Effect of Different Order Stiffness and Varying Gap and Thickness on Pull-In Voltage of Fixed-Fixed RF MEMS Switch

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Abstract — **In this paper pull-in voltage of RF MEMS fixed-fixed beam is studied with spring structure for beam. We examined effect of linear and cubic stiffness simultaneously on pull-in voltage. Afterward, role of beam's thickness and gap was investigated by changing these parameters in simulation. As results show, in small gaps linear stiffness has dominant effect, but in bigger gaps, cubic stiffness could not be neglected.**

Keywords — **CVD Diamond, Fixed-Fixed Beam, Gap, Instability Point, Pull-In Voltage, RF MEMS Switch, Stiffness.**

I. INTRODUCTION

RF MEMS is one of the enormous applications of MEMS (Micro Electro Mechanical Systems) in communication circuits. The utilization of RF MEMS helps to fulfill the increasing demand for more flexible and functional, lightweight, and low-power-consumption wireless systems. RF MEMS switches are one of the applications of RF MEMS. The performance of RF MEMS switches tends to be better than p-i-n or FET switches that have been used extensively in switching networks [1],[4],[6].

There are a lot of structures for MEMS switch that each one has a certain application in communication circuits. Here, we chose fixed-fixed beam structure which is widely used in CPW (CoPlanner Waveguide) (Fig. 1).

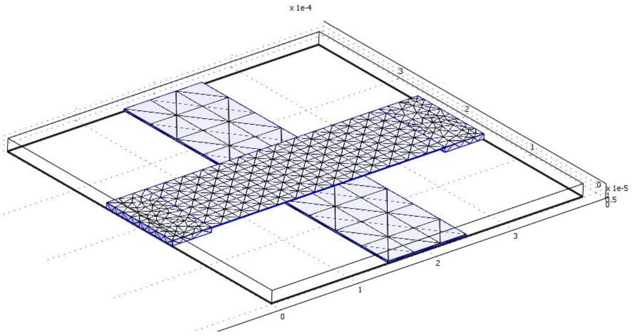

Figure 1. A typical fixed-fixed beam RF MEMS switch

Coplanar waveguide is a one-sided three conductor transmission line. CPW has two grounds and a center conductor in the middle, as shown in Fig. 1, which reduces the coupling effects and allows for easy installation of elements. CPW lines are used mostly for circuit elements and interconnecting lines. CPW provides the potential of lower conductor and radiation losses as compared to microstrip lines. The thickness of dielectric in ideal CPW is infinite. However, in practice the thickness should be sufficiently large to remove the electromagnetic field before they get out [1], [7].

There are two options available for determining beam's structure: cantilever or fixed-fixed beam. Fixed-fixed beam structure consists of a long beam and two anchors that hold beam above three conductors (Fig. 1). Sometimes Gold or Aluminum is chosen for beam but because of glamorous behavior of Diamond, here, we preferred to work with CVD Diamond. This kind of diamond is prepared and produced in Labs. It has some advantage in comparison with most kinds of metal like: wide range of Ohmic resistor (due to its doping), high Young's Modulus and low Poisson ratio (that yields high stiffness of beam), resistant (adamant) to harsh chemical environment and so on [2] and [3].

For each switch we should define a voltage called pull-in voltage. This is a voltage that pulls down the beam to achieve a short circuit in CPW. Sometimes for defining this voltage, we consider a point called instability point. A voltage is applied to the beam; it starts to come down

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gradually until it reaches instability point. At this point, beam suddenly sticks to the lower contact. The voltage in instability point is called as “Pull-In Voltage” [4].

This voltage highly depends on stiffness of spring beam. Stiffness is directly related to geometrical parameters of beam and material that beam is made of. Just like a spring, we have tow stiffness, linear and cubic. Majority of studies until now were conducted only on linear stiffness and they neglected cubic stiffness of spring however it’s more important than linear stiffness especially when the gap is more than 1μm [4].

II. ANALYTICAL SOLUTION FOR A TYPICAL BEAM

For typical beam we used equations in [5] and all simulations were done on a beam depicted in Fig. 2.

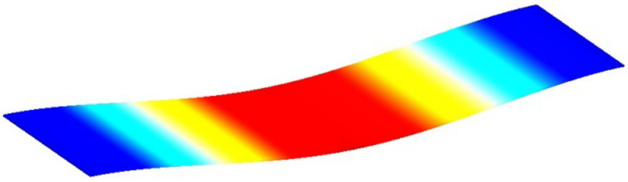

Figure 2. A fixed-fixed beam model for simulation

Any beam (spring) has two stiffness: linear and cubic. For a typical spring, equation of force vs. movement is [5] d and d_0 are displacement and total displacement (gap) respectively:

$$f_{int} = k_1(d - d_0) + k_2(d - d_0)^3 \quad (1)$$

In so many cases cubic stiffness, K_2, is neglected [4]. In a real MEMS device, elastic restoring force caused by deformation, is produced in beams, plates and membrane. Big movement in switches produces a nonlinear elastic force that should be taken into account with adding cubic stiffness of beam in equations. Nearly in all structures, mass (weight) of beam is neglected since it’s too small and hasn’t remarkable effect on pull-in voltage [5]. For fixed-fixed beam, k_1 and k_2

$$k_1 = \frac{32Ebh^3}{l^3} \quad and \quad k_2 = \frac{2\pi^2 Ebh}{l^3} \quad (2)$$

Where E is young’s modulus and b, h, l are width, thickness and length respectively [5].

Nowadays there is a high demand for low power consumption in electronic devices, so decreasing working voltage could be a valuable goal to achieve. RF MEMS devices are widely used in communication and wireless system so that we can’t contrive such gigantic power supply for them to produce high voltage or high current. So the importance of low pull-in voltage for RF MEMS switch is obvious.

When a pull-in voltage is applied on beam it produces an electrostatic force that should overcomes the weight and restoring force of beam but as mentioned above, this pull-in voltage shouldn’t be so high then selection of spring with appropriate stiffness is an important issue.

For our simulation we used parameters of CVD Diamond. Diamond not only has glamorous mechanical behavior because of its high young’s modulus but also kind of doping (n-type or p-type) would produce wide range of ohmic resistor between 10-10^6 Ω/Cm [2],[3].

III. SOLVING STATIC EQUATIONS

We used static equations defined in [5] to obtain instability point and therefore, effect of different order stiffness could be seen:

$$V_{Pi} = \sqrt{2\frac{{\lambda_{Pi}}^2{d_0}^3}{\varepsilon_0}\left[{k_1}^2(1-\lambda_{Pi}) + {k_2}^2{d_0}^2(1-\lambda_{Pi})^3\right]} \quad (3)$$

$$d_{Pi} = \lambda_{Pi} d_0 \quad (4)$$

We considered static pull-in displacement (d_{Pi}) as a portion of total gap (d_0).

If only linear stiffness being considered, the instability point and pull-in voltage would be:

$$d = \frac{2}{3}d_0 \quad and \quad V_{Pi} = \sqrt{\frac{8k_1{d_0}^3}{27\varepsilon_0}} \quad (5)$$

When the linear stiffness is neglected:

$$d = \frac{2}{5}d_0 \quad and \quad V_{Pi} = \sqrt{2\frac{3^5 k_2 {d_0}^5}{5^5\varepsilon_0}} \quad (6)$$

According to above equations $\frac{2}{3}d_0$ and $\frac{2}{5}d_0$ are boundary points and instability point vary between this two points [5].

IV. SIMULATION RESULTS

As shown in Fig. 3 if we consider g=d_0-d, instability point in small gap where stiffness is more linear goes to $\frac{1}{3}d_0$ but in more gap’s height where stiffness is nonlinear it goes to$\frac{3}{5}d_0$.

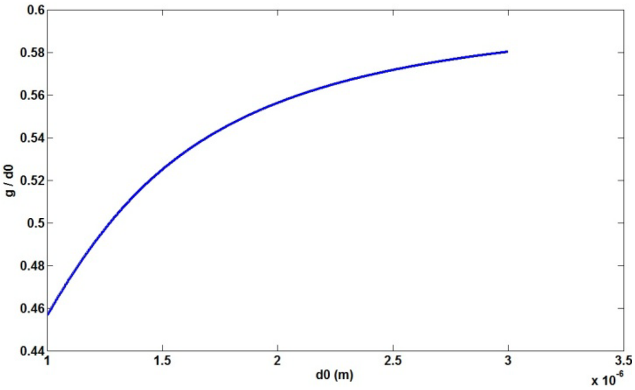

Figure 3. d_0 versus normalized displacement.

The Beam was surveyed in tow state:

A. Constant height, variable thickness

First we put height constant as 1µm and change thickness from 0.5µm to 3µm with 0.5 resolution. Fig. 4.

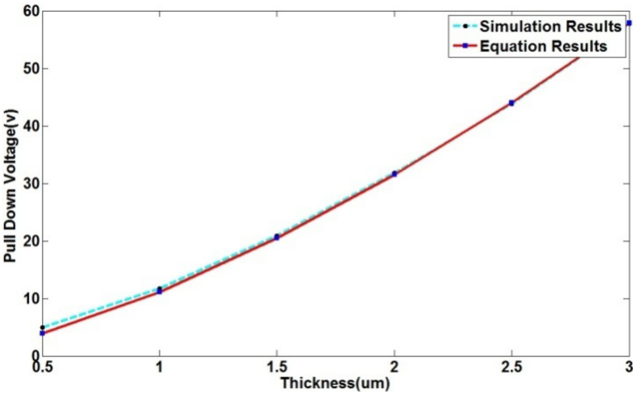

Figure 4. Pull-in voltage versus thickness of beam

In Fig. 5, curve shows force vs. deflection for thickness of 2µm. Plain line and dotted line are obtained from linear model and third order nonlinear model respectively for beam. The other line is for simulation. Simulation curve which should particularly resemble behavior of a real model has some deviation from linear and cubic cure, and this deviation increases as force increases and beam comes down.

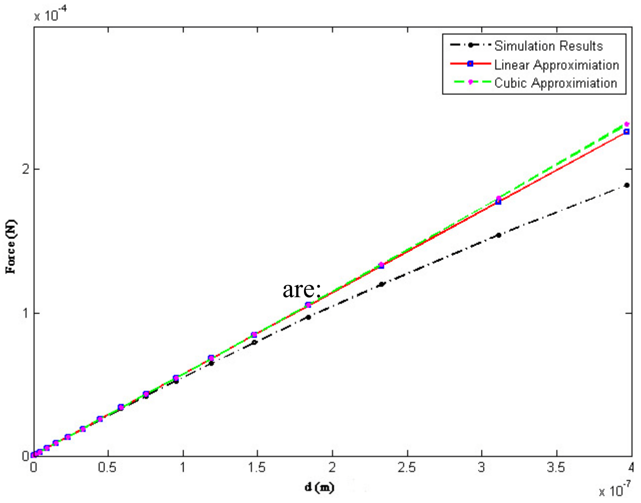

Figure 5. Force versus displacement

B. Variable height, constant thickness

In this state thickness is constant (1µm). First gap is 1µm and increased to 3µm with 0.2µm resolution. In Fig. 6 for lowest curve (dash dotted curve) we only consider linear stiffness and used equation (5) and plot pull-in voltage with respect to gap's height. Next we use third order nonlinear model and equation (6) and with analytical solver obtained pull-in voltage for each height (dotted line curve). Finally plain line curve shows simulation result for each gap's height. Is obvious that simulation curve has deviation from linear and nonlinear model and this deviation increases as the gap increases due to simplification that was done in models. Also, because of increasing in nonlinear parameters in beam model, deviation becomes more as the gap increases. Another important issue that can be understood from Fig. 6 is that in the first part of curve that gap is small deviation is not significant but as the gap becomes larger, deviation increases but cubic stiffness curve still has close resemblance.

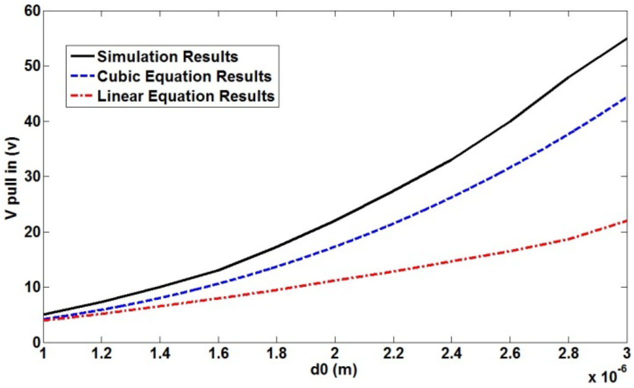

Figure 6. Pull-in voltage versus displacement for linear model, cubic model and simulation.

Finally for each gap, simulation results give a third order model. Curves are in Fig. 7. These models are obtained with least mean square error (LSME). You can see that when the gap increases the needed force also increases. For each one, more displacement results in more force. For each curve a third order equation was fitted and coefficient of third order part (K_2) was extracted.

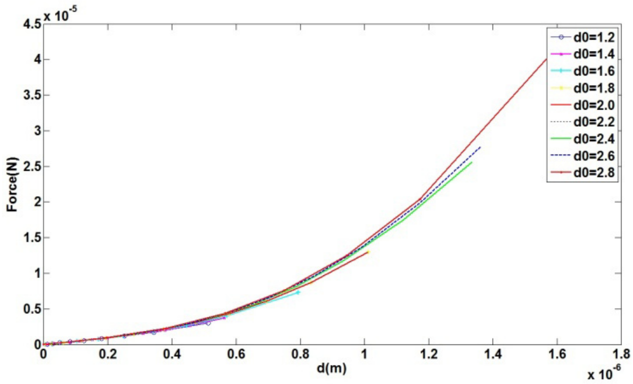

Figure 7. Force versus displacement for nine different gaps.

We extract k_2 for each gap and plot it in Fig. 8. Variance of this coefficient versus gap is so much nonlinear but obviously it's incrementally and never decreases until the gap gets more. Variance of this coefficient is so nonlinear and it's hard to fit a common curve on it.

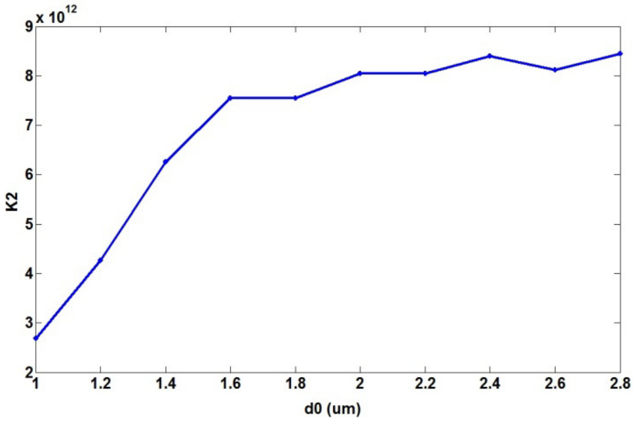

Figure 8. Coefficient of third order part of equations.

V. CONCLUSION

The fixed-fixed beam RF MEMS switch has been simulated and presented. Both linear and cubic stiffness and their effect on pull-in voltage were studied. Now we can say if the gap is small only linear (first order) stiffness can be considered (with small error) but as the gap becomes larger third order (cubic) stiffness should be calculated to obtain pull-in voltage and it shouldn't be neglected because it has significant effect on pull-in voltage. On the other hand, mechanical behavior of CVD Diamond has been shown to be adequate for RF MEMS switches.

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