Design, Simulation and electromechanical Modeling of RF MEMS Capacitive Switches

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***Abstract*—**The purpose of this paper is to design and characterize electrostatically actuated RF MEMS capacitive shunt switches. The design is mainly aimed at reducing actuation voltage, which is an important switch parameter. In this paper, there are many variations of support beam used to minimize spring constant of RF MEMS devices such as fixed-fixed beam, fixed-fixed flexure beam and serpentine flexures. The actuation voltage so achieved is in the range of 2-4 V for these designs. The analysis results are presented by varying geometry of the switch.

***Keywords*—** *RF MEMS switch, Actuation voltage, Spring constant*

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I. INTRODUCTION

Microelectromechanical system (MEMS) switches are surface micromachined devices which use a mechanical movement to achieve a short circuit or open circuit in RF transmission line. RF MEMS switches are the specific micromechanical switches which are designed to operate at RF to mm-wave frequencies (0.1 to 100GHz). Compared to conventional switches such as PIN diodes or FET, MEMS switches have many advantages like zero power consumption, low loss and very low intermodulation distortion [1].RF-MEMS switches have some drawbacks, such as relatively low-speed, low-power handling, high-voltage, low long-term lifetime and packaging problems [2]. Especially, a large electrostatic force produced at very high voltages of 20 V to 80 V is required for RF-MEMS switches to have a reliable operation. For some applications such as mobile phone, automotive and wireless applications there is a need for low voltage power supplies [3]. The actuation voltage or the pull in voltage of the RF MEMS switches is higher than the standard voltages of CMOS, which usually is 5V or less. This requirement results in the non- compatibility of RF MEMS switches with other devices and control circuity of the whole system [4]. This also leads to the issue of non- integration on a single chip. Therefore one of the important requirement is to reduce the actuation voltage of RF MEMS switches.

In [5] they have proposed thatholes of 10μm in diameter are formed on the switch to facilitate easy etching of the sacrificial layer during the release. These holes not only help in the release process but also improve the dynamic performance of the switch by reducing the squeeze-film damping effect and hence the switching time. In [6]residual stress issues associated with this family of switches have been addressed and it has been experimentally demonstrated that sputtered seed layer films result in devices with superior performance when compared with evaporated films. Author in [7] has proposed a RF MEMS switch fabricated in 0.35μm CMOS process and they are able to achieve a pull-in voltage of 7V. In [8] have proposed a bi-stable RF MEMS switch was designed with a low actuation voltage of 5V. In [9] have introduced a CMOS membrane-based switch with actuation voltage of 12.5 V. In [10] have proposed a serpentine flexure beam with AlN(aluminum nitride) dielectric layer and they are able to achieve an actuation voltage of 4V.From [11] the material gold is suitable For RF MEMS switches due to a low contact resistance, a high power handling ability, and a minimum of surface adhesion wear in metallic contact

In this paper, new designs for RF MEMS switches have been investigated to meet the requirement of low actuation voltage for many RF and Microwave application. There are many variations of support beam used to minimize spring constant of MEMS devices such as fixed-fixed beam, fixed-fixed flexure beam and serpentine flexures to achieve low actuation voltage.

II. DESIGN AND ELECTROMECHANICAL MODELING OF PRAPOSED RF MEMS SWITCHES

The minimum potential required to actuated the switch is the pull-in voltage Vp, which is given by [1]

$$V_p = \sqrt{\frac{8Kg_0{}^3}{27\varepsilon_0 A}} \qquad (1)$$

The preceding equation shows the dependency of an actuation voltage on various parameters such as stiffness (k), the air gap (g_0) and actuation area (A) between the electrodes of the switch. There for in order to get a very low actuation voltage, the switches have a lower spring constant, k, and low air gap.

a)Fixed-Fixed beam switch

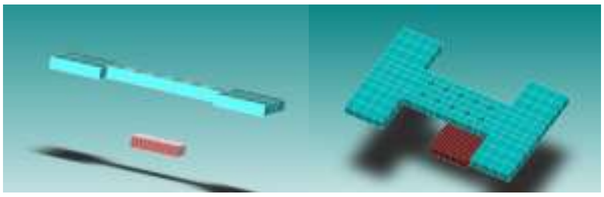


Fig.1 Top view and bottom view of fixed-fixed beam.

The spring constant of the fixed-fixed beam is

$$\text{K=-P/=-£l/y=}32Ew\,(\frac{t}{l})^3 \qquad (2)$$

Where, t-Thickness of beam,
l-Length of beam,

w-width of beam,
E-young's modulus and k- is spring constant.

b) Fixed-Fixed Flexures

Fig.2 Fixed-fixed flexure beam

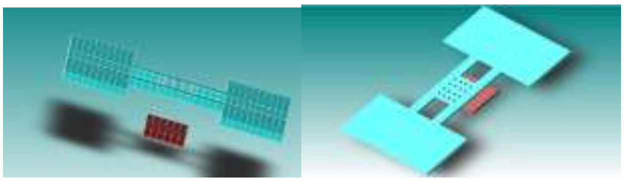


Fig. 3Top view and bottom view of fixed-fixed flexures

The spring constant of the fixed-fixed flexures beam is

$$K=4Ew\left(\frac{t}{l}\right)^3 \qquad (3)$$

Where, t-thickness of beam,
l-length of beam,
w-width of beam,
E-young's modulus and k- is spring constant.

c) Serpentine Flexures

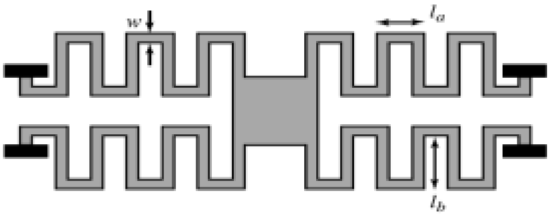


Fig.4 Serpentine flexures

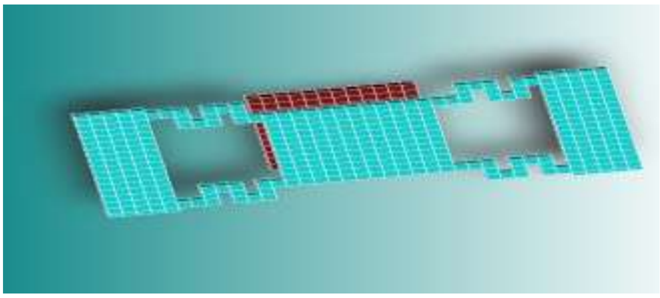


Fig.5:Top view of Serpentine flexures

The spring constant of the serpentine flexures beamis

$$K=4Ew\left(\frac{t}{nl_a}\right)^3 \qquad (4)$$

Where, t-thickness of beam,
l-length of beam,
w-width of beam,
E-young's modulus
k- is spring constant and n-is the number of meanders in the serpentine flexures

III. DESIGN FABRICATION STEPS

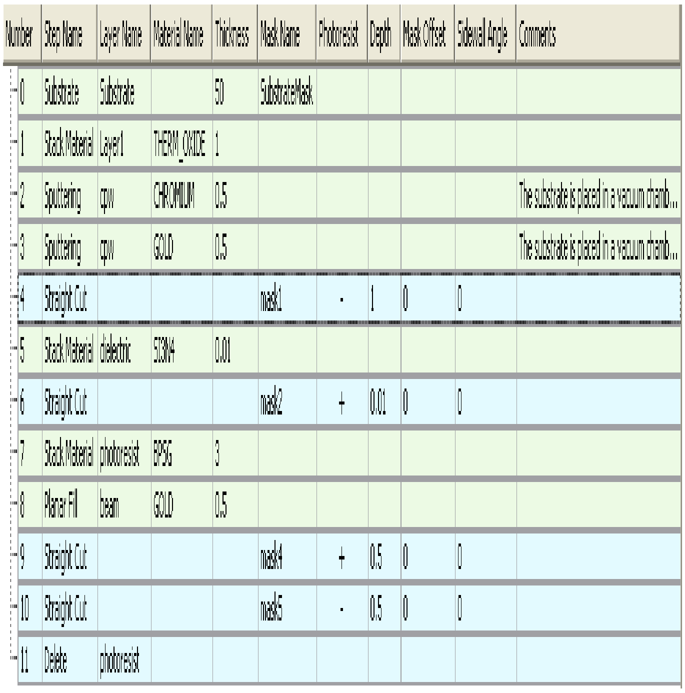
Step 1:- CPW lines are fabricated on Substrate by sputtering gold.

Step2:- Photoresist BPSG has been used as the sacrificial layer which provides the required gap between the switch and the signal line. 2.2µm thick PR is spin coated and patterned.

Step 3:-Structured layer of 0.5µm thick gold layer is sputtered
and patterned.

Step 4:-Holes of (10X10)µm are formed in the switch to facilitate easy etching during the release.

Step5:-Sacrificial layer is etched completely leaving behind the free standing gold layer. Solution used is (Sulfuric acid + Hydrogen peroxide).Below figure shows the process file used to build switch structure.



Number	Step Name	Layer Name	Material Name	Thickness	Mask Name	Photoresist	Depth	Mask Offset	Sidewall Angle	Comments
0	Substrate	Substrate		50	SubstrateMask					
1	Stack Material	Layer1	THERM_OXIDE	1						
2	Sputtering	cpw	CHROMIUM	0.5						The substrate is placed in a vacuum chamb...
3	Sputtering	cpw	GOLD	0.5						The substrate is placed in a vacuum chamb...
4	Straight Cut				mask1	-	1	0	0	
5	Stack Material	dielectric	SI3N4	0.01						
6	Straight Cut				mask2	+	0.01	0	0	
7	Stack Material	photoresist	BPSG	3						
8	Planar Fill	beam	GOLD	0.5						
9	Straight Cut				mask4	+	0.5	0	0	
10	Straight Cut				mask5	-	0.5	0	0	
11	Delete	photoresist								

Fig.6 Process file

IV. RESULTS AND DISCUSSION

a) Fixed-Fixed beam

In general when the load is distributed across the beam and deflection at the center is used to calculated spring constant. In the case of electrostatic actuated MEMS switches, the load distribution depend on the location of actuation of electrode. The fixed-fixed beams with load distributed over the entire beam and the case of load distributed only at the centre portion of the beam were analyzed. All the designs are simulated in COVENTOR WARE (2010), which is an Finite Element Method (FEM) based MEMS simulator.

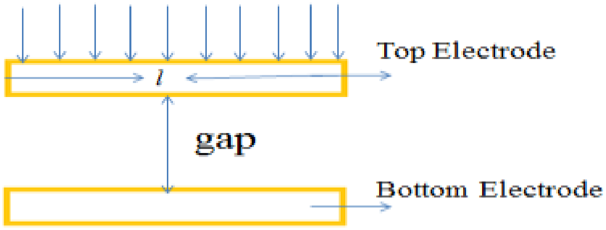


Fig.7 Case1load is distributed over entire beam

For this analysis the beam made of Aluminum, with the dimensions as given in the below table. Spring constant for this case calculated from above equation (2).

Table 1: Dimension detail

Beam length (µm)	Beam width (µm)	Beam thickness (µm)
100	10	0.3 to 0.7

With this kind of load distribution a parametric analysis has been performed by varying the thickness of the beam. Given below is the table showing this analysis.

Table 2: comparison of spring constant and thickness for Case1

k/w(µm Nm)	**t/*l* (µm)**
0.05961	0.03
0.141	0.04
0.2760	0.05
0.4761	0.06
0.7575	0.07

In second case load distributed over the center portion of fixed-fixed beam

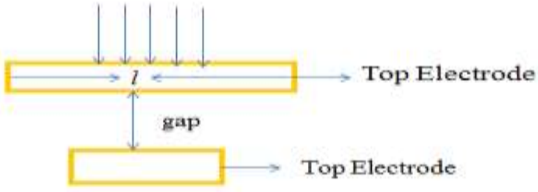


Fig.8 Case 2 load is evenly distributed about the center portion of beam

The spring constant of the fixed-fixed beam for case2 is

$$K=32Ew\left(\frac{t}{l}\right)^3\frac{1}{8\left(\frac{x}{l}\right)^3-20\left(\frac{x}{l}\right)^2+14\left(\frac{x}{l}\right)-1} \quad (5)$$

For case 2 considering same parameter as used for case 1, the spring constant for this case calculated from equation (5).

Table 3: Comparison of spring constant and thickness for Case2

k/w(µm Nm)	**t/*l* (µm)**
0.0298	0.03
0.0706	0.04
0.138	0.05
0.238	0.06
0.3786	0.07

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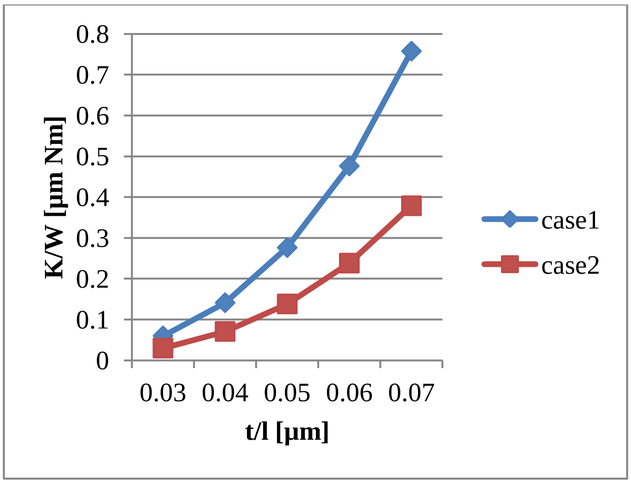

Fig.9 Comparison of thickness vs spring constant

In case of fixed-fixed beam, concentrating the load more toward the center of the beam results in a lower spring constant than the case where load is evenly distributed over entire beam.

Based on the above conclusion various models of switches have been proposed such that the load is concentrated on the centre of the beam rather than over the entire beam.

In fixed-fixed beam, anchors are grounded on CPW line and holes are added to reduce the stiffness of the beam.

Table 4: Gives the details of dimensions of model1 and model2

Design Name	Beam Width	Beam length	Beam thickness	Holes dimensions	Spring constant
Model 1	100µm	300µm	0.5 µm	10µmX10µm	0.57N/m
Model 2	120µm	300µm	0.5 µm	10µmX10µm	0.68N/m

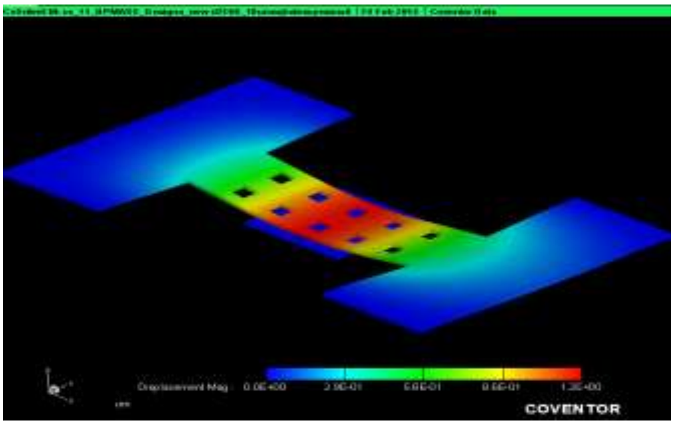

Fig.10 Displacement profile for model1

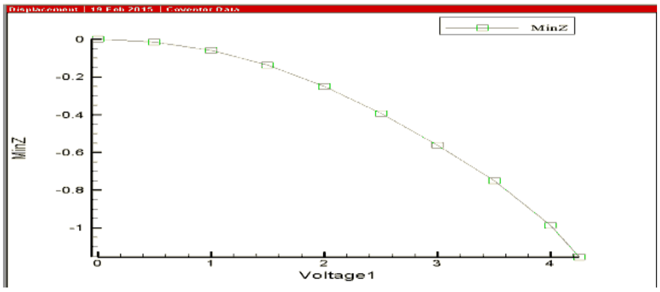

Fig.11 Displacement Vs. voltage

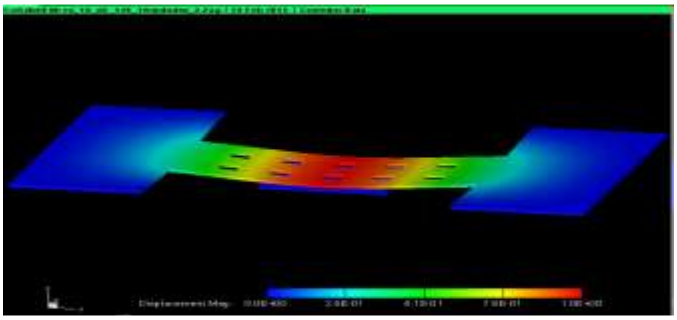

Fig.12 Displacement profile for model2

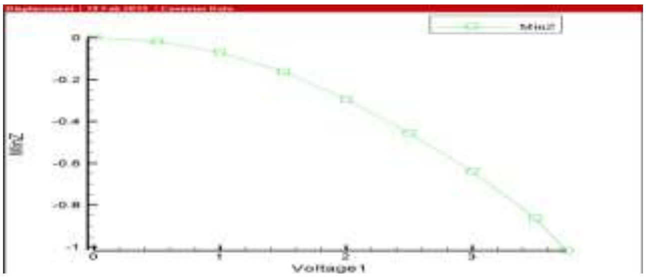

Fig.13 Displacement Vs voltage for model 2

The simulation result of the proposed model2 shows lower pull-in voltage 3.75V compared to 4.25V for model1, because actuation area is inversely proportional to pull-in voltage.

Table 5: Theoretical and simulated pull in voltage for different gap For model

Gap (µm)	Pull-in voltage (Simulated) (v)	Pull-in voltage (Theoretical) (v)
2.2	4.25	4.25
2.5	5.5	5.15
2.75	5.75	5.93
3	6.76	6.76

Table 6: Theoretical and simulated pull in voltage for different gap For model

Gap (µm)	Pull-in voltage (Simulated) (v)	Pull-in voltage (Theoretical) (v)
2.2	3.75	3.86
2.5	5.5	4.65
2.75	5.75	5.50
3	6.25	6.14

It is seen from the simulation results of model1 and model2 that the gap between top and bottom beam plays a pivotal role in determining the actuation voltage of the switch.

b)Fixed-Fixed flexure beam

Table 7: Dimension detail for model1, model2 and model3

Design Name	Beam Width	Beam length	Beam thickness	Holes dimensions	spring constant
Model 1	30µm	90µm	0.5 µm	10µmX10µm	1.60N/m
Model 2	40µm	90µm	0.5 µm	10µmX10µm	2.13 N/m
Model 3	50 µm	90 µm	0.5 µm	10µmX10µm	2.67N/m

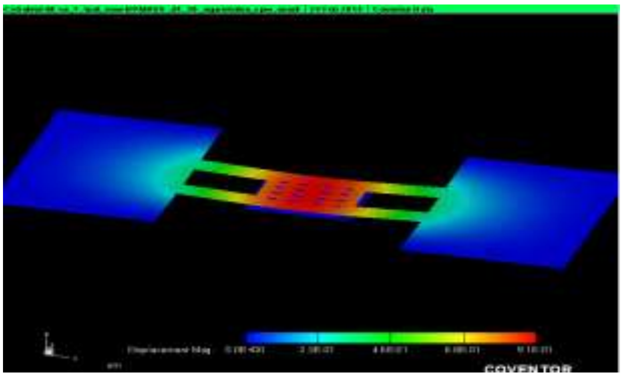

Fig.14 Displacement profile for model 1

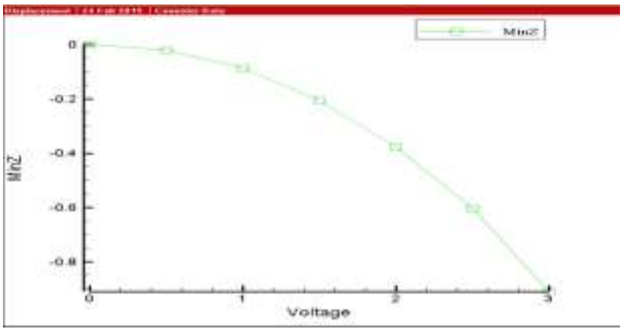

Fig.15Displacement Vs voltage for model1

The graph shows the displacement of the switch with respected to applied voltage. For 2.2µm gap, the actuation voltage in this case is 3v and displacement of beam of9.1µm.

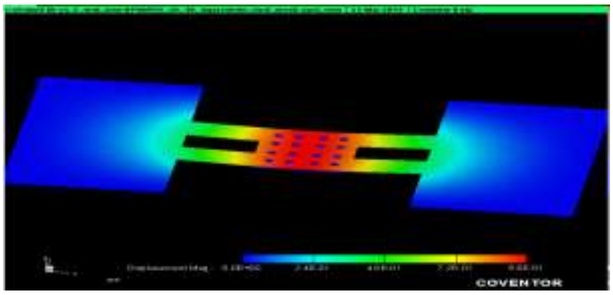

Fig.16 Displacement profile for model2

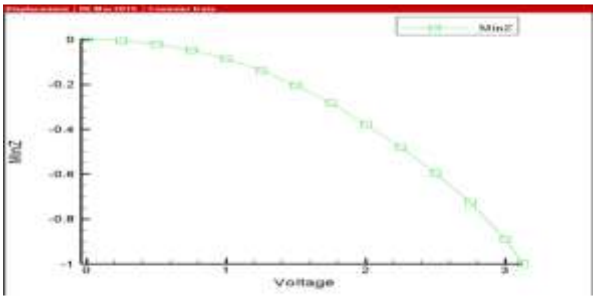

Fig.17 Displacement Vs voltage for model2

The graph shows the displacement of the switch with respected to applied voltage. For 2.2µm gap, the actuation voltage in this case is 3.125v and displacement is 0.96µm.

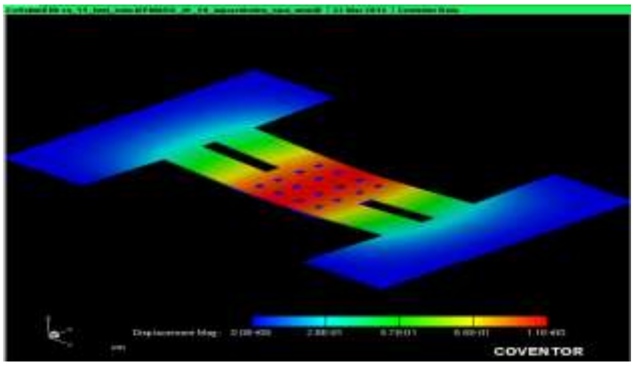

Fig.18Displacement profile for model 3

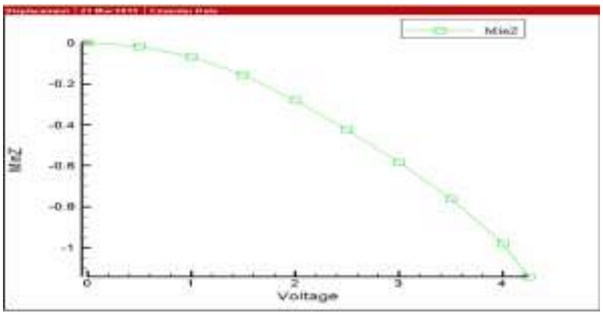

Fig.19Displacement Vs voltage for model3

The graph shows the displacement of the switch with respected to applied voltage. For 2.2µm gap, the actuation voltage in this case is 4.25v and displacement of beam is 1.1µm.

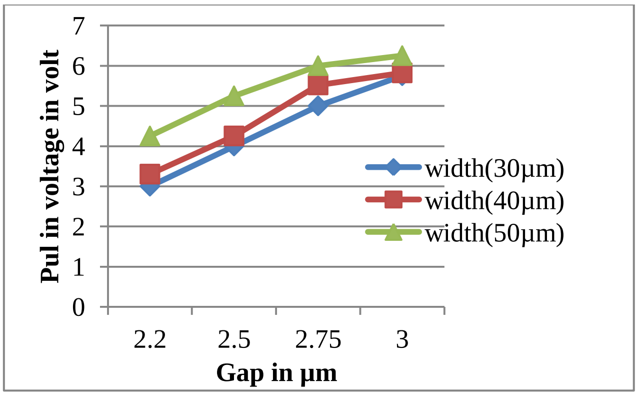

Fig.20 Pull-in voltage versus gap for different width

It is seen from the simulation results of model1 and model2 and model3 that the gap between top and bottom beam plays a pivotal role in determining the actuation voltage of the switch.

c) Serpentine flexure

In serpentine flexures beam as number of meanders increases actuation voltage decreases but reliability problems occurs but decreasing number of meanders actuation voltage increases.

Width(µm)	*la*(µm)	b(µm)	Thickness	Gap(µm)
10 µm	30 µm	15 µm	0.5 µm	2.2µm

Table8 Dimension table for serpentine flexures

For n=2,(where n is number of meanders in the serpentine

Flexures) and actuation area 100x100µm.

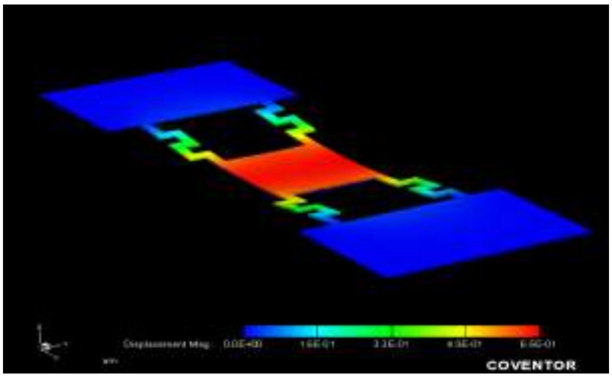

Fig.21 Displacement of serpentine flexures

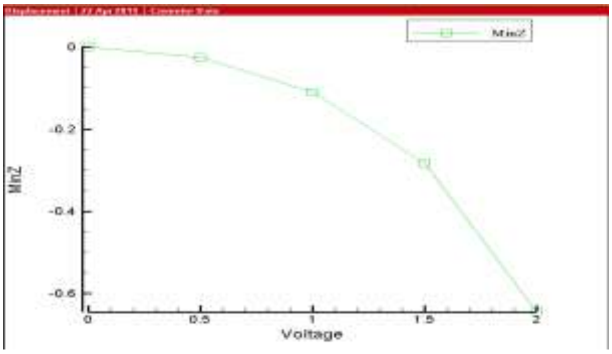

Fig.22 Displacement Vs voltage

In serpentine flexures beam the stiffness of beam is reduced in this structure and pull-in voltage achieved is 2V.

IV. CONCLUSIONS

The result of the simulations performed on all three configuration of switch is presented in this paper. It observed that the RF MEMS switch with serpentine flexure shows lower pull-in voltage compared to the other two configurations such as fixed-fixed and flexure beam.

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