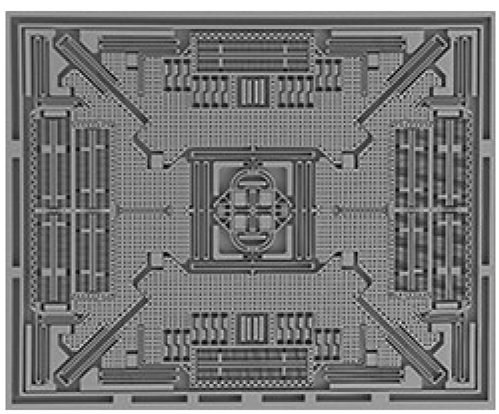
Miki Norihisa & Takahashi Hidetoshi's course - 2020

MEMS: design and fabrication
Report 1: RF-MEMS[1]



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[1]Even though RF-MEMS are investigated, an introduction is performed for the overall MEMS domain. That is why the picture presented on this page is a sensor-MEMS from the French-Italian group STMicroelectronics from `https://www.st.com/content/st_com/en/about/innovation---technology/mems.html`

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1 Introduction

"MEMS" standing for "Microelectromechanical systems" is a technology which originates from the miniaturization of electronic components during the second part of the 20th century. Two major technologies allowed the creation of MEMS, the integrated circuit (IC) technology and the MOSFET [1]. The MEMS technology consist in microstructures, devices which are systemized. Built on Silicon chips, the different elements are mostly manufactured using Silicon, but can also use material such as polymers, metals or ceramics. Using cutting edge IC fabrication technologies, it displays advantages such as low cost through bulky production, high replicability from state-of-the-art etching techniques and lithography and miniaturization of devices resulting in better performances as well as size and cost reduction [2]. Also, the mechanical parts, being made using Silicon, are compatible with IC fabrication and allow the entire small device to be integrated on one chip, resulting in a single entity, able to perform functions and communicate with the outside [2]. Finally, the Silicon based property also makes it compatible with the rest of the electronic devices, being able to be assembled on the same chip.

Early commercialized MEMS technologies, in the 1980s, consisted in inkjet nozzles for printers or microsensors [3]. In the course of years, the domains of application have been diversified and nowadays the terminology "x-MEMS" is used to target the application for which it is designed [4]. While sensor-MEMS, power-MEMS or even optical-MEMS have been used for some time, recently developed and particularly newly applied MEMS are the RF-MEMS. Those are used to replace the quartz devices in electronics, to overcome the problem of quartz's devices miniaturization. As RF-MEMS markets parts have been linearly increasing in the past years, more than other MEMS, it makes it very interesting to study and learn more about it [5]. This report will therefore be dedicated to RF-MEMS description.

2 Avantage over other technologies

There is a need for circuits to work at higher and higher frequencies. Such circuits, at super high frequency (3-30 GHZ) and extremely high frequency (30-300 GHz) are called radio frequency integrated circuits or RFICs. The elements for those circuits, principally the switches and variable capacitors, were only made using MOS switches. Those circuits were suitable for applications up to 6 GHz. For higher frequencies, in the millimeter-wave range (30-300 GHz), the best options consisted in circuits with III-V field effect transistors, p-i-n diodes and varactors. But those circuits exhibited high power consumption, low reliability and high cost or size. Instead, a better solution was found, the use of RF-MEMS [6, 7]. For high frequencies applications, it allows to reduces the losses and it provides better linearity of performances. Also a single RF-MEMS unity is able to replace the entire previously designed circuits thus resulting is lower cost, size and weight.

3 Physics

It is important to note that in RF-MEMS, moveable parts are actually responsible of the tuning of the electromagnetic properties in each small device. This is an important difference with simply "micromachined" units where the objective is more to increase the bandwidth of transmission lines or the quality factor of passive parts [8]. The moveable parts are more often actuated using electrostatic forces, other techniques such as thermal actuation, electromagnetic or piezoelectric [8]. Electrostatic is usually preferred because of very low DC power consumption, fast switching or even standard fabrication already established previously. As the electrostatic principle is mostly used, the physical description will be based on this one.

3.1 Electrostatic actuation in RF-MEMS

The global electromechanical functioning can be described by using a simple mass-spring model, a well known model in mechanics. A schematic of this model in RF-MEMS application is displayed on figure 1 [9]. Before mathematical equations, a quick description is necessary to explain the operation principle of this small systems. Two parallel plate are presented, one attached to a string, the other is fixed, those are connected by a voltage source. When a potential difference is applied, charges appears on the plates and upper plate moves trough the fixed plate due to the electrostatic force.

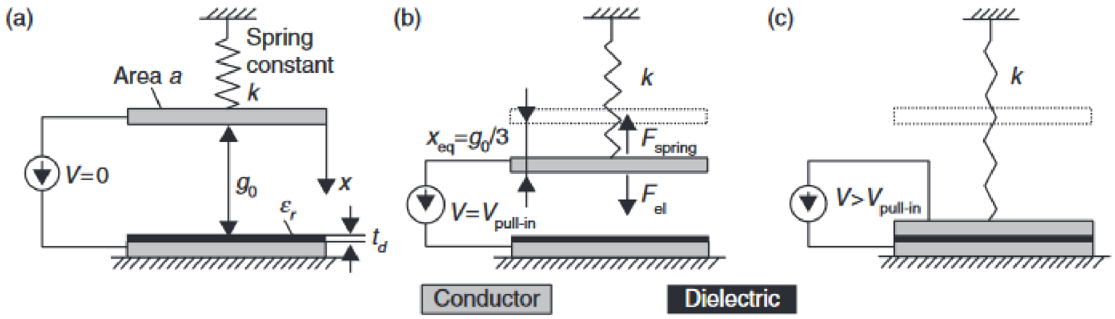

Figure 1: RF-MEMS, driven by electrostatic force. The left image shows the resting position, the center the action of static pull-in then the right one after the pull-in [9]

3.1.1 Static pull-in

Static pull-in refers to the artificial approach(study case) where it is considered that voltage varies slowly enough so that we can consider the system to be in static equilibrium, therefore there is no movement of the plate because the forces cancel [9]. For voltages not too big this will result in a final equilibrium position between $x = 0$ and $x_{pull-in}$. Above this "pull-in position", cause by a particular "pull-in voltage" as seen on figure 1(b) the plate is totally attracted to the bottom plate as seen on figure 1(c) [9].

In the case were dynamic pull-in is considered, there is a fast varying voltage, then dumping ratio and inertia are taken into account but this only changes a little the equilibrium position. In this report, only static pull-in is explained for the understanding of the physical phenomenon.

Refering to figure 1(b) the two forces acting on the plates are each moments are the spring force (in linear mode) F_s and electrostatic pulling F_{elec} force such that:

$$F_s = -kx \tag{1}$$

$$F_{elec} = -0.5\frac{\epsilon_0 a V^2}{\left(g_0 + \frac{t_d}{\epsilon_r} - x\right)^2} \tag{2}$$

where k is the spring constant, ϵ_0 and ϵ_r the permittivity of the air and the dielectric, a is the are of the small plates, g_0 is the initial distance between the plates and t_d is this dielectric thickness [10].

The equilibrium is simply found by equaling the two equation in absolute value. It is $|F_s| = |F_{elec}|$. The "pull-in voltage" can also be found, here a graphical analysis is proposed on figure 2 [10], this figure is linked to figure 1. The different A, B and C voltages are displayed and compared to the spring force. The pull-in distance is found to be a third of the original one.

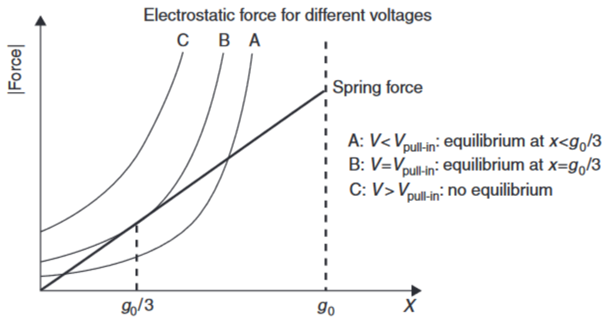

Figure 2: RF-MEMS, driven by electrostatic force [10]. Graphical analysis linked to figure 1

3.1.2 Switching time

Another parameter to take into account is the switching time, it can also be calculated. Here only the concept is explained. It refers to the time take to the top plate to move from its resting position to its final position of operation.

3.1.3 Release time

It is the time after which, when the voltage is no more applied, the system goes back to its initial position. In the static-model previously developed it means after oscillations of the mass-spring model.

3.1.4 Physical parameters

The insertion loss, measure has the drop in energy between input and output of the device/component. The linearity, meaning the independance of the device impedance on the input power. And a very important one is the quality factor Q, define as the ratio of the energy stored in the device and what is dissipated at each cycle [7].

4 Components of RF-MEMS : common structures and operating principles

The components typically built in RF-MEMS are usually built as bridge, cantilever or circular shapes. The kind of connection is either serie or shunt(parallel) and the contact is either of capacitive type or of the ohmic type. A description of very important components is proposed below.

4.1 Shunt capacitive switch and tunable capacitor

The component is represented on figure 3 [11]. The principle is that, given a transmission line, this little bridge is place in parallel with its corresponding lower plate on the line. It is composed by the same part as the device of figure 1.

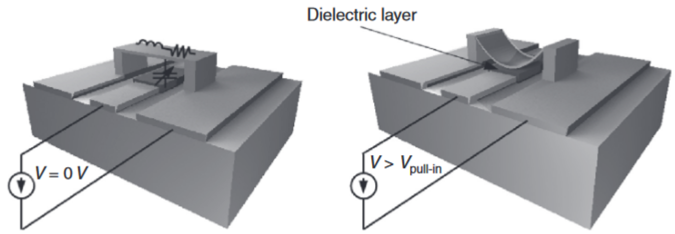

Figure 3: On the left, up state with no voltage difference and equivalent circuit [11]. On the right, activated state of the component

When no voltage is applied the bridge is at rest and it is designed to only interfere a little with the line because of its small initial capacitance. Then with the applied voltage, an electrostatic force is created. As shown on right of figure 3, the upper part moves through the lower plate, making the two capacitor's plate closer from each other and therefore increasing the capacitance (as it is inversely proportional to the distance between the two plates). This is how is RF-MEMS a tunable capacitor is obtained and can be use also to create a switch in the transmission line.

Using circuit theory, a circuit analysis of this component is obtained [11]:

$$Z_{bridge} = \frac{1}{j\omega C} + j\omega L + R \tag{3}$$

With resonance frequency of RLC circuit :

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \tag{4}$$

For frequency way smaller than f_{res} we have a capacitance, at f_{res} a resitance and above f_{res} an inductance.

On the quantitative point of view, for capacitive operating mode in RF-MEMS, the initial capacitance is designed small to have low losses from it while the activated capacitance is 3 to 6 times bigger. For switching operating mode, the low-state capacitance has to be as great as possible usually 10 to 20 times bigger than the resting state [11]. It operates at almost resonance frequency f_{res} and is typically short-circuiting the line.

4.2 Cantilever bridge series switch

The component is represented on figure 4 [12]. Opposite to the shunt bridge this one is put in series in the transmission line. The idea is that this small bridge, built over a hole in the transmission line, will go down and close the hole when the voltage is applied. The losses will be mainly due to the series resistor induced by the bridge, although it is designed to have small value at the operating frequency.

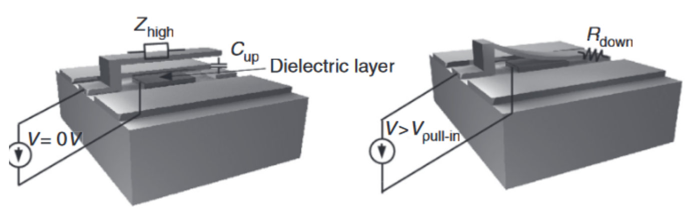

Figure 4: On the left, up state of the bridge. On the right down state of the bride [12].

5 Manufacturing : fabrication techniques

The fabrications materials and the techniques used to build them are [13]:

- The low-loss substrates : high resistivity Si, quartz or GaAs using electon beam lithography or IC compatible techniques
- Dielectrics are built with Chemical Vapor Deposition (CVD or PECDV)
- For metals, micromachining is mostly used
  - 0.5 μm thick non-moveable electrodes by etching or lift off
  - several μm thick moveable structures by electroplating or sputtering

Usually the thickness determines the values of equivalent circuits elements. Also other features have to be invastigated for RF-MEMS such as packaging or temperature stability.

6 Applications

The last part of this report is dedicated to the applications of the previously describe RF-MEMS. It is used in general in *mm* wave circuits. The applications some are listed below [14]:

- Tunable antenna : reconfigurable pattern antennas using RF-MEMS switches
- Tunable filters : usually many filters are used together on a chip, each giving a different bandpass function, here the RF-MEMS adaptable properties could adapt and vary the filters depending on the case therefore redusing size and losses on chips
- Impedance tuners

7 Conclusion

For this first report, at first, an overall historical presentation of the MEMS was first presented, describing where there were coming from, how those came to be built and how it could be used, explaining that in the last year the interest for RF-MEMS has been increasing. Then, the advantages of RF-MEMS over traditional semiconductor circuits (using III-V field effect transistors) was presented in the scope of super high frequency (3-30GHZ) and extremely high frequency (30-300 GHz) circuits improvements. A global physic description was therefore explained for electrostatic actuation and how the components were actuated using this principle. Following this, the fabrications techniques were presented and then finally the applications.

References

[1] *Wikipedia - Microelectromechanical systems*. `https://en.wikipedia.org/wiki/Microelectromechanical_systems` [Accessed: 04.05.20].

[2] J Jason Yao. RF MEMS from a device perspective. *J. Micromech. Microeng. 10 R9–R38*, page R9, 2000.

[3] *Wikipedia - Microsystème électromécanique*. `https://fr.wikipedia.org/wiki/Microsystème_électromécanique` [Accessed: 04.05.20].

[4] Miki Norihisa & Takahashi Hidetoshi's slides of "RF MEMS: design and fabrication" course. Course #1, slide #17.

[5] Miki Norihisa & Takahashi Hidetoshi's slides of "RF MEMS: design and fabrication" course. Course 1, slide #42 & #43.

[6] T. PURTOVA and H. SCHUMACHER. Overview of RF MEMS technology and applications. *Woodhead*, page 3, 2013.

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