Electromechanical Modeling and Simulation of RF MEMS Switches

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Abstract

The design of RF MEMS switches involves several disciplines: mechanics, materials science and electrical engineering. While significant progress has been made in the RF design of the switches, mechanical and material studies are required for mass commercialization of reliable devices. Senturia and co-workers at MIT have presented a closed form solution to describe the electromechanical behavior of a fixed-fixed switch. However, in some practical applications, multi-domain simulations are required to account for membrane shape, non-uniform state of residual stress, temperature and other effects. In this presentation, we will describe the modeling and simulation of MEMS switches and discuss their electromechanical performances. The switch, bottom electrode and surrounding air were all included and meshed in the model. Iterations between the electrostatic and structural analyses were performed until the solution converged. The developed method is applicable to all types of electrostatic switches, though the design of a capacitive coupling shunt switch has been examined.

Introduction

Microelectromechanical systems (MEMS) technology is on the verge of revolutionizing RF and microwave applications. The increasing demand for more flexible and functional, yet lightweight and low power consumption wireless systems, has generated the need for a technology that can dramatically reduce manufacturing cost, size, weight, and improve performance and reliability. With the potential to enable wide operational bandwidths, eliminate off-chip passive components, make inter-connect losses negligible, and produce almost ideal switches and resonators in the context of a planar fabrication process compatible with current IC processes, RF MEMS is just the technology.

Micromechanical switches were first demonstrated in 1971 by Petersen [1]. Since then, different actuation mechanisms and switch topologies have been investigated and commercialization of RF MEMS switches has been initiated. Various designs include electromagnetic [2], magnetostatic [3], and electrostatic [4] actuation. Structure designs include surface micromachied cantilevers [5], double-fixed membranes [6], bulk micromachined or wafer bonded designs [7]. Among these, electrostatically-actuated membrane switches have been widely studied. Mechanical design plays an important role in the design of an RF MEMS switch, as do RF design and materials science. Grétillat et al. [8] presented the electromechanical behavior of an electrostatic microrelay. Chauffleur et al. [9] reported the effect of membrane shape on the membrane stiffness of RF switches. Chen et al. [10] proposed a method to measure the residual stress for MEMS suspended membrane structures. Espinosa et al. [11] analyzed the coupled effects of Young's modulus, residual stress and membrane shape on the mechanical response of RF switches under the loading of a nanoindenter.

However, the mechanical study is far behind electric and material studies. Two key mechanical characteristics for RF switches are the actuation voltage and the reliability of the device. The stiffness and residual stress state of the switch structure are dominant to the actuation voltage. At the same time, RF switches have functioning requirements for various temperatures such as in satellite and airplane applications. Therefore, the temperature effect is of particular relevance to the reliability. However, there is no closed-form solution or even numerical simulation to account for the electromechanical coupled problems yet.

In this paper, an electromechanical simulation for RF switches is discussed and some effects on the switch behavior are investigated. The rest of the paper is organized as follows: 1) operation of RF switches and the electromechanical analysis of the switch behavior are introduced; 2) development of a Finite Element Method (FEM) model and verification of the model are presented; 3) effects of membrane geometry and initial stress are discussed; 4) conclusions are drawn from the above analyses.

Electromechanical Analysis of RF switch

A. RF Switch Operation

A typical capacitive RF MEMS switch consists of a fixedfixed thin metallic film suspended over a dielectric film deposited on top of the bottom electrode. This dielectric film serves to prevent the electric short between two conductors and provide a low impedance path for the signal. When the switch is unactuated, there is a large capacitance between the membrane and the bottom electrode, and the device is in the OFF state. When an electrostatic voltage is applied between the two conductors, an electrostatic force is created to pull the membrane down. At a certain voltage, the membrane collapses and comes in contact with the bottom electrode, and the device is in the ON state.

When a voltage is applied between the movable structure and the fixed bottom electrode, electrostatic charges are induced on both the movable structure and the bottom electrode. The electrostatic charges causes an electrostatic force, which deforms the movable structure. In consequence, such deformation results in an elastic force, which tries to restore the structure to its original shape. In general, the deformation will also result in the reorganization of all surface charges on the device. This reorganization of charges is adequate to cause further structural deformation. The device exhibits a coupled electromechanical behavior. For a certain applied voltage, an equilibrium position is defined by balance of the elastic force and the electrostatic force. In order to model and simulate this coupled behavior, numerical iterations between electrostatic energy domain and elastostatic energy domain have to be engaged.

B. Closed-Form Solution

The pull-in voltage is determined primarily by the stiffness of the switch structure. A first-order approximation is to model the switch as a parallel-plate capacitor. The parallel-plate capacitor is suspended above a ground plane by a linear spring. The pull-in voltage can be solved as

$$V_p = \sqrt{\frac{8K_s g_0^3}{27\varepsilon_0}} \tag{1}$$

where K_s is the stiffness of the structure, g_0 is the initial

gap between the two plates, and \mathcal{E}_0 is the air permittivity. The disadvantages of this model are obvious. First, the switch is clamped at both edges, so the deformation of the switch doesn't follow that of the parallel-plate capacitor. Second, the stiffness of the switch structure is not constant, especially at large deformation. Third, it doesn't take into account the effect of residual stress, which proves to be significant for MEMS structures, in particular, thin films.

Senturia and co-workers at MIT [12-13] developed a beam model to predict the pull-in voltage. The assumptions were that the structure was modeled as a beam and the load varied inversely with the position-dependent gap, *g*. The governing differential equation under this assumption is given as

$$EI\frac{d^4g}{dx^4} - T\frac{d^2g}{dx^2} = -\frac{\varepsilon_0 V^2}{2g^2}(1+0.65\frac{g}{b}) \quad (2)$$

where *E* is the Young's modulus, $I = \frac{1}{12}bt^3$,

 $T = \sigma_0 (1 - \nu)bt$, *b* is the beam width, *t* is the beam thickness, σ_0 is the biaxial residual stress, ν is the Poisson ratio, and the factor in parentheses on the right-

hand side is a fringing-field correction. An empirical equation for the pull-in voltage was obtained by fitting the numerical solution to the analytical expression. However, the closedform solution is long and complex, and it doesn't account for in-plane shapes other than rectangles and circles, and neither for the out-of-plane shape.

In order to acquire the aforementioned information, 3-D numerical simulation is required to solve this electrostaticstructural coupled problem. In the following section, the development of the simulation model is discussed.

Development of FEM Model

The simulation of the RF switch response involves the interaction between both the electrostatic and structural domains. In ANSYS, this interaction is simulated by the transfer between two databases, the so-called physics environments: the electrostatic environment and the structural environment. Initially, in the electrostatic environment, the boundary condition is the applied voltage on both top and bottom conductors. By solving Laplace's equation, the voltage distribution in the surrounding air is obtained and the electrostatic force between the two conductors is calculated. Then, the electrostatic environment is switched to structural environment with the electrostatic force as messenger. This force deforms the switch structure following the shell theory. After the geometry is updated, the program is switched back to the electrostatic environment. The electrostatic mesh has to be updated according to the updated device geometry. Iterations between these two physics environments are executed in sequences, until the convergence for both environments is reached.



Fig. 1. Model of a parallel-plate capacitor.

To verify the accuracy of this coupled-domain analysis, a parallel-plate actuator was tested. Increasing the voltage attracts the upper plate down. At a critical point, the upper plate collapses to the fixed plate. This collapse is called pullin. The formula linking the voltage with the corresponding gap is given by:

$$U(x) = \sqrt{\frac{2k}{\varepsilon_0 A} x^2 (d-x)}$$
(3)

where x is the gap, k is the stiffness of the spring, d is the initial gap between the upper and bottom plates and A is the plate area.

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The FEM model is shown in Figure 1. It consists of four spring elements for the spring, a mechanical element for the structure, and an electrostatic element for the air. The analytical and simulation results are shown in Figure 2. The results demonstrate the accuracy of the FEM model. Thus, the model was extended to RF MEMS switches.





In this application, capacitive coupling shunt switches [6] will be discussed, though this method is applicable to all the electrostatic switches. The switch, bottom electrode and surrounding air were all included and meshed in the model. Since the thickness of the switch is far less than the length and width, the shell element was employed to model the switch. The solid element was used to model the air to account for the electrostatic field. The element type of the structure was SHELL93, and the element type of the surrounding air was SOLID122. Since the model is symmetric along x and y axes, only a quarter of the model is shown in Figure 3. The mesh in purple represents the surrounding air, while that in green is the switch. The bottom electrode is not shown. The gap between the switch and the bottom electrode is 4 μm and the bottom electrode is covered by a 200-nm-thick electrically insulating layer.



Fig. 3. A quarter of the model including the switch (structure) and surrounding air (electrostatic field).

Results and Discussion

In this section, we begin discussing the effects of switch inplane geometry followed by the effects on initial stress.

A. Effects of in-plane geometry

Three geometries, rectangle, straight-edged bow tie, and curved bow tie, as shown in Figure 4, were investigated. All three geometries have the same length, 316 μ m. For the rectangular type, the width is 115 μ m. For the straight-edged bow tie, the central width is 115 μ m and the edge width is 175 μ m. For the curved bow tie, the central width is 115 μ m and the edge width is 115 μ m.



Fig. 4. Out-of-plane deformations of the three switch shapes at the same voltage. The deformations are exaggerated.

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The out-of-plane deformations of three switches at a particular voltage are shown in Figure 4. Given the same thickness, the stiffness of the switches was related to their in-plane geometries. Shape 1 has the smallest stiffness, while shape 3 has the largest. On the other hand, the electrostatic force is proportional to the switch area at small deflection. Shape 1 undergoes the smallest force, while shape 3 undergoes the largest. It is shown that shape 2 has the smallest deformation at this voltage. The pull-in curves of three switches are shown in Figure 5. One can see that all three switches are pulled in at about 1/3 of the gap.



Fig. 5. Pull-in curves of the three switch shapes. One can see that the straight-edged bow tie shape possesses the largest pull-in voltage.

B. Effects of initial stress

Initial stress is inherently introduced during microfabrication. Due to the double-fixed structure of the switches, compressive stress may result in buckling of the device. In general, certain microfabrication processes have to be employed to avoid compressive stress [6]. In this section, we will only consider the effect of tensile stress. The tensile stress in RF switches usually ranges from several to over one hundred MPa [10]. 20 MPa tensile stress was applied to switch shape 2 to examine the effects. The pull-in curves of switch shape 2 with 20 MPa stress and without stress are shown in Figure 6. One can see that the tensile stress increased the pull-in voltage significantly.



Fig. 6. Pull-in curves of the switch shape 2 with and without initial stresses. The tensile stress increased the pull-in voltage significantly.

Conclusions

A coupled-field FEM model was developed to simulate the electromechanical behavior of RF MEMS switches. A parallel-plate capacitor was tested to verify the accuracy of the procedure. Three in-plane switch geometries were examined. It is found the straight-edged bow tie shape possesses the largest pull-in voltage. Another important finding is the effect of tensile initial stress, which increases the pull-in voltage significantly. The FEM model will be used to investigate other effects, such as out-of-plane profile and temperature.

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