Design of A Novel Bulk Micro-machined RF MEMS Switch

Zhang Haixia[1*], Hao Yilong[1], Xiao Zhiyong[1], Luo Dongmei[2**],
Nora Finch[3], James Marchetti[3], Dan Keating[3], Vatsa Narasimha[3]
[1]Institute of Microelectronics, Peking University, P.R. China
[2]Technovena Pte Ltd., Singapore
[3]Corning IntelliSense Corporation, USA

Abstract:

A RF MEMS capacitive switch fabricated using bulk silicon micro-machining is investigated in this paper. The switch includes a vertically movable dielectric integrated in the folded beam. It is electrostatically actuated, allowing for fast response, low power consumption, and easy system integration. Detailed discussions of the movable elements and the simulations of the switch are presented. The effect of the beam shape, the beam thickness, and the air gap were studied. Several design optimization strategies for RF switches are presented.

Keywords: RF switch, MEMS, Simulation, CAD

Introduction:

MEMS-based RF switches have a number of advantages over traditional switches, such as PIN diodes or GaAs FETs, because they have neither semiconductor PN nor metal semiconductor junctions. Without these junctions, RF MEMS switches have lower insertion losses, good isolation, much lower intermodulation distortion, and lower power consumption. Micro-machining technology introduces other advantages for RF MEMS switches: small volume, light weight, low cost, high performance, IC compatibility, etc. These switches have the potential to be applied to numerous applications within an RF system, such as digitally controlled antennas, impedance matching networks, transmitters/receivers, phase shifters, phase array antennas/radars, tuning circuits, and so forth.

Previously reported RF MEMS switches were usually electrostatically driven and were fabricated using surface micro-machining, consisting of a cantilever constructed from sputtered or evaporated thin metal films with a silicon nitride or dioxide layer, which was released by etching a sacrificial material layer [1, 2]. These devices have shown a minimum driving voltage of 8V, a low insertion loss of 0.08dB at 10GHz, isolation of 42dB at 5GHz, and an on/off capacitance ratio of 600. But they still have shortcomings. First, the actuation voltage is much higher than semiconductor switches: many reported switches have actuation voltages ranging from 10-80V [2][3]. Second, mechanical actuation results in their being much slower than electronic switches. And, sometimes stiction occurs which causes failure of devices.

In this paper, a novel bulk-silicon fabricated RF MEMS capacitive switch was designed and analyzed. This RF switch has a short response time, low power consumption, and an IC compatible design. To lower the driving voltage and insertion loss, multiple geometries for the movable beam, membrane, and air gap were investigated using IntelliSuite™, an available CAD for MEMS™ tool [3]. Finally, optimization strategies are proposed to guide future device design.

RF Switch Principles:

The bulk micro-machining RF MEMS capacitive switch was shown in Figure1, which consists of a glass substrate, a lower electrode, an upper electrode, a movable hinge, and a multi-layer silicon membrane. The membrane is a sandwich structure: a dielectric layer deposited on the surface of the silicon substrate with a metal layer deposited to cover the silicon membrane after bonding. This D-S-M (dielectric-silicon-metal) structure reduces both the insertion loss and resistive loss. Also, using bulk silicon processing improves the mechanical performance compared to traditional RF MEMS switches with metal membranes.

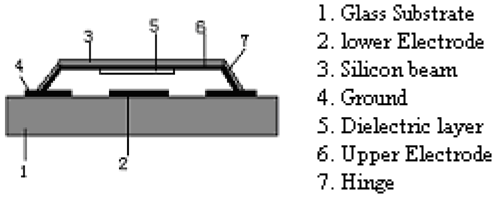

Figure 1 Schematic drawing of RF MEMS switch

The on/off state of the switch is controlled by the driving electrostatic force, and the insertion loss and isolation is determined by the on/off state capacitance. When designing RF MEMS switches, it is important to determine general approaches to reduce the threshold voltage, which will ultimately reduce the actuation voltage of device. The following analysis and research were focused on this question.

Based on the assumption that the capacitor is an ideal parallel plate capacitor and the spring force is linear with displacement, when the effect of the thin dielectric film is neglected the threshold voltage can be calculated by the following equation,

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[*] Zhang Haixia: Zhanghx@ime.pku.edu.cn [**] Luo Dongmei: MdmLuo@technovena.com

to be presented at the International Conference on Micro and Nano Systems, August 8-11, 2002, Kunming, P.R. China

$$V_P = \sqrt{\frac{8}{27}\frac{Kh_A^3}{A\varepsilon_0}} \qquad (1)$$

where, K is the effective spring constant of the movable structure, A is the effective area of the equivalent parallel plate capacitor, and h_A is the air gap height.

From equation (1), we can see that the threshold voltage of the switch is affected by the effective spring constant K, the air gap height h_A, and the effective area A of capacitor.

One of the most common approaches to changing the effective spring constant K is to vary the shape of the hinge. This paper outlines three factors affecting the behavior of an RF MEMS switch: hinge shape, hinge thickness, and air gap height.

Model Creation:

There are two methods to create the 3D models of MEMS devices in IntelliSuite™; one is directly from the fabrication process, the other is through the 3D geometry interactive builder.

Using the fabrication process, the masks for the MEMS device were imported first, then a process table was generated which included all of the process steps necessary to create the device and from which the resulting material properties were determined. During process design, the imported mask set was linked to the process, which provided the definition of the x-y geometry of the structure. Then the 3D model of the device could be visualized in the 3D Viewer, and the model exported to an analysis module.

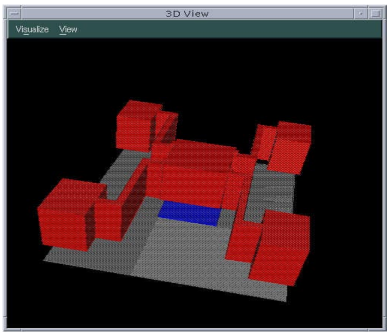
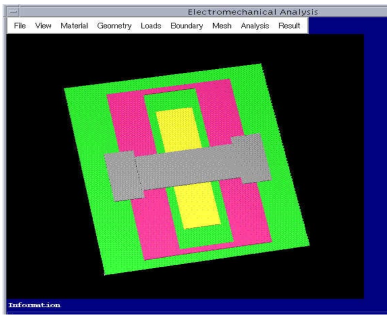


Figure 2 3D model of the RF MEMS switch generated using the fabrication process

The IntelliSuite™ software automatically generated all of the necessary models directly from the process table. The only modifications to the original process were substituting different mask sets for different geometries and changing the process parameters for the material layers to change the thickness and other varying parameters. Figure 2 shows an example of an RF MEMS switch designed using the fabrication process.

Using the 3D geometry interactive builder to build a 3D model is like building with blocks. The layouts of the device should still be imported first. Each level, from bottom to top, was created by adding elements that described a final structure. The x-y geometry was obtained from the mask, and thickness (z) was designed by defining a level height. The different materials in device were defined by using multiple entities. Figure 3 shows one example of an RF MEMS switch created using the 3D geometry interactive builder.



Comparing these two methods of 3D model generation, the fabrication process is generally better if the designer knows the process. One advantage is that by using this approach the model will be easier to modify. The 3D interactive builder is useful when the process is not well understood or is difficult to define for simulation. It does allow for quick, simple model creation or the insertion of process steps, such as packaging using epoxy or solder. Therefore, in our research we generated the 3D model of the RF MEMS switch using the fabrication process.

The Hinge Shape:

Both the number of folds and the size of the hinge affected the structure and performance of the switch. Figure 4 shows the various hinge shape were investigated in this paper. The results that were considered were the first mode of natural frequency, driving voltage, and stress. The thickness of the silicon hinge was 4 microns, and the air gap was 2.5 microns. Models were created in IntelliSuite for each hinge shape and then analysed in its mechanical analysis module.

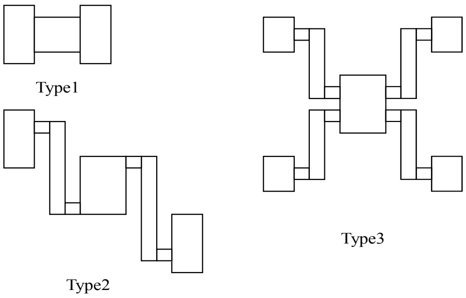


Figure 4 Schematic of various hinge geometries

The simulation results for the different hinges are shown in Table 1.

Table 1 Natural frequency results

Hinge shape	1st Mode		2nd Mode	
	F (kHz)	Dir.	F (kHz)	Dir.
Type1	477.3	Z	663.2	Y
Type2	34.4	Z	57.7	Y, Z
Type3	92.9	Z	193.0	Y, Z

Here, Z represents vibration on the z-axis, as shown in Figure 5, which is the ideal first vibration mode. Y, Z represents twisting about the y-z axis, as shown in Figure 6.

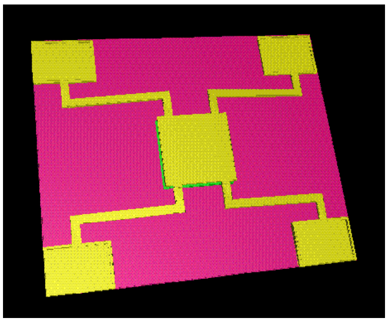


Figure 5 The 1st mode of a Type3 hinge

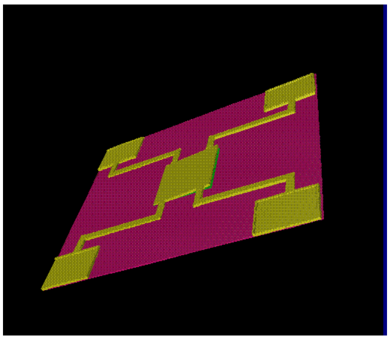


Figure 6 The 2nd mode of a Type3 hinge

Following mechanical analysis, electromechanical analysis was performed for each structure using IntelliSuite. This research was focused on the z-direction movement characteristics of the movable plate when the switch was electrostatically actuated, including the maximum z-displacement of the switch as a function of the applied voltage, the local z-displacement results, and the resulting stresses.

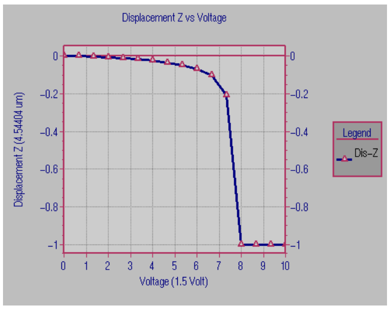


Figure 7 Displacement Z vs Voltage

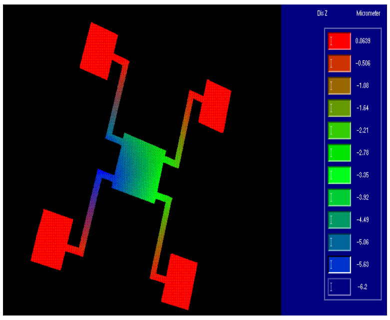


Figure 8 Localized z-displacements

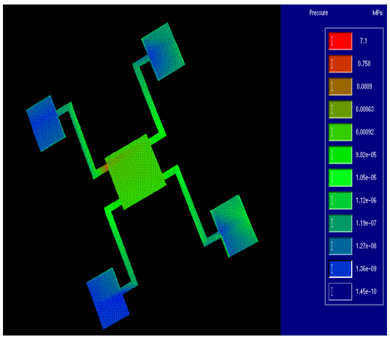


Figure 9 Von Mises stress distribution

Figure7 is a plot of z-displacement versus voltage. Figure 8 shows the localized z-displacements, and Figure 9 shows the Von Mises stress distribution.

The threshold voltage of the RF switch for each hinge shape was obtained from the simulation results, as shown in Table 2.

Table 2 Threshold voltage for each hinge shape

Hinge Type	1	2	3
Threshold voltage (V)	190-195	10-12	25-30

From the simulation results, we can conclude that the longer and the more symmetric the hinge is, the lower the first mode of natural frequency (the lower this mode is, the better the vibration), the lower the threshold voltage, and the more even the stress distribution. In Table 1, the vibration of the type1, type2, and type3 hinges are along the z-axis, which is the preferred vibration axis. Among these three hinge shapes, the one with the lowest resonant frequency will perform the best. Therefore, the type2 and type3 hinges are better than the type1 hinge because their threshold voltages are much lower. Therefore, the research was continued with the type2 and type3 hinges.

Design of the Hinge Thickness

In an RF MEMS switch, the thickness of the silicon hinge is one of the key factors affecting the performance of the switch. For these simulations, the gap height was set at 2.5 microns and the thickness of the silicon hinge was changed from 3, to 4, to 5 microns. The results are shown in Table 3.

Table 3 Threshold voltage vs. hinge thickness

Hinge Thickness (microns)	3	4	5
Threshold voltage of Hinge 1 (V)	140	195	280
Threshold voltage of Hinge 2 (V)	7.2	12	15
Threshold voltage of Hinge 3 (V)	17	30	50

The data show that the thinner the membrane, the lower the resonant frequency, the lower the threshold voltage, and the better the mechanical performance.

The Effect of the Air Gap Height

The air gap height, between the multi-layer silicon membrane and the lower electrode, determines the capacitance of an unactuated RF MEMS switch. This capacitance determines the actuation voltage. The air gap height is, therefore, one of the key factors in RF MEMS switch design. In this research, a 4-micron thick membrane was used to study the effect of the air gap height. The air gap height was varied from 1.5 to 3.5 microns. The results are shown in Table 4.

Table 4 Threshold voltage vs. air gap

Air gap(microns)	**1.5**	**2**	**2.5**	**3**	**3.5**
Threshold voltage of Hinge 1 (V)	**127**	**150**	**195**	**236**	**292**
Threshold voltage of Hinge 2(V)	**8**	**10**	**12**	**19**	**28**
Threshold voltage of Hinge 3(V)	**20**	**24**	**30**	**44**	**61**

The threshold voltage and air gap height data shows that, the larger the air gap the higher the threshold voltage. However, for fabrication considerations require the air gap to be greater than 2 microns to avoid adhesion.

Conclusions:

This paper discusses the significant structural elements in RF MEMS switches and the effects of changes to their parameters. From this, we present the following optimisation strategies:

1. To lower the resonant frequency and driving voltage, the hinge supporting the upper electrode and dielectric membrane should be designed as a folded beam. The longer and more symmetric the beam, the lower the first mode of natural frequency of the switch (the better the vibration direction), the lower the threshold voltage, and the more even the stress distribution.
2. The thinner the hinge, the better the switch will perform. However, the thinner the membrane, the more difficult fabrication becomes and the shorter the life of the switch. Therefore, the thickness of the hinge should not be less than 3 microns.
3. The air gap height directly determines the driving voltage. The smaller the air gap, the lower the threshold voltage.

This switch is close to final processing and will be tested soon.

Acknowledgements:

The work is supported by the Major State Basic Research Development Program "Integrated Micro-Optical-Electro-Mechanical System," Contract No. G1999033109.

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