Design and Simulation of Micro-Switches for RF Applications

Yashu A. Cotia
A.P. Thakur college of Engineering & Technology
Kandivali (E), Mumbai-101

Vivekanand Bhatt, Ph.D.
Scientist - 'D',Ministry of Defence,
Research & Development Establishment (Enggs),
DRDO

ABSTRACT

The acronym MEMS is used almost universally to refer to all devices that are produced by micro fabrication or micromachining except integrated circuit (IC). Micro machining is any process that deposits, etches, or defines materials with minimum features measured in micrometers or less. Micro-switches are essentially micro-cantilevers that are fixed at both ends. They are mainly used in MEMS applications such as filters and switches. The main stiffness of a fixed-fixed constant rectangular cross-section is the one relating to z-translation (bending about the y-axis) and is formulated at the midpoint of the switch.The work presented in this paper involves design and simulation of MEMS switches.The devices consist of different dimensions micro-switches varying length from 300um to 500um with three different widths (20um to 40um).The work focuses on the realization of electrostatic low actuation switches with main emphasis on the pull-in voltage and RF response.

General Terms

MEMS, Micro-machining, Micro-switches, Design

Keywords

RF MEMS, MUMPS, MEMSCAP, FEM.

1. INTRODUCTION

Micro-Electro-Mechanical-Systems (MEMS) technology offers several advantages forsystems design. These advantages include

the reducing the losses and providing a betterlinearity whencompared with semiconductor based devices. The advantages that areoffered by MEMS designs have been implemented in circuit tuning elements (capacitors,inductors), resonators, filters, microphones and switches.RF MEMS switches have experienced increased use for telecommunication application in the last ten years due to their high performance compared to other microelectronic switches [1]. A design of the DC contact RF MEMS switch is presented in this paper. The design was optimized in the terms of activation mechanism, which included switch beam thickness, beam gap and materials. The pull-in voltage, contact and resonance frequency were analyzed with commercial CAD finite element analysis software such as CoventorWare [15] .The optimized design was micro-fabricated by PolyMUMPS process [17].

Micro-switches are designed with regard to their switching speed and pull-down voltage. The switches are required to fulfil the requirements of high speed and moderate pull-down voltage for switching. Nowadays, these are becoming increasingly popular in RF applications due to their attractive advantages such as high isolation and low insertion loss [3].

Micromachining is the underlying foundation of MEMS fabrication, and a keyfactor for MEMS processes. In general, micromachining is such a process that selectivelyetches away parts of the silicon (or other substrate) wafer or adds new structural layers toform the mechanical and electromechanical devices [4]. The motivation for micromachiningthe MEMS devices is that it allows miniaturization and parallel processing, which leads toinexpensive fabrication in large quantities. This coupled with thin film deposition andetching techniques is used to create complex MEMS structures.

The structures were fabricated through the Multi-User MEMS Processing Service (MUMPS) provided by MEMSCAP.CoventorWare is used to simulate and analyze the behaviorof the device.

CoventorWare supports both system-level and physical design approaches [16]. The system-level approach involves use of behavioral model libraries with a high-speed system simulator. The physical approach starts with a 2-D layout and involves building a 3-D model, generating a mesh, and simulating using FEM or BEM solvers. Finally, the verified 2-D layout can be transferred to a foundry for fabrication.

2. MICRO-SWITCH STRUCTURE
2.1 Schematic and Activation Mechanism

The micro-switches are required to fulfil the requirements of high speed and a moderate pull-in voltage for the switching, as switching speed increases with actuation voltage. In this work, the fixed-fixed beam shunt switches are designed and simulated. Highly doped silicon substrate constitutes the bottom electrode. When a DC bias voltage is applied between the top and bottom electrodes, the developed electrostatic force attracts the beam towards the fixed ground plane [9]. As both ends of the beam are fixed, unlike the parallel plate actuator, a higher charge concentration occurs in the middle region of the beam compared to the regions near to the fixed ends. Consequently, the beam experiences a higher force in the middle region compared to the fixed ends as shown in the following Figure 1. At static equilibrium, the electrostatic attraction force is counterbalanced by the elastic restoring force [13]. During operation, if the electrostatic force due to an increased drive voltage overcomes the elastic restoring force, the equilibrium is lost and the beam collapses on the fixed ground plane due to the ‘pull-in’ phenomenon. The name ‘bridge’ shall be used interchangeably for the fixed-fixed beam.

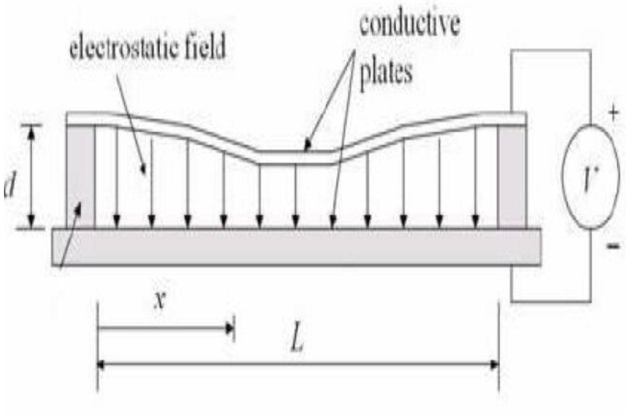


Figure 1- Electrostatically deflected fixed-fixed beam

When the voltage is applied between a fixed-fixed beam and the pulldown electrode, an electrostatic force is induced on the beam [5]. The electrostatic force applied to the beam is found by considering the power delivered to a time-dependent capacitance and is given by

$$F_e = \frac{1}{2}V^2\frac{dC(g)}{dg} = -\frac{1}{2}\frac{\varepsilon_0 WwV^2}{g^2} \quad (1)$$

where V is the voltage applied between the beam and electrode. Ww is the electrode area.

The electrostatic force is approximated as being distributed evenly across the beam section above the electrode. Equating the applied electrostatic force with the mechanical restoring force due to the stiffness of the beam (F= Kx),

$$\frac{1}{2}\frac{\varepsilon_0 WwV^2}{g^2} = k\,(g_0 - g) \quad (2)$$

Where g0 is the zero-bias bridge height. At (2/3g0), the increase in the electrostatic force is greater than the increase in the restoring force, resulting in the beam position becoming unstable and collapse of the bam to the down-state position. The pull-down (also called pull-in) voltage is found to be

$$V_p = V(2g_0/3) = \sqrt{\frac{8k}{27\varepsilon_0 Ww}g_0^3} = \sqrt{\frac{8k}{27\varepsilon_0 A}g_0^3} \quad (3)$$

As shown in Eq. (3), the pull down voltage depends on the spring constant of beam structure, and, beam gap g0 and electrode area A. To reduce the actuation voltage, the key is beam structure of low spring constant k. The pull-in voltage was investigated in terms of beam thickness, gap and beam materials.

A simpler expression for resonance frequency can be written as a function of spring constant and mass of the beam.

$$f_{res} = 1/2\pi\,(K/m)^{½} \quad (4)$$

The relation in Eq.(4) shows that the resonance frequency increases as a function ofincreasing spring constant and of decreasing with cantilever mass.

The resonance frequency f_0 for a micro-switch can be given as

$$f_0 = 1.028\, t/l^2\,(E/p)^{½} \quad (5)$$

Where p is the mass density.

2.2 Fabrication

In the present work, micro-switceswere fabricated using the three layers polysilicon surface micro-machining PolyMUMPSprocess.In this process polysilicon is used as a structural layer and silicon dioxide is used as a sacrificial layer. The sacrificial layer is etched out by dry etching process using hydrogen fluoride, which results to release the array of cantilever beams. A layer of gold was deposited above the top polysilicon layer, which acts as the top electrode for characterization [6].

In this work, we have used Scanning Electron Microscope (SEM) to visualize thefabricated devices, that whether they are perfectly released or not. Following Figure 2shows the SEM(Scanning electron microscopy)photograph of the fabricated micro-switches. From following figure, it is clear that the micro-switch beam is released successfully.

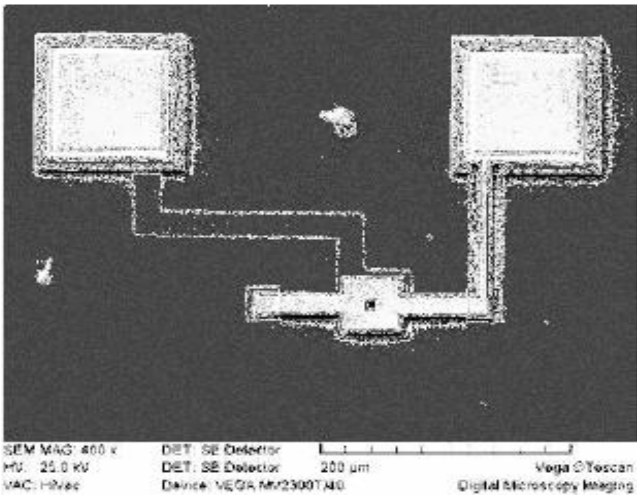


Figure 2- SEM photograph of released micro-switch

3. SIMULATED RESULTS

CoventorWare is one of the most versatile MEMS simulation tool in the market at present.It allows for user to perform a wide variety of simulations on any MEMS structure and can provide significantly accurate results using Finite Element Method (FEM).It supports both system level and physical designs approaches. The system-level MEMS designs can be used to generate 2-D layout for physical level verification. The physical approach starts with 2-D layout and involves 3-D models, generating a mesh and simulating. The 3-D model for micro-switch is shown in figure 3.

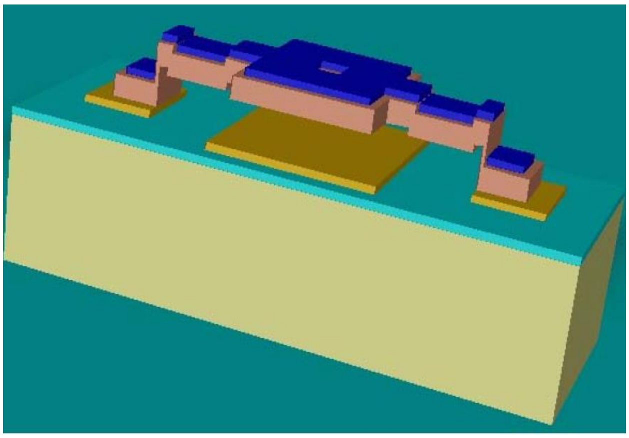
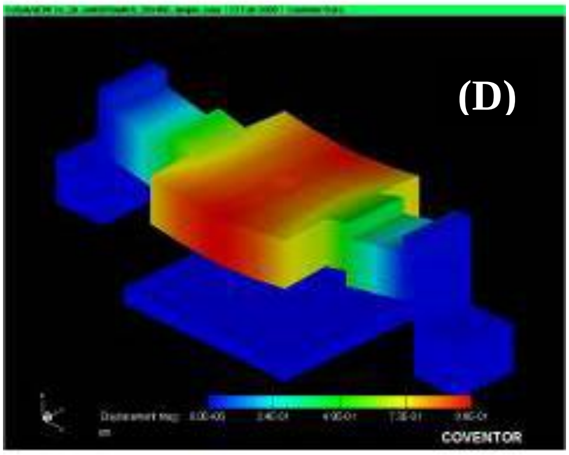


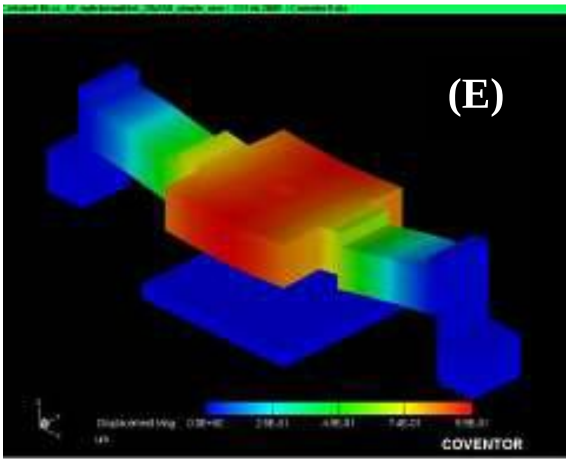
Figure 3- 3D solid model of micro-switch

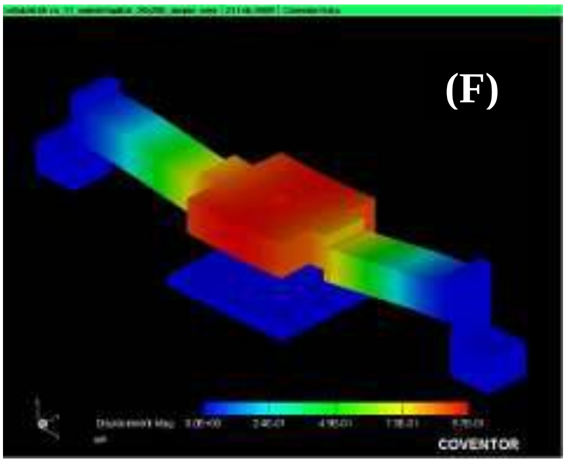
All of the simulations are performed using the MemElectro Solver, Mechanical Solver and CoSolve EM solver. Following are some simulated results:

3.1 Pull-in Analysis

The following Figure 4,shows the deflection profile of various different dimensionalmicro-switches. It is cleared from the analysis that maximum deflection occurs at the center of the switch whereas minimum deflection occurs at the anchors. Pull-in voltages of different devices are summarized in Table 1. The shorter length switch has the higher pull-in voltage.







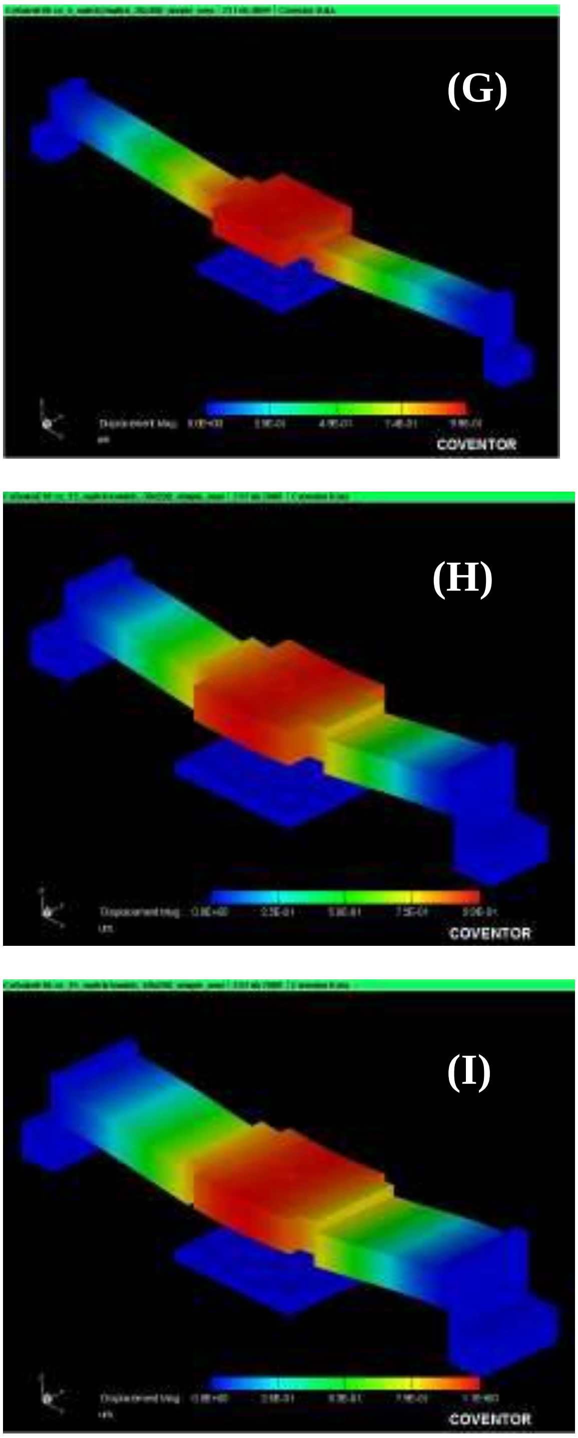


Figure 4- 3D view showing pull-in voltage profile of Different kind of Micro-switches. Pull-in voltage decreases from Type (D to I)

Table 1- Pull-in voltage for different kind of micro-switches

Device Name	Pull-in voltage (volts)	
	Simulated	Theoretical
Type D	219.6875	245.27
Type E	145.625	109.0
Type F	88.75	61.31
Type G	45.3125	27.25
Type H	99.375	61.31
Type I	105.3125	61.31

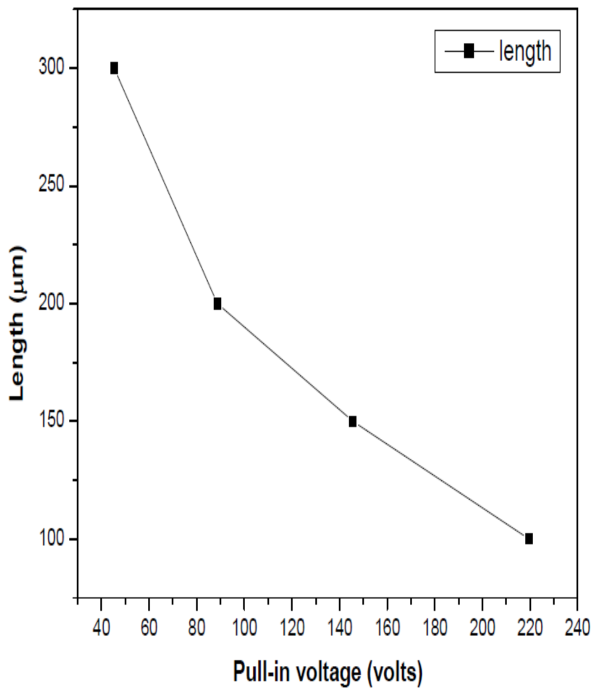


Figure 5 - Length vs Voltage

Figure 5 shows the curve for Length vs Pull-in voltage. From the Figures it has beendirectly cleared that as we increase the length pull-in voltage goes down.

The following Figure 6 shows the Displacement profile for lengths varying from100µm to 300µm at constant width of 20µm. After the occurrence of pull-in voltage, thedisplacement increases constantly.

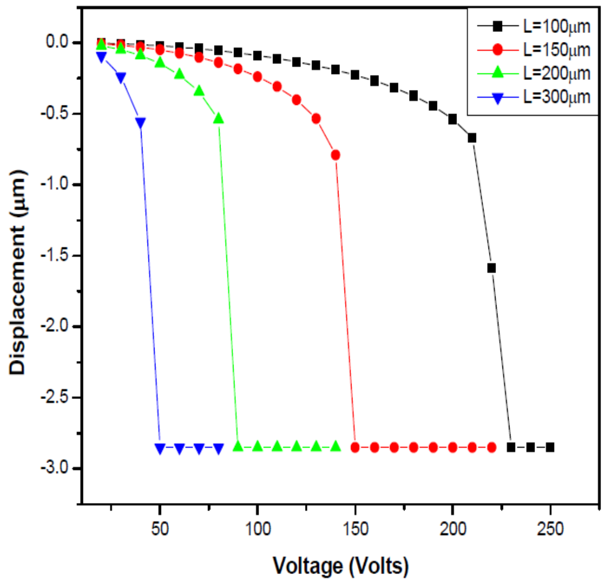
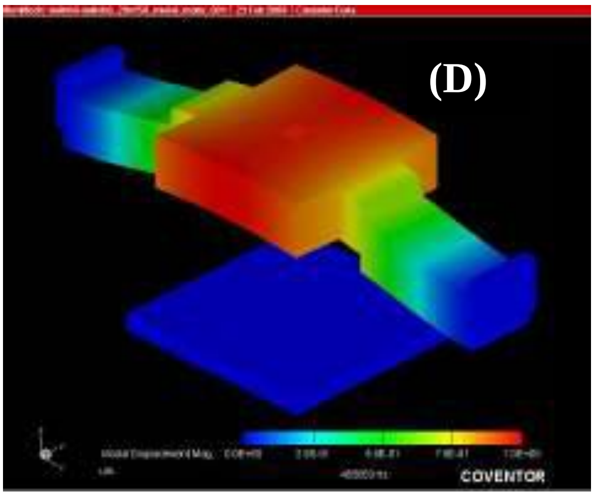
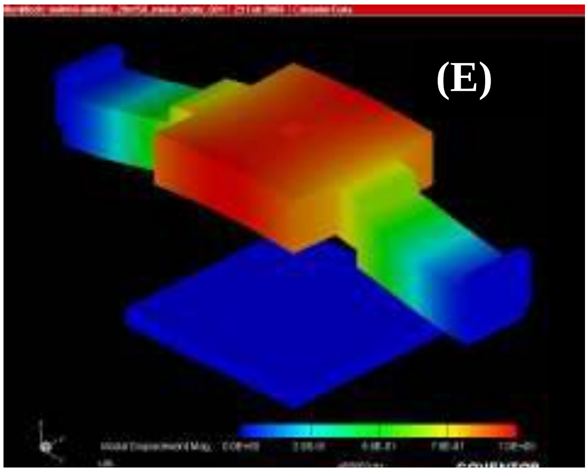


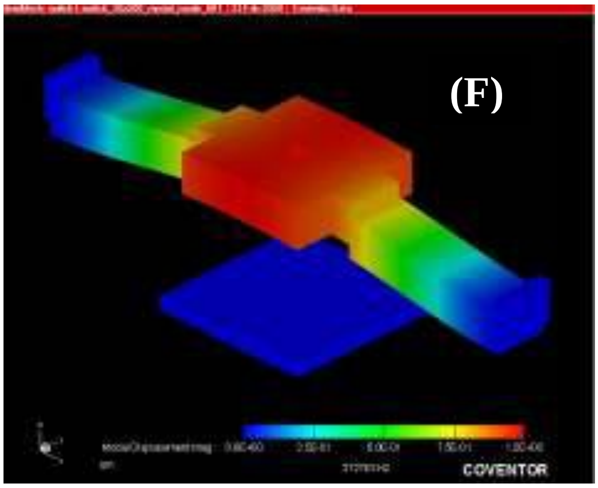
Figure 6- DisplacementVs Voltage Curve for constant width =20µm.

3.2. Resonance Frequency Analysis

Figure 7 shows the resonance frequency profile for different dimensional micro-switches.As the length of the fixed-fixed beam increases the resonance frequencydecreases. Table 2 shows the values of the resonance frequency for different dimensions.







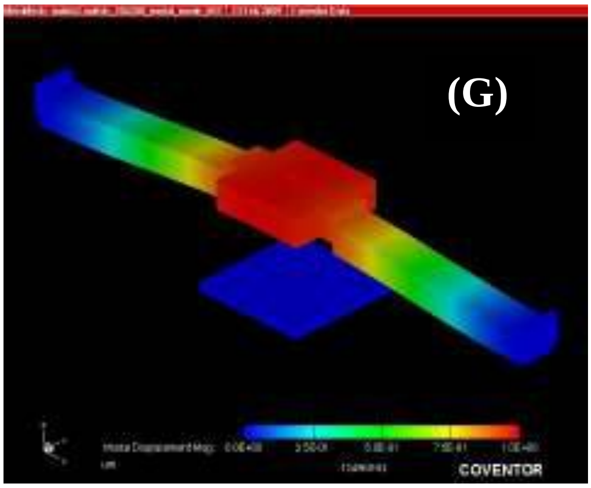


Figure 7- 3D resonance frequency profile of different dimension switches from Type (D to G)

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Table 2 - Resonance frequency for different kinds of micro-switches

Device Name	Resonance Frequency	
	Simulated (MHz)	Theoretical (MHz)
Type D	1.7	1.3
Type E	0.48	0.58
Type F	0.27	0.32
Type G	0.12	0.14
Type H	0.29	0.32
Type I	0.29	0.32

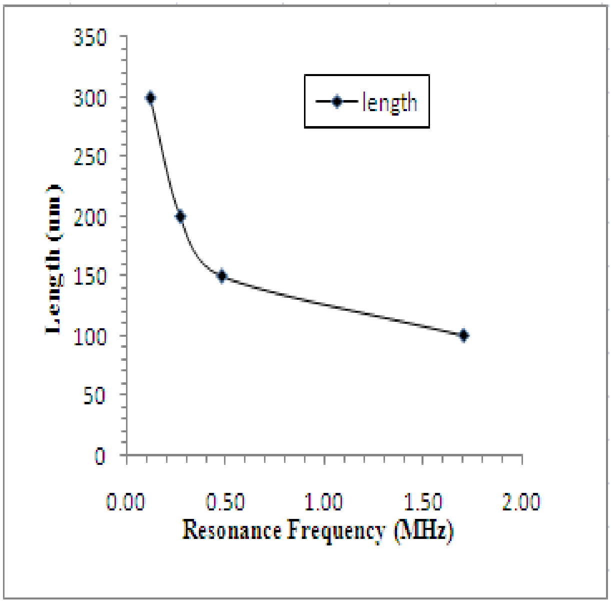

Figure 8 - Length vsResonance Frequency

Figure 8 shows the curve for Length vs Resonance Frequency. From the Figures it has beencleared that as we increase the length resonance frequency decreases.

4. CONCLUSION

In this paper, we study the behaviour of various kinds ofmicro-switches to solve the static part of the problem and decidedthe pull-in voltage and resonance frequency for different geometric parameters of the beam. The parameters studied were beam length, thickness,width and gap.Micro-switches have higher spring constant. The pull-involtage of micro-switches is higher because of higher stiffness of fixed fixed beam. The shorter length switch has the higher pull-in voltage.Resonance Frequency decreases as the length of the Switches increased.Future work of characterization is in progress.

MEMS based switches promise superior performance relative to conventional devices.Through its superior performance characteristics, the MEMS switches are developed in anumber of existing circuits, including switches, phase shifters and filters.

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