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Abstract — *Capacitive RF MEMS switches demonstrate that it is difficult to obtain a perfect capacitive contact for a low actuation voltage. Architectures of MEMS switches with resistive contact are then developed. The objective is to minimize the contact resistance to obtain the best RF performances while keeping a low actuation voltage. First set of results have shown that good RF performances, with contact resistance lower than 1.3Ω, can be obtained with a 30V actuation voltage and with a 6µm gap height. With cantilever height around 1.5µm it will be then possible to obtain enough contact force with 6V applied voltage.*

Key Words: *DC contact MEMS switch, actuation voltage*

I INTRODUCTION

Despite excellent RF characteristics (high isolation, low insertion, excellent signal linearity, low power consumption, high compactness) [1, 2, 3], electrostatic actuation RF MEMS switch shows limited performances like high switching time, costly packaging, and a high actuation voltage. In this way, four possible configurations of switch are investigated to reach the objective of low actuation voltage. Development of RF MEMS switches for 2-5 GHz frequency range applications needs to consider several issues : microwaves requirements (isolation, losses, frequency bandwidth), the electromechanical behavior (actuation voltage, switching time), the options and limitations offered by the technological process in terms of mechanical optimization and material properties, the deformation induced by initial stress relaxation, the ability for the switch to withstand temperature variation and RF power, and the available area. Thus the design of an electromechanical switch becomes rapidly complex. Our study is focused on the feasibility of low stiffness gold microstructure to reduce the actuation voltage. A great importance is attached to the effect of design parameters on RF MEMS switches performances.

II DESIGN AND FABRICATION

Four configurations of switch (shunt capacitive, shunt DC contact, series capacitive, series DC contact) are possible to fit 2-5 GHz frequency range applications. Each configuration involves risks. It is difficult in the development of DC contact switch to obtain a small contact resistance for a low actuation voltage, while for capacitive switch, it is critical to obtain a high capacitance (22pF) in the down state and a large inductance (70pH) to obtain 4 GHz resonant frequency.
A first run of switch has been launched with shunt capacitive design. The devices were able to provide high inductance and were consistent with good mechanical behavior and low actuation voltage.
However, the capacitive contact wasn't perfect and intensive analyses have shown that it was very difficult to control and reproduce a capacitance value exceeding 10 pF for large area and low microstructure stiffness.
Assuming these results, we decided to develop an innovative architecture and a new technological step to provide direct gold/gold contact to investigate the feasibility of DC contact switches.

II.1 DESIGN PARAMETERS OPTIMIZATION

To overcome the problem related to capacitive contact and to optimize the metal/metal contact properties, new design of serial and shunt switch have been performed with DC contact.
The overall goal is to decrease the contact resistance in order to increase the isolation or reduce insertion losses. The design parameters optimization is critical to achieve the desired contact performances.
The four switch parameters (actuation voltage, displacement, restoring and contact forces) are tightly coupled to each other, which makes good switch design very difficult. On figure 1, it is shown how the contact material and the design parameters control the active forces and the contact performance of the switch, expressed in the contact resistance and in the contact reliability.
A low contact resistance requires a high contact force, and a high restoring force is desired to

improve the contact reliability in preventing contact stiction problems. A high restoring force can be achieved by a relatively stiff structure and a large displacement, resulting in an increased electrostatic force to pull down the structure. Also, increasing the restoring force demands an increased electrostatic force to maintain the desired contact force, requiring a higher actuation voltage or a larger actuation electrode area. Thus, it is difficult to create a switch with a low actuation voltage for the electronic compatibility, small actuation electrode to reduce the size and cost of devices, large distance between electrodes for a high RF isolation, a high restoring force for the contact reliability and a high contact force for a low contact resistance. The optimization of the switch behavior is then a trade-off between microwaves and electromechanical parameters, while considering the feasibility of the technological process.

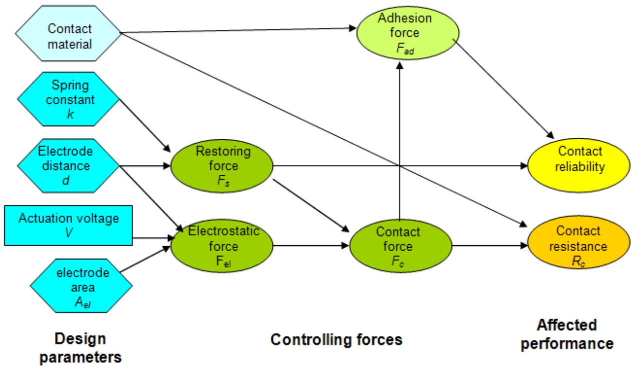

Figure 1. Illustration of the connection between the design parameters and the active forces in the switch model and how they affect its performance

On the basis of analytical models and electromechanical simulations, two series and shunt DC contact switches composed of a stressed evaporated/electroplated gold bilayer [7] have been designed with a 1.5µm height air gap in order to achieve an actuation voltage close to 5V. These designs are consistent with good RF performances.

II.2 DESIGN DESCRIPTION AND FABRICATION

The design of serial DC switch and shunt DC switch are shown respectively in Figure 2 and in Figure 3. In series configuration, a 30 µm gap is created on the signal line to allow a high isolation in the up state. When a voltage is applied between the actuation electrode and the cantilever, a short circuit is generated between ends of signal line.

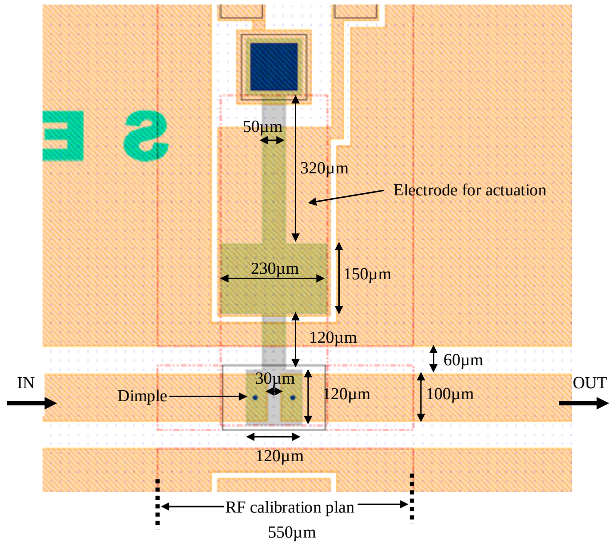

Figure 2. Design of a DC series switch

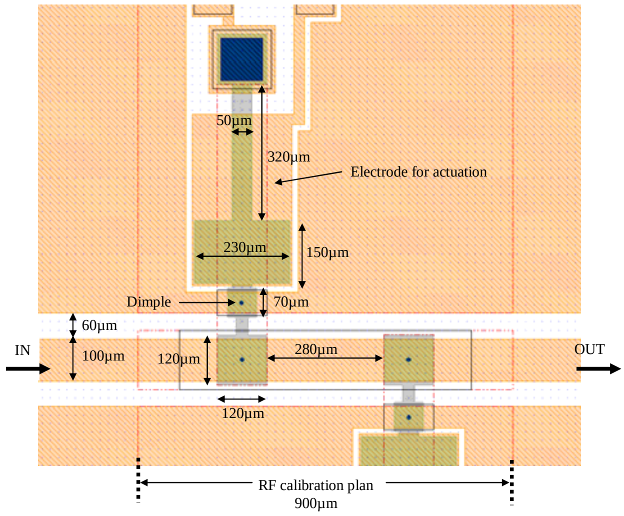

Figure 3. Design of a DC shunt switch

Concerning the shunt configuration, both actuated cantilevers establish electric contact between the central conductor and ground planes.

The switches are fabricated using metal surface micromachining, shown in figure 4. To reduce the actuation voltage, the switch consists of a low stiffness gold microstructure with a small displacement and large actuation electrodes. The gap height is then set to 1,5µm. 0.5µm height Gold contact dimples are added under the cantilever to improve the contact performances, leaving 1µm of travel required for contact. A 2µm layer of gold is patterned to define the coplanar lines and actuation electrodes. A 400 nm layer of PECVD silicon nitride is then deposited and patterned to insulate the electrodes. The cantilevers consist of a 4µm thickness electroplated gold layer.

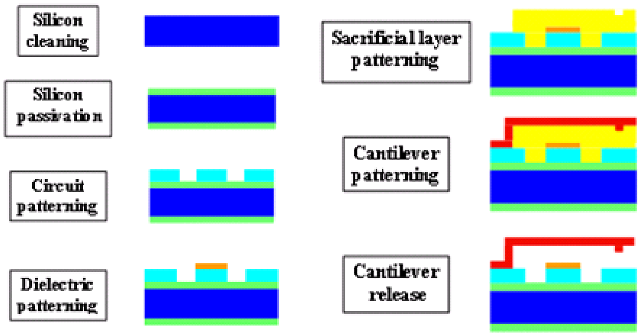

Figure 4. Low actuation voltage switch process flow description

The electrical contact between the bump and the line is a direct gold/gold contact. Gold, according to the literature is the contact material of first choice [1, 2, 3], due to its low hardness and low resistivity, which imply a low contact resistance, its relatively high melting point temperature for a soft material and its resistance to absorption of surface contaminants.

III RESULTS AND DISCUSSIONS

III.1 INITIAL DEFLECTION ANALYSIS

An example of cantilever profile is given in figure 5 and in figure 6 after sacrificial layer etching and CO_2 drying respectively for a serial and shunt DC switch. The photoresist sacrificial layer is spun on 3µm instead of 1.5µm to reduce technological problems. The results show that it is possible to obtain quite flat cantilever. However, the deflection is not very reproducible from cell to cell and it seems that the low level of bridge planarization induces this problem.

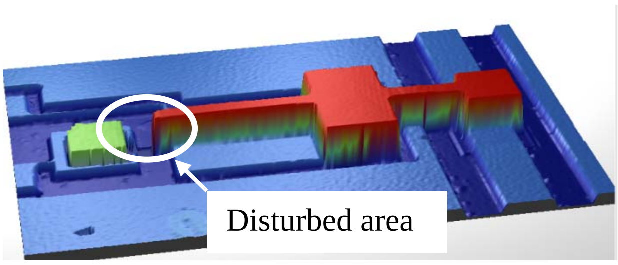

Figure 5. Optical profilometer measurement for a DC serie switch after release

In this example the cantilever height is about 6µm but again the reproducibility is not very good as we obtained values ranging from 4µm to 7µm. This problem was unexpected because the sacrificial photoresist layer was planned to be close to 3µm. This effect can be related to a sacrificial layer problem (default during spinning, bad planarization) or if there is a large deflection close to the anchorage. In order to confirm this assumption, we can observe in figure 5 and in figure 6 that there is a disturbed area close to the anchorage which can perhaps explain this issue.

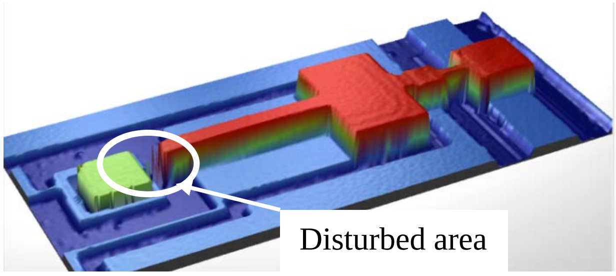

Figure 6. Optical profilometer measurement for a DC shunt switch after release

Cantilever deflections are difficult to control, but they can be reduced by suppressing the non flat area with efficient planarization and by strengthening the anchorage to reduce the rotation.

III.2 RF RESULTS

To evaluate the losses in the active part of the switches, calibration kits have been used to obtain the results between the calibration plane showed in figure 2 and figure 3. The measured losses in this calibration kits are quite high (0.7dB/mm at 10GHz) and higher than previous results obtained on high resistivity silicon (0.06dB/mm at 10GHz). These losses can be attributed to bad RCA cleaning of silicon before silicon passivation with silicon oxide.

Concerning the serial DC switch, the actuation voltage has been evaluated for several cantilevers between 10V and 20V. These values are consistent with the cantilever height ranging from 4µm to 7µm. However, at 10 V and 20 V, the force was not strong enough to ensure a high quality contact. Therefore 30V have been applied to insured the best contact performance. Between 1GHz and 5GHz the measured isolation is better than -35dB. As for the measured losses they are lower than 1dB. These losses originate mainly from the transmission line (550µm length) because of cleaning problem. If we subtract theses dielectric losses, the electrical model gives constant losses around 0.2dB in the 1GHz/5GHz range. These losses can be modeled with 1.1Ω contact resistance for each DC contact.

Concerning the shunt DC switch, between 1GHz and 5GHz the measured losses are lower than 0.8dB and are related to surface states associated with a cleaning problem as mentioned before. Without this effect, the losses would be lower than 0.1dB as shown by simulation curve. In the down state, the measured isolation is better than -12dB. It has to be noticed that there is a significant difference with the value expected from simulation (-40dB). This effect can be related to the distance between the two cantilevers (280µm) which allows the propagation of a common mode.

This effect could be drastically reduced by minimizing this distance or by using complete symmetric bridge. The electrical model shows that with symmetric cantilever it will be possible to obtain isolation better than -25dB for a contact resistance equal to 1.3Ω.

III.3 ANALYSIS OF ACTUATION VOLTAGE EFFECT ON RF PERFORMANCES

In order to evaluate the effect of applied voltage on RF performances we simulated the contact force versus the applied voltage for a typical cantilever used both in serial and shunt DC switch.

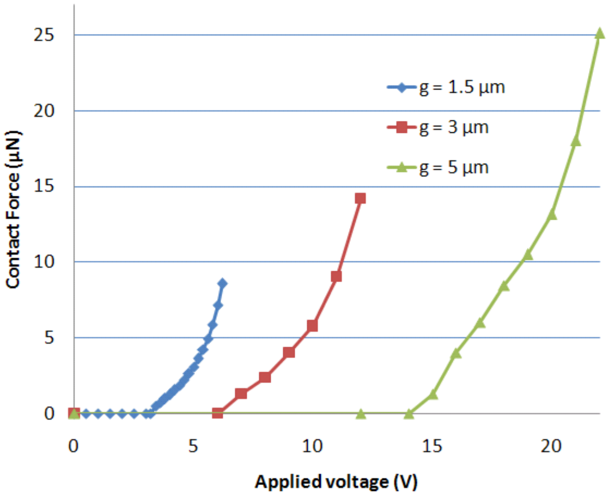

Figure 7. Contact resistance as a function of applied voltage for different gap height

The results are illustrated on figure 7 for three cantilever height (1.5, 3 and 5µm). The graph shows that it is desired to use a voltage higher than pull down voltage to increase the contact forces. It will be possible with 1.5µm cantilever height to obtain 10µN contact forces for 6V. This contact force will be enough if we see the literature to obtain contact resistance lower than 2Ω.

IV CONCLUSIONS

Capacitive switch development is limited, due to the difficulty to control and reproduce high capacitance value in the down state. Therefore, new shunt and series DC contact switches have been designed and fabricated.

First results show that good RF performances, with contact resistance lower than 1.3Ω, can be obtained with contact forces evaluated to 30µN. This contact force has been generated by 30V actuation voltage related to higher cantilever height than expected. The cantilever heights are between 4µm and 7µm instead of 3µm planned that shows that it will be possible to get device featuring actuation voltage in the 10 Volts range or even lower. With cantilever height around 1.5µm it will be then possible to obtain enough contact force with 6V applied voltage.

Simulations show that it is possible to obtain quite flat microstructure using a stable industrial process with well control stress in the layers. This reproducibility is very difficult to reach in an academic research center but some structures show a good behavior and the feasibility has been demonstrated. These new designs of DC MEMS switch require for validation an evaluation of reliability, packaging and reproducibility.

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