Variable Capacitance and Pull-in Voltage Analysis of Electrically Actuated Meander-Suspended Superconducting MEMS

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Abstract: Variable capacitors between the fF and pF range are very interesting for high frequency applications like variable filters, resonators, etc. For radio astronomy applications variable capacitors, realized by electrostatically actuated, micromechanical Meanders-suspended bridges (MEMS) made of superconducting Niobium, have been measured to find *C*(*V*). A non plane capacitance behavior have been observed. To analyze these complex electromechanical devices, multiphysics COMSOL simulations of the bridges were performed. The simulations are in agreement with the theoretical approach and the measurements. Finally we can estimate the main electrical features *C*(*V*) and pull-in voltage.

Keywords: Meander-suspended MEMS (Micro ElectroMechanical Systems), Electromechanical COMSOL Simulation, Intrinsic stress gradient, Tunable capacitors.

1. Introduction

Superconducting electronic components are widely used in the field of radio astronomy, because they have low noise and loss performances. Furthermore, in that field, tuneable electronic devices could be widely used in the receiving instrumentation. For instance, notch filter between the antenna and Superconductor-Insulator-Superconductor (SIS) tunnel junction mixer could suppressed the upper or lower side band of heterodyne receivers, which is important for these applications [1-4] (Figure 1).

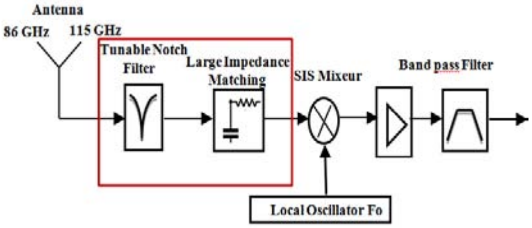

Figure 1. Schematic of heterodyne receiver which employed Notch Filter and Large Impedance Matching based on MEMS.

Tunable capacitances, so-called varactors, represent one important class of tunable circuit elements. They are widely applied in wireless communications or radars, where they act as basic elements for adjusting the operation range of variable filters, phase shifters or transceivers [5]-[6].

New devices manufactured with superconducting materials meet these demands and are well established in this field [7]. Some of these variable devices based on capacitive MEMS were fabricated by the IRAM which realized superconducting suspended microbridges with an electrostatically controlled variable height above an electrode. “ Supra MEMS ” employ superconducting Niobium (Nb) fabrication process in order to be integrated with most of the superconducting circuits and mm-wave detectors [3]-[7]. They are of interest to replace mechanical notch filter used at IRAM [8]-[9].

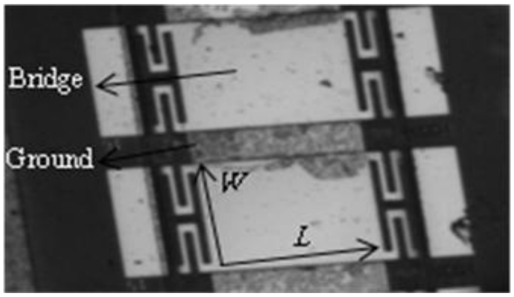

Figure 2. Series of Nb microbridges suspended by meander.

Schicke et al developed a tunable microcapacitor (varactor) made of superconducting Niobium (Figure 2) [10] designed as an electrostatically actuated micromechanical bridge. The bridges can be deflected by applying an appropriate DC voltage between the movable part and fixed ground electrode. Thus, the gap underneath the bridge, and thereby the capacitance of the device, can be tuned.

This paper is organized in four parts.

In the first section, the principle of the meander – suspended MEMS is shortly described.

In the second one, optical profilometric measurements of the bridges and capacitance value versus voltage $C(V)$ characteristics are presented, This last is compared with a simple plane capacitance model.

Then, in section three, mechanical simulations were done to justify the initial bridge deflection observed in the profilometric measurements.

In section four, COMSOL electrostatic simulations are performed to explain the difference between the capacitance value and the simple model calculated one.

In section five, coupled electromechanical simulations are described to infer the MEMS $C(V)$ characteristic.

Finally, this paper draws out conclusions .

2. MEMS description

For decade now, many superconducting electronic circuits are based on Niobium (Nb) with a critical temperature of 9°K. The fabrication process of IRAM MEMS is described by using the same technology as used for superconducting high-frequency devices and, thus, can be easily integrated into the respective electronic GHz circuit within the same process steps [10].

In order to reduce the stiffness of the mechanically movable part and, thus, to reduce the actuation voltage of the devices, the suspensions of the bridges can be realized as meanders, as it is schematically shown in Figure 3. Thin film structures from Nb have great rigidity as can be seen from the Young's modulus of 105 GPa. This fact and the possibility to etch even thick Nb layers highly anisotropically by inductively Coupled Plasma (ICP) etching with helium substrate cooling opened the opportunity to introduce meander-like spring suspensions for variable capacitances [11]. This type of suspension provides flexibility to obtain small actuation voltage, reliable actuation, and process robustness.

The length of the rectangular bridge varies between 100µm and 200µm, and the width between 100µm and 1080µm. The meanders are at least 2µm wide; the thickness of the Nb bridges is 1,5µm. It can be noticed that, a dielectric layer ALN 410 nm thickness was added to avoid the collage between the bridges and the ground and AL layer (16nm) was added too below the Nb bridge.

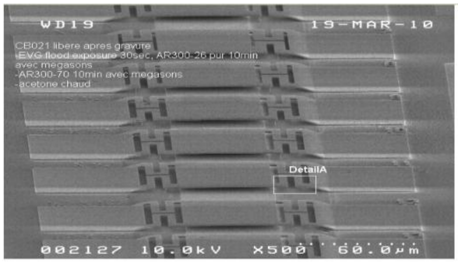

Figure 3. Photography of 165 µm long and 100 µm wide bridges with several meander dimensions. Bridge height is 2,6 µm and Nb thickness is 1,5 µm .

3. Experimental characterization

The topography of bridges was analyzed using a white-light interferometer. This characterization method uses white light with a short coherence length, which enables the non contact topographical analysis of microstructures with high vertical resolution.

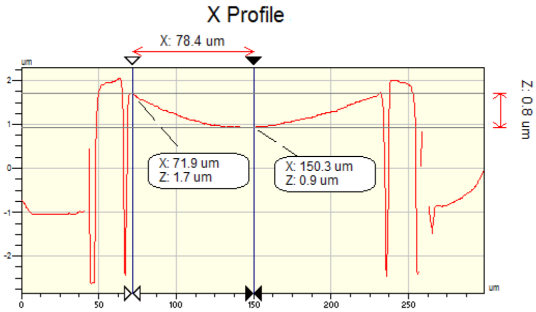

Figure 4. a) Successive Interferometric measurements of the bridge surface: deflection along the length.

Interferometric measurements (Figure 4) shows that the MEMS bridge is initially slightly deflected.

MEMS Varactors deposited on a 200µm quartz substrate were measured in static.

Measurements of capacitance variation *C(V)* are shown in Figure 5; we can noticed that *C(0)* is 79.2 fF, the voltage *Vpi* is 27.6 V and the variation *ΔC(V)/C(0)* is 33%.

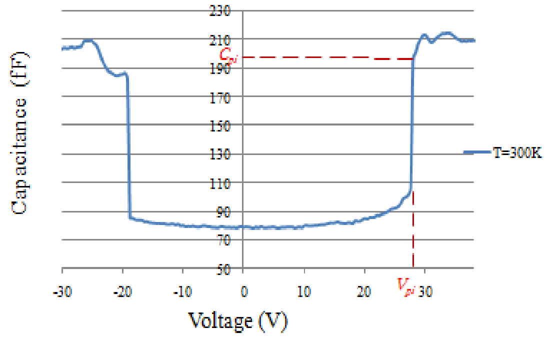

Figure 5. Measured *C*(*V*) of the MEMS.

4. COMSOL mechanical simulation

The observed deflection of the bridges could be due to intrinsic stress gradient in the beam. We assume that the gradient is the result of the Nb deposit process. In the first step, to check the observed deflection shape, our simple method consists in dividing the bridges thickness in three layers with different intrinsic stress as described on (Figure 6). In each layer, Nb Young's modulus (*E*) and Poisson's ratio (*υ*) are assumed isotropic.

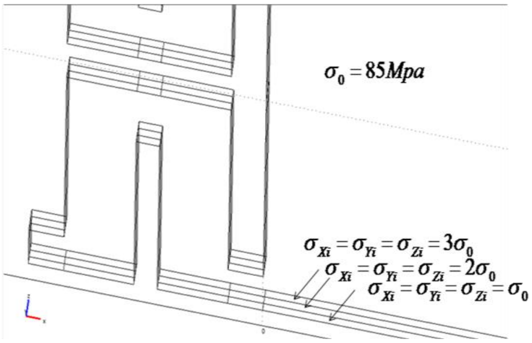

Figure 6. Initial gradient stress arbitrary chosen.

In this context a 3D simulation is used in the model Navigator: from the COMSOL MEMS Module, the structural Mechanics is used from Plane stress and from the COMSOL Multiphysics Module the Deformed Mesh, where the COMSOL Multiphysics translates the application-mode equations between the fixed and moving frames

(Figure 7) is showing the obtained results of a 3D simulations of the MEMS with the previous modeling. A linear stress gradient demonstrate a deflection about 0.8μm.

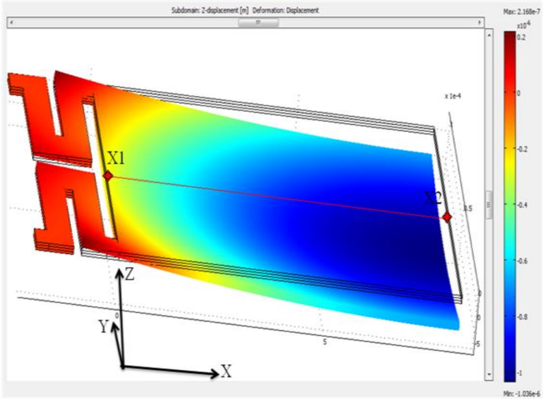

Figure 7. 3D simulation of the deflection of MEMS deduced by intrinsic stress.

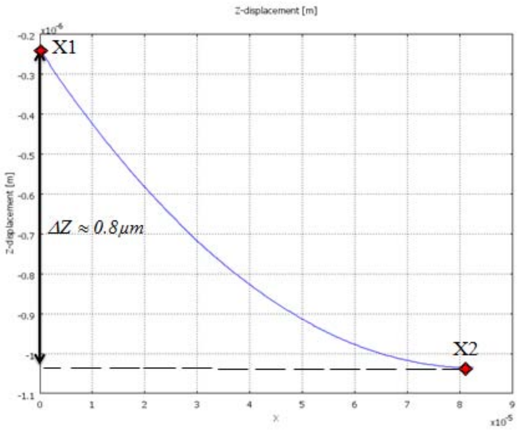

Figure 8. Horizontal displacement of the Figure 7 between XI and X2.

From Figure 8 we can deduce that the measurement deflection (Δ*Z*) is equal to the simulated one.

5. COMSOL electrical simulation

Then the second step consists in finding the values of the capacitance *C*(0) with take into account the initial deflection: the method is to use in the MEMS Module the "Electrostatics application mode".

Now $C(0)$ can be calculated from the stored electric energy in the capacitance, U_e and the voltage across the capacitor:

$$C(0)=\frac{2U_e}{\Delta V^2}=68fF \tag{12}$$

This value is 16% smaller than the measured one. The difference could be due to an added capacitance linked to the electrical field in the quartz substrate. Two simulations were done with 300µm ground plane: one without substrate and the other with the substrate (see Figure 9), in the end the simulated added capacitance is found equal to 11.6 fF.

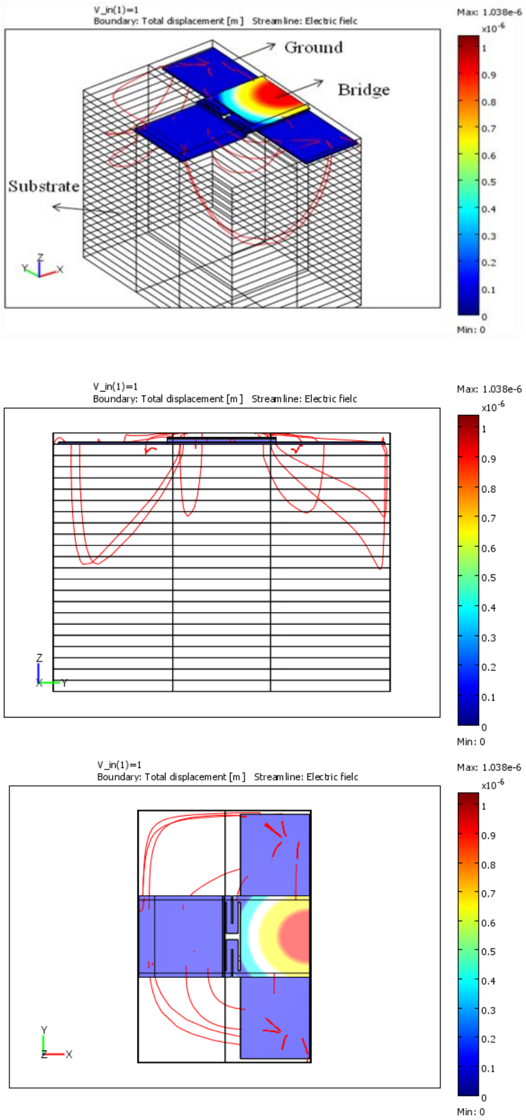

Figure 9. Electric Field magnitudes for half schematic of the suspended-meander MEMS with substrate.

This is confirmed by a measurement between the pads and the ground of the capacitance in the quartz that is equal to 12 fF.

6. Simulations of $C(V)$ and V_{pi}

To extract $C(V)$ a segregated parametric simulation on the voltage is defined, For each point, a simultaneous simulation using four modules is necessary. The first one is the mechanical module which mainly defines the stress gradient and the forces generated by the electrostatical module. The second module is the adaptative mesh previously presented in this paper. The third module is the electrostatical module which automatically creates the 3D electrostatical forces (named Fes_nTx_emes, F_nTy_emes and F_nTz_emes) depending on the parametric voltage. The last module is also an electrostatic module but it is used to calculate the capacitance value from the stored energy.

Besides, during the simulation an error message ("Failed to find a solution for all parameters , even when using the minimum parameter step.") appears. This indicates that the pull-in voltage has been reached: we find $V_{pi}=26$V.

Total CPU time of the final simulation is 4 hours on a 2.0 GHz Dual processor with 2.0 Go RAM. The number of nodes is 145405. (Figure 10) is showing a good agreement between the simulated C(V) and the measured one.

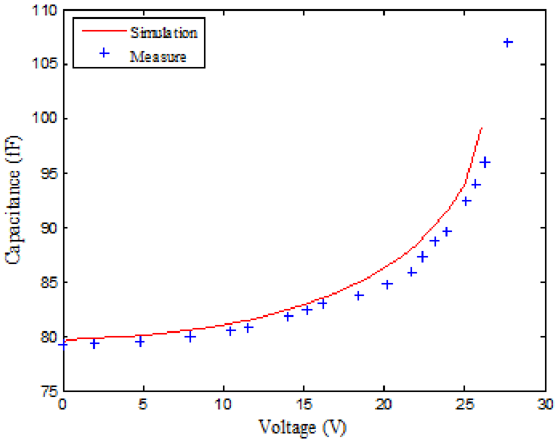

Figure 10. Comparison between measure, theory and simulations of the MEMS $C(V)$.

7. Conclusions

Profilometric and *C(V)* measurements were performed on meander-suspended MEMS made in Niobium for radioastronomy applications and it was observed that the behavior is not in agreement with the famous plane capacitance model. Thanks to COMSOL electrostatic simulations, we were able to draw out that the MEMS capacitance is the sum of two parts: a fixed one due to the substrate and a tunable one due the bridge. Then, mechanical simulations were done to validate the assumption of an intrinsic linear gradient stress to explain the observed deflection of the MEMS. Finally, coupled electromechanical simulations could predict *C*(*V*) and the Pull In voltages.

8. References

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