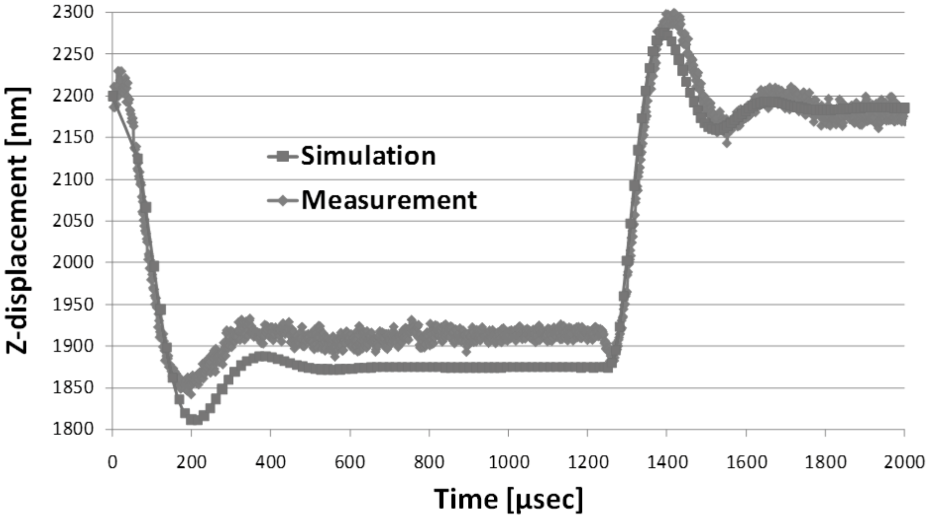

Figure 7. Experimental versus simulated transient response of the MEMS variable capacitor to a voltage square pulse with peak value of 4 V and frequency of 400 Hz.

Modal Analysis in Ansys^{TM}

The presence of internal stresses, also known as intrinsic or residual, in suspended parts of MEMS devices is typical in microsystems manufactured in such technology. Intrinsic stress may be experienced by microstructures without any external applied load or influence from the surrounding environment. Stress gradients are usually induced either during doping and deposition of materials, performed during the fabrication phase, or as a consequence of the packaging step. In the latter case, residual stress gradient mainly acts on the two substrates, the device one and the package, leading to the arching of the whole chip because of different thermal expansion properties associated to the wafers. After removing the samples from a deposition chamber, these cool down from 500 - 800 ^{0}C to room temperature. Due to variations in the thermodynamic characteristics such as thermal expansion, materials characterized by multilayer structures tend to compress with a different rate induced by stress gradients. The intrinsic stress is tensile when deposited material tends to shrink, while it is compressive when the suspended membrane tends to increase its length. Packaging causes the same mechanism of residual stress at wafer-level, as discussed above, and this is the main phenomenon analyzed in this section.

In any case, presence of residual stress, within the suspended MEMS structures, as well as at wafer-level during the packaging step, can be harmful to the normal operation on MEMS devices. For example, a too large amount of compressive or tensile forces may change the geometry of suspended parts making them not anymore operable. On the other hand, not severe amount of residual stresses may cause variations of critical MEMS characteristics as the pull-in voltage, resonant frequency etc. In particular, the latter one allows also to evaluate the presence and the amount of residual stress depending on the resonant frequency shift of the device under test.

To this purpose modal eigenfrequency analysis is performed in ANSYS^{TM}. Let us consider as test structure a fixed-fixed suspended beam with a substrate consisting of two stacked layers used to account for different materials. First of all, it is essential to have a reference set of frequencies and mode shapes with which all further results will be compared. Such information is obtained by determining the vibration characteristics of the described test sample without any intrinsic stress gradient. At this stage any contribution from external excitation or loading is neglected. The results of modal analysis under stress-free conditions are depicted in the left side of Figure 8 concerning the first 3 eigenfrequencies. Then we have changed the properties of the layers laying underneath the bridge by applying different stress-strain distribution within each of them. The upper layer is supposed to have a larger tensile force and as a result the substrate bends, inducing a load on the suspended membrane that becomes stiffer. The modal analysis in this case includes the pre-stress option. It means that the structure is first analysed in terms of static behaviour and then all contribution from calculated residual stress will be considered as input values for the modal solution. The result of the second part of the problem is demonstrated on the right side of Figure 8. The resonance shift is always towards lower frequencies (see Table 1). This is explained with the fact that the substrate ends bend upward (see the schematic to the right of Figure 8), leading to a slight reduction of the distance between the membrane anchoring ends, and consequently to the lowering of the elastic constant associated with the suspended part.

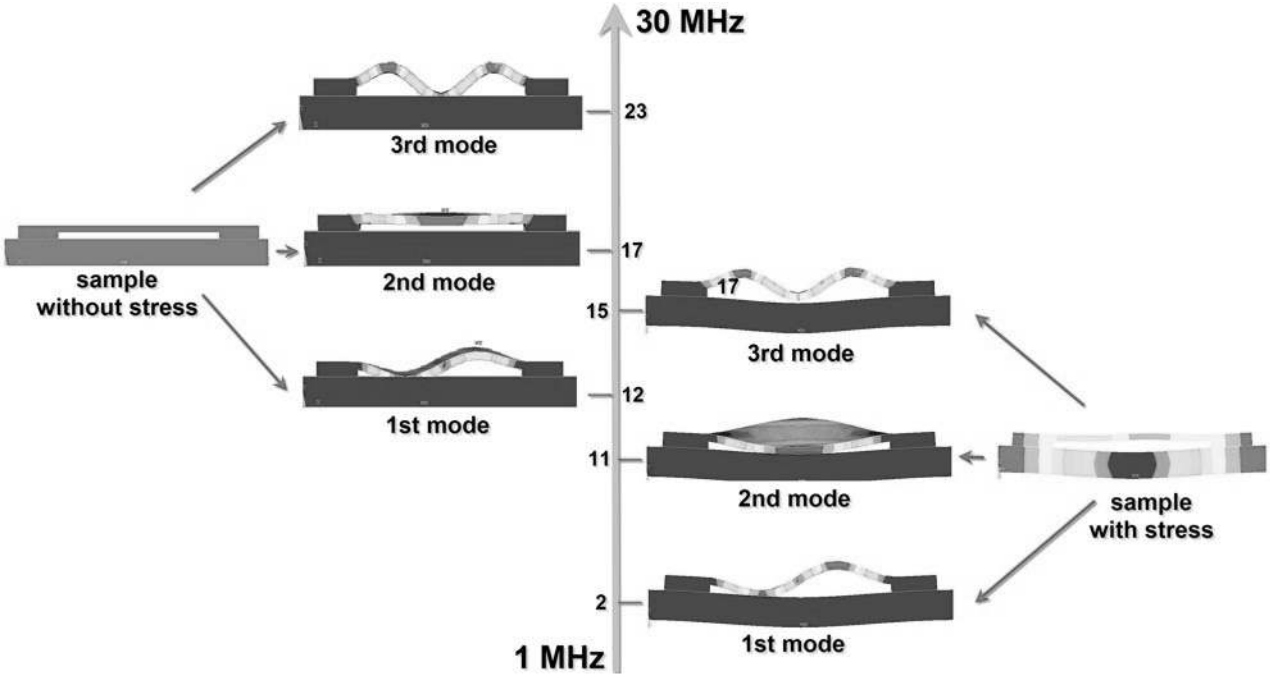

Figure 8. Eigenfrequency shifting of samples without residual stress (left) and with residual stress (right) within the substrate. The colour scale represents the sum of displacement along the XYZ-axes.

Mode	Without stress (MHz)	With stress (MHz)
1	11.914	2.296
2	16.954	10.686
3	23.086	15.371

Table 1. Comparison of the first three resonance modes for a clamped-clamped suspended structure without and with initial stress applied to the substrate (see Figure 8).

Conclusions

In this work we presented our approach for the accurate prediction of the coupled electromechanical behaviour of RF-MEMS devices. The method is based on the employment of a commercial FEM-based (Finite Element Method) tool i.e. ANSYS^{TM} Multiphysics. Validation of simulated data has been carried out by exploiting experimental data collected on a variable capacitor sample realized in FBK RF-MEMS technology. Both the variable capacitor static behaviour (pull-in/pull-out characteristic) and the dynamic behaviour (transient) have been successfully simulated and compared against measurements, showing in all the analyzed cases a very good agreement with experimental data. Additionally, we also described the influence of residual stress within the substrate by means of eigenfrequency analysis. Presence of stress leads to a significant frequency shift of the analyzed mode, and such information can be exploited to assess the amount of residual stress due to high-temperature process steps.

Acknowledgement

The authors would like to thank the ARCES Research Centre of the University of Bologna (ITALY), for providing the instruments exploited for the electromechanical characterization of the variable capacitor discussed in this paper.

References

[1]. L. Dussopt and G.M. Rebeiz, “High-Q millimeter-wave MEMS varactors: extended tuning range and discrete position designs,” Microwave Symposium Digest, 2002 IEEE MTT-S International, Volume: 2, Pages: 1205 1208, ISBN: 0-7803-7239-5.

[2]. M. Bedani, F. Corazza, R. Gaddi, A. Gnudi, B, Margesin and F. Giacomozzi, “A Reconfigurable Impedance Matching Network Employing RF MEMS Switches,” Proceedings of DTIP 2007, Stresa, Italy, 25-27 April 2007.

[3]. Lu Yumin, D. Peroulis, S. Mohammadi, and L.P.B. Katehi, “A MEMS reconfigurable matching network for a class AB amplifier,” Microwave and Wireless Components Letters, IEEE, Oct. 2003, Volume: 13, Issue: 10, Pages: 437 439, ISSN: 1531-1309.

[4]. R. Gaddi, M. Bellei, A. Gnudi, B. Margesin and F. Giacomozzi, “Interdigitated Low-Loss Ohmic RF MEMS Switches,” Proceedings of NSTI 2004 Nanotechnology Conference and Trade Show, Nanotech 2004, Boston, MA, Volume 2, Pages 327 330, 7-11 March 2004.

[5]. Dimitrios Peroulis, Sergio P. Pacheco, Kamal Sarabandi, and Linda P. B. Katehi, “Alleviating the Adverse Effects of Residual Stress in RF MEMS Switches”, Proceedings of European Microwave Conference, London, 24-28 September 2001.

[6]. W.S. Griffin, H.H. Richardson and S. Yamanami, “A study of fluid squeeze-film damping”, Journal of Basic Engineering, Trans. ASME, Pages 451-456, 1966.

[7]. “Modal Projection Method for Squeeze Film Analysis”, Documentation for ANSYS^{TM} Release 11.0.